The Bass clarinet in bassoon form: its history, repertoire and acoustics

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[The tone of the bass clarinet] has something indescribably pleasant about it ... Anyone who hears the bass clarinet will certainly thank Mr. Streitwolf for this new orchestral gift.

Johann Gottfried Heinroth (1829).

Cover picture: the earliest surviving bassoon-form bass clarinet, made by Heinrich Grenser in Dresden, 1793, now in Stockholm (S.S.m.M2593). Image courtesy Scenkonstmuseet/Swedish Museum of Performing Arts, Stockholm. Photograph Sofi Sykfont.

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[1] https://mimo-international.com/MIMO/about-mimo.aspx. The images in this database are freely reproducible.

Abstract

This thesis explores the history, repertoire and acoustical properties of the bassoon-form bass clarinet: arguably the first successful bass clarinet type. More than 80 such instruments have been found in museums. The emphasis throughout the thesis is on understanding the empirical evidence that exists in the surviving instruments and in the musical repertoire.

The establishment of this form is traced through primary and secondary sources and the extant instruments. An improved typology of the bassoon-form type is presented, based upon the acoustic properties of its different variations: true bassoon-form, bassoon-form with left-hand keys, half-bassoon-form and ophicleide form.

The early repertoire for the bass clarinet is reviewed. It is shown that bassoon-form instruments (1793 onwards) and straight-form instruments (1838 onwards) were both introduced in Art music and in military and civil bands, until *c*.1850. The straight form then became the instrument of choice for Art music, whilst variants of the bassoon-form continued in bands until *c*.1914 and were probably preferred for the latter role.

The main original contribution made in this thesis is to the modelling and analysis of the acoustical resonances of a set of thirteen bass clarinets, selected to examine various stages in their history. It was possible to calculate the intonation and pitch of the instruments with careful dimensional measurements, without playing them. Verification of the modelling was obtained by experimental and playing tests on one well-preserved instrument; musical examples are provided to illustrate the accuracy of the modelling. The Matlab™ code and data files are provided to allow continuation of this work. Significant acoustical differences were found between the bassoon- and straight- form instruments, primarily on the value and regularity of the important cutoff frequency. This was traced to the constraints innate in the different designs and methods of construction of the instruments.

Conventions

Before embarking upon the main narrative, it is useful to gather together and to discuss the nomenclature, notations and definitions that are used throughout this thesis.

Pitch notations

Many notations have been used to describe absolute pitch.[1] SPN (Scientific Pitch Notation) is used in this thesis. In SPN, notes are represented by their ordinary English names, capitalised and including any accidentals after the name, followed by a number representing the octave. Middle C is C4 and the tuning pitch of a modern orchestra is A4 = 440 Hz. Only the ranges appropriate to clarinets are shown though there is no limit to the ranges that can be expressed in this notation. SPN is increasingly used in the secondary literature on musical instruments as well as for almost all work on musical acoustics. It is precise and unambiguous (as long as 'SPN' is specified) for *sounding* pitch and it is very convenient for use in the acoustic description and analysis. However, it must be noted that since clarinets are transposing instruments, an additional step is required to specify which note is fingered on the clarinet, as discussed below. The notation is shown for reference in Figure C.1, together with ranges of clarinets and bass clarinets.[2]

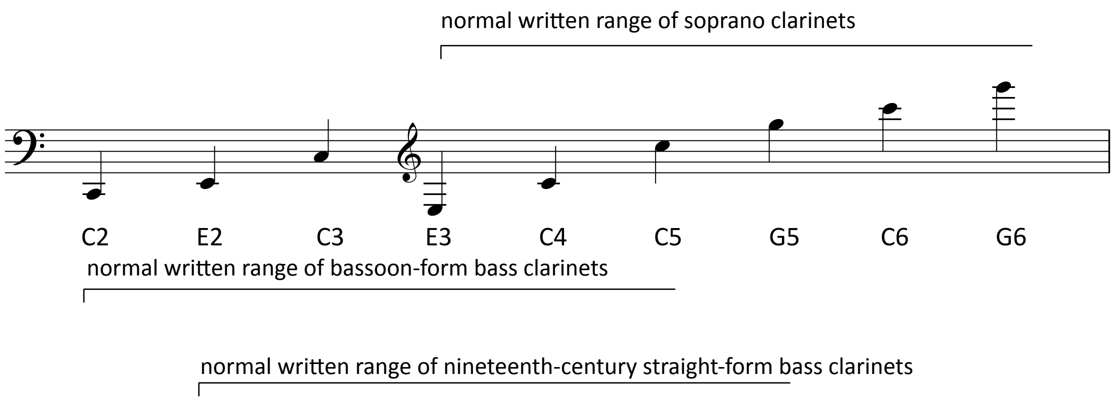

Figure C.1 SPN (Scientific Pitch Notation) and ranges of bass and soprano clarinets.

In this thesis, exact pitch names are given in SPN, e.g.

> … the lowest pitch of a standard soprano clarinet is E3 …

These are *as written in the score for the clarinet part* whatever clef or pitch class of clarinet is used, and should then be appropriately transposed according to Table C.1 to arrive at sounding pitch. For example, written C4 (middle C) *written in the treble clef* sounds B♭3 on a B♭ clarinet, A3 on an A clarinet, F3 on a basset horn in F and B♭2 on a bass clarinet in B♭. At first confusingly, if written in the bass clef, C4 sounds B♭3 on a bass clarinet in B♭ and F2 on a basset horn in F.

[1] Don Michael Randel, *The Harvard Dictionary of Music.* Cambridge, MA: Harvard University Press, 1986, 638.
[2] SPN is also known as American Standard Pitch Notation (**ASPN**) and International Pitch Notation (**IPN**))

Pitch classes are capitalized without number e.g. '… bass clarinets in A …', and these refer to the sounding pitch class when any written C is played on the instrument.

Written musical notations

Since clarinets are transposing instruments, it is necessary to distinguish between the pitch read by the player (and so labelled on the fingering charts for the instrument) and that produced by the instrument. The former is called *written* pitch and the latter *sounding* or *concert* pitch in this thesis. The *pitch class* of a clarinet, e.g. clarinet in B♭, means that a written C sounds a B♭. This notation does not say whether the B♭ is below or above the written C. Such distinction must be made by the name, e.g. 'piccolo clarinet in E♭' or 'alto clarinet in E♭'. Clarinets have been made in many pitch classes, but those of concern in this thesis are primarily bass and soprano clarinets in B♭, C and A, alto clarinets in F or E♭ and basset horns in F. The notations and transpositions are summarised in Table C.1.

Usual name	**Transposition of the instrument from the written part**		
Soprano, sopranino and basset clarinets			
Piccolo clarinet in E♭	Minor third up		
C	None		
B♭	Major second down		
A	Minor third down		
Alto or Tenor clarinets			
Basset Horn in F	Treble clef: perfect fifth down (usual notation) Bass clef (rarely used): perfect fourth up		
Alto clarinet in E♭	Treble clef: major sixth down Bass clef not used.		
Bass clarinets	*French notation*	*German notation*	*Russian notation*
Bass clarinet in A	Minor tenth down	Bass and treble clefs: minor third down	Bass clef: minor third down Treble clef: minor tenth down
Bass clarinet in B♭	Major ninth down	Bass and treble clefs: major second down	Bass clef: major second down Treble clef: major ninth down
Bass clarinet in C	Octave down	Bass and treble clefs: none	Bass clef: none Treble clef: octave down

Table C.1. The principal instruments of the clarinet family and their transpositions

Three notations are used for music for the bass clarinet.[3] The more common, known as *French notation*, is to write the music in the treble clef at a ninth (B♭ instruments) or minor tenth (A instruments) above sounding pitch. The parts are read in the same way as for the soprano instrument and it sounds an octave lower than the latter. In contrast, in *German notation* the notes are written in the bass clef at (transposed) pitch. Occasional high passages are written in the treble clef, also at transposed pitch (requiring the player to transpose an octave down from their normal expectation from soprano clarinet playing). Richard Wagner, Richard

[3] Oskar Kroll, *The Clarinet*, First English Edition edition (Batsford, 1968), 116.

Strauss, Gustav Mahler, Bohuslav Martinů and others used German notation routinely. Occasionally (as in works by Nikolai Rimsky-Korsakov, and Igor Stravinsky in *Rite of Spring* and sometimes even by Wagner) the bass clef is written in German notation and the treble clef parts in French notation. Quite convenient for the player, this is sometimes informally called *Russian notation* after its use by Stravinsky.[4] Sometimes the notation is ambiguous and in such cases the score may be more authoritative than the parts. It is usually possible to settle the question by looking at the highest and lowest notes written for the instrument and seeing whether they fit into its range, and by looking at passages that transit the clefs. In some early works for the bass clarinet, tenor clef is used at an octave higher than sounding pitch for the B♭ instrument, and in some cases publishers have changed the notation from the original manuscript to conform with market expectations. Figure C.2 shows a three-octave arpeggio written out in each of the main notations.

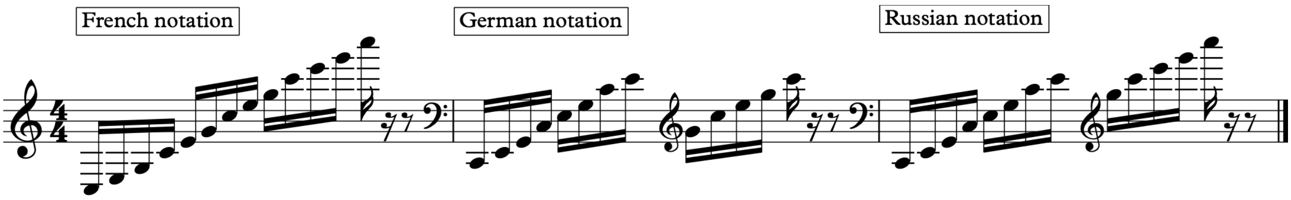

Figure C.2. A three-octave arpeggio written in the three common notations.

Nomenclature

The bass clarinet is pitched exactly an octave below the corresponding soprano clarinet, and commonly stands in B♭; instruments were and are occasionally made in C and A. The range is normally chromatic down to written E2 or E♭2 (the latter is an additional semitone with respect to the soprano clarinet) and 'extensions' down to C2 or even below are common for orchestral and clarinet choir instruments. Instruments intended for wind bands are usually to E2 or E♭2, and this was the range used for straight-type instruments during almost all the nineteenth century.[5] Bassoon-form instruments, however, almost invariably descended to C2 and in some cases to B1 or B♭1. The bass clarinet is approximately twice the length of the soprano clarinet, but not twice the bore. For proper acoustic scaling, the *area* of the bore should be approximately double that of the soprano instrument. The soprano clarinet is normally 14 – 15 mm bore, which should therefore scale to 19.8 – 21.2 mm in a bass clarinet. However, the modern bass is between 21 and 24 mm bore. In contrast, the nineteenth-century instruments, were usually 18 – 22 mm bore with most around 20 mm. They would thus have been less powerful, but more similar in sound to a soprano clarinet. Most German bass clarinets are still around 19 – 20 mm bore, for example the 1964 Fritz Wurlitzer formerly

[4] Jason Alder, 'A Guide to Understanding Bass Clarinet Clef Notation,' (blog), https://www.jasonalder.com/blog/2020/02/20/a-guide-to-understanding-bass-clarinet-clef-notation/ accessed 15 July 2021.

[5] D. Keith Bowen, 'The Rise and Fall of the Bass Clarinet in A,' *The Clarinet*, 38 (2011) 44–51; D. Keith Bowen, 'The Rise and Fall of the Bass Clarinet in A'. MA Dissertation, The Open University, Milton Keynes, 2009.

owned by Sir Nicholas Shackleton (GB.E.u.4923) at 19.2 mm.[6] The straight-form instruments made by Adolphe Sax and his immediate followers, however, had much larger bores, up to 30 mm.

Many terms have been used to describe the bass clarinet, for example Baßclarinetten, Clarinettenbass, Schollbass, clarone, bass orgue, basse tube, clarion, clarone, clarinette violoncello, fagottino, polifono, contro clarinetto, glicibarifono, bass guerrière, bimbonclaro, clariofon etc. (for attributions see Rice[7]). Part of the difference is linguistic, part commercial in an attempt to make the new instrument sound attractive to customers, and part a simple individual attempt to name a completely new instrument. Note that its analogue in other soprano woodwind families would not become popular until later in the nineteenth century (bass oboe) or twentieth century (bass flute).[8] Unless the exact term is relevant, I shall use *bass clarinet* or sometimes simply *bass* where the context is clear.

Fingering notations

Where needed, a conventional fingering diagram is used. Sometimes precise fingering and hole descriptions are needed in text. The fingers are denoted as T1234 and the left and right hand by R or L, respectively. Thus the middle C on a soprano clarinet is fingered as LT123. All woodwinds have six primary holes, three for each hand, covered by L123 and R123. The holes themselves are referred to as I II III IV V VI. These are illustrated in Figure C.3.

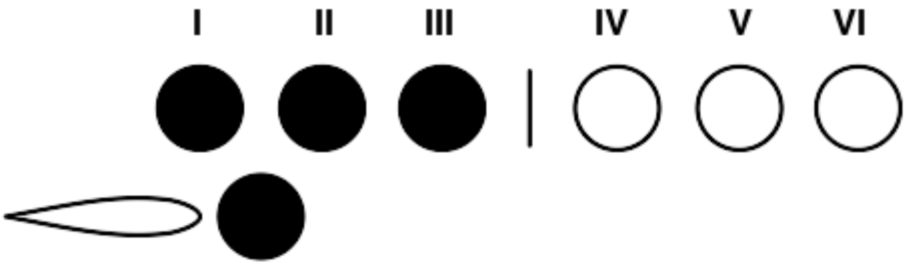

Figure C.3: The primary hole labelling on almost any woodwind instrument. The fingering for middle C on a soprano clarinet is shown.

[6] Arnold Myers, *Catalogue of the Sir Nicholas Shackleton Collection*. Edinburgh: EUCHMI, 2007, 741. All instruments discovered are catalogued, in Chapter 4, *Extant bassoon-form bass clarinets*.

[7] Rice, Albert R. *From the Clarinet D'Amour to the Contra Bass: A History of the Large Size Clarinets*, 1740-1860. New York: OUP USA, 2009, 250.

[8] Janet K. Page and Michelle Vigneau. "Oboe." *Grove* Music *Online.* 31 Jan. 2014; Accessed 9 Nov. 2021. https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-1002257105; Page, Janet K. Geoffrey Burgess, Bruce Haynes, and Michael Finkelman. "Oboe." *Grove Music Online*. 2001; Accessed 9 Nov. 2021. https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000040450; Montagu, Jeremy, Howard Mayer Brown, Jaap Frank, and Ardal Powell. "Flute." *Grove Music Online*. 2001; https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000040569

Museum sigla and instrument designations

The usage in this thesis, known as the New Grove notation, follows the latest recommendations by the Comité International des Musées et Collections d'Instruments et de Musique (the International Committee of Museums and Collections of Instruments and Music) known as CIMCIM. A list of museums and their sigla is provided online.[9]

The siglum for a museum collection containing musical instruments consists of three (and only three) fields, separated by periods.

- The first field, which must be in upper case, is the reference for the country.
- The second field, which must also be in upper case, is the reference to the city.
- The third field, which must be in lower case, refers to the museum name.

The abbreviations for countries, cities and museums are given in the CIMCIM list. If a city name does not appear in the list then it is spelt out in full. This might happen for private collections. In that case the name of the collector is also spelt out, in the third field.

After these three fields, which uniquely designate the collection, is added (after another period) the museum inventory number. For example, the instrument shown in Figure 1.1 has the sigil S.S.m.M2653. On consulting the CIMCIM list, we see that the country is Sweden, the city Stockholm, the museum the Musik– & Teatremuseet and its museum collection number is M2653. This method uniquely identifies any instrument in any collection.

[9]'Sigla for musical instrument collections'. https://cimcim.mini.icom.museum/wp-content/uploads/sites/7/2020/05/Sigla-for-Musical-Instrument-Collections.pdf accessed 5 November 2021.

Chapter 1

Introduction and context

Introduction

The development of sections of the modern orchestra has not been uniform across all types of instruments. The string instruments trace their recognisable forbears to the sixteenth century.[1] Whilst brass and wind instruments originally appeared in the prehistoric period, their adoption into the instrumental ensemble known as the orchestra came at different times for the different instruments.[2] The clarinet was the most recent addition, from the mid-eighteenth century. In any woodwind family, the bass instruments were the last to emerge, for technical reasons of manufacture. In the case of the clarinet family, there was over a century of experimentation until the modern form of the bass clarinet was developed. But, as already noted in 'Conventions', despite the clarinet being the last major orchestral wind instrument to be adopted, its bass versions became available much earlier than those of the flute and oboe. It was clearly perceived to have an important use, first in opera (e.g. Mercadante, Verdi, Rossini and Wagner) and later in the orchestra (e.g. Liszt, Dvorak, Strauss).[3] In parallel, it soon found an important use in the military or civil wind band, to provide a more portable and more powerful woodwind bass than the bassoon. These uses have been maintained until the present day and indeed burgeoned, so that the bass clarinet is now also a popular and recognised solo instrument.

A visitor to a musical instrument museum will frequently notice instruments in the bass clarinet section which look nothing like modern clarinets, even though the latter have existed in near enough their current form for much more than a century.[4] Instead of being one straight pipe from top to bottom, with curved necks or bells for the larger instruments, they are compactly folded like a bassoon. The air column bends back on itself at the bottom of the instrument and emerges in a bell near the head rather than by the feet of the player. Such folded instruments are even to be seen occasionally in soprano, alto or bassethorn versions.[5]

As a player of a modern bass clarinet, I became fascinated by the possibilities of an instrument that was half the overall length of the unwieldy modern professional bass clarinet and yet, on inspection, turned out to have been provided with all the low notes that the modern instrument has, even with its so-called low-C extension. Its range descends an octave plus at least a major third lower than the contemporary soprano clarinet; an identical range, an octave lower, to the famous basset clarinet of Anton Stadler, for whom Mozart wrote the

[1] Philibert Jambe de Fer, *Epitome musical des tons, sons et accordz, et voix humaines, fleustes d'Alleman, fleustes à neuf trous, violes et violons: item, un petit deuis des accordz de musique, par forme de dialogue interrogatoire & responsif entre deux interlocuteurs.* Lyon: Du Bois, 1556.
[2] Adam Carse, *The Orchestra*. London: Max Parrish & Co. 1949. (Whole book).
[3] Albert R. Rice, *From the Clarinet D'Amour to the Contra Bass: A History of the Large Size Clarinets, 1740-1860* New York: OUP USA, 2009. 339-386.
[4] e.g. Oskar Kroll, *The Clarinet*, First English Edition edition. London: Batsford, 1968. 112.
[5] Over 80 such folded instruments are known; a comprehensive list appears in Chapter 4.

clarinet quintet K581 and the concerto K622.[6] Stadler's instrument was, if not unique, certainly very rare and not re-created until the mid 20th century.[7] Yet a compact bass instrument with this range would surely be of value in, for example, the marching band and the opera pit.

The great majority of bassoon-form clarinets are bass clarinets. It is pertinent to inquire how such instruments were used, what changes occurred in their design during their period of use, why such instruments are no longer in use, and even whether the bassoon-form instrument should be revived for period performances.

The bassoon-form bass clarinet is the topic of this doctoral project: its history and development, and its eventual decline. We can only obtain pointers to the reasons for growth or decline in the use of a particular design of musical instrument, since this forms part of a complex network that includes not only makers but players, composers, conductors, critics, audiences and even the politics surrounding both the construction of ever-larger concert halls and opera houses and the imperial expansion in many countries that demanded impressive standards of military bands. It might be possible to address this complexity by the methodology of actor-network theory, but this is beyond the scope of this thesis.[8] My choice has been to focus on the empirical evidence: that of the instruments themselves and of the available and reported repertoires, and the relationships between these two points of the network. This is not to neglect the examination of historical documentary and iconographic sources but to complement it with material that such sources cannot reveal.

First, one may ask how bassoon-form bass clarinets were constructed, how they fit into the overall typology of the instrument, and how they fit into the oeuvre of reputable makers. I examine the information provided by the large numbers of bassoon-form bass and other clarinets in museums, and in particular, discover what may be learned from a detailed study of their construction, acoustical behaviour, the geographical distribution of their makers and their use in the repertoire. This approach goes well beyond qualitative observation of the design and construction of the instruments. Rather than the simple measurement of sounding length (which is all the quantitative information to be found in most publications on instruments in collections), very detailed measurements are made of the bore profile, tone hole and keypad positions and shapes in a number of important cases. A computer program based on existing acoustical theory was developed and validated in order to predict the fingering, pitch and intonation of an instrument and an estimate of the quality of its sound, from these dimensional measurements. A set of thirteen bass clarinets (including two examples of both forms made by the same maker) was examined by this computer modelling approach of their acoustic behaviour. They were selected to answer critical questions,

[6] Pamela Poulin, 'Anton Stadler's Basset Clarinet: Recent Discoveries in Riga,' *Journal of the American Musical Instrument Society* 22 (1996) 110–27.

[7] Albert Rice, 'The Basset Clarinet: Instruments, Makers, and Patents'. In *Instrumental Odyssey: A Tribute to Herbert Heyde,* Ed. L. Libin, Hillsdale, New York: Pendragon Press, 2016, 157-178. Eric Hoeprich, *The Clarinet.* New Haven and London: Yale University Press, 2008, 121-122.

[8] Benjamin Piekut. 'Actor-Networks in Music History: Clarifications and Critiques'. *Twentieth-Century Music* 11 (2014) 191–215. https://doi.org/10.1017/S147857221400005X

including how the instruments developed acoustically, and whether any systematic acoustic differences can be expected between bassoon-form instruments and straight instruments.

The other empirical evidence is that of the available repertoire, whether surviving or reported. How were the instruments used in operatic or orchestral repertoires and in civil and military bands? How was the bass clarinet in general used in the musical repertoire of the nineteenth century, and are any differences found between the uses of the bassoon-form and the straight-form instruments? The musical repertoire for the bass clarinets of the period, and comments by contemporary sources, provide evidence about the usage of the instruments, and their adoption or otherwise in the main fields of bands, recitals, operas and concert halls.

The bassoon-form bass clarinet

During the eighteenth and early nineteenth centuries, as the clarinet became established as a major orchestral and chamber music instrument, there were many attempts to produce a tenor or bass instrument in the clarinet family. The first successful such instrument – defining 'success' as meaning adoption by many makers and composers or players rather than by a sole inventor – was the eighteenth-century basset horn. This was a clarinet made longer so as to be pitched a fourth lower than the usual B♭ instrument; the lower range was also extended downwards, usually by a major third.[9] However, the bore was not scaled appropriately with the length and was kept at around 14-15 mm, similar to the common soprano clarinet. This resulted in an instrument that had a range down to sounding F2 (at the bottom of the bass clef), but was still a perfect fourth higher than the lowest note of a cello and a fifth higher than that of a bassoon. It also had a unique tone, distinct from the soprano clarinet, and generally less powerful. Whilst used to great effect by Mozart and his contemporaries in chamber groups, operatic *obbligati* and occasional concerti, its relatively quiet dynamics meant that it did not work so well for a bass line in larger groups. It was rarely used in orchestral or operatic ensembles until the time of Richard Strauss, who used it to colour the harmony and in soloistic roles,[10] but did not find it useful for most harmonic writing.[11] A comprehensive list of orchestral works that use the basset horn has been published by Grass and Demus.[12]

[9] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 95.
[10] As, for example in Richard Strauss. *Der Rosenkavalier* (1910). Berlin: Adam Fürstner, 1910.
[11] Hector Berlioz and R. Strauss, '*Treatise on Instrumentation.'* (Tr. Theodore Front) New York: Kalmus 1948. Dover Reprint. New York: Dover 1991.
[12] Thomas Grass and Dietrich Demus, *Das Bassetthorn: seine Entwicklung und seine Musik*. Vol, *2. Auflage.* Norderstedt: Books on Demand, 2004, 227ff.

Figure 1.1. Bass in B♭, Heinrich Grenser 1793, Dresden, Germany. S.S.m.M2653. Image courtesy Scenkonstmuseet/Swedish Museum of Performing Arts, Stockholm. Photograph Sofi Sykfont.

There are a number of solitary inventions, or reports of inventions, of bass clarinets during the eighteenth century, which will be described in Chapter 2, *The development and typology of the bass clarinet*. However, it was not until the last decade of the century that a really successful model of bass clarinet was invented, using the above definition of success. This was the instrument in bassoon form, made by Heinrich Grenser in Dresden in 1793, shown in Figure 1.1.[13] Heinrich had been apprenticed to his uncle Augustin (a supplier of woodwinds to the Court of Saxony) during the period 1779 – 86, and indeed Augustin himself made a near copy of this instrument in 1795 - with the important invention of a second register key, which, as will be seen in Chapter 8, *Acoustic spectra of historical bass clarinets*, greatly improves the intonation of the upper register.[14] In 1796 Heinrich succeeded to the ownership of his uncle's workshop, on Augustin's retirement.

A later example (*c*.1828) of the bassoon-form instrument, due to Johann Heinrich Gottlieb Streitwolf is shown in Figure 1.2, labelled with the principal components of the instrument. This basic design and its descendants lasted over a century. The latest examples known are two instruments by Schediwa of Odessa, Ukraine, dated 1900 – 1910 by their museum collections.[15] More than 80 bassoon-form clarinets survive in museums in the world with at least 35 known makers, and there are about a dozen instruments without any makers' mark.[16]

[13] Now in Stockholm, S.S.m.M2653
[14] Now in Darmstadt, D.DS.hi.KG67:133
[15] GB.O.ub.401 and GB.E.u.4819
[16] See Chapter 4, *Extant bassoon-form bass clarinets*, for a full catalogue.

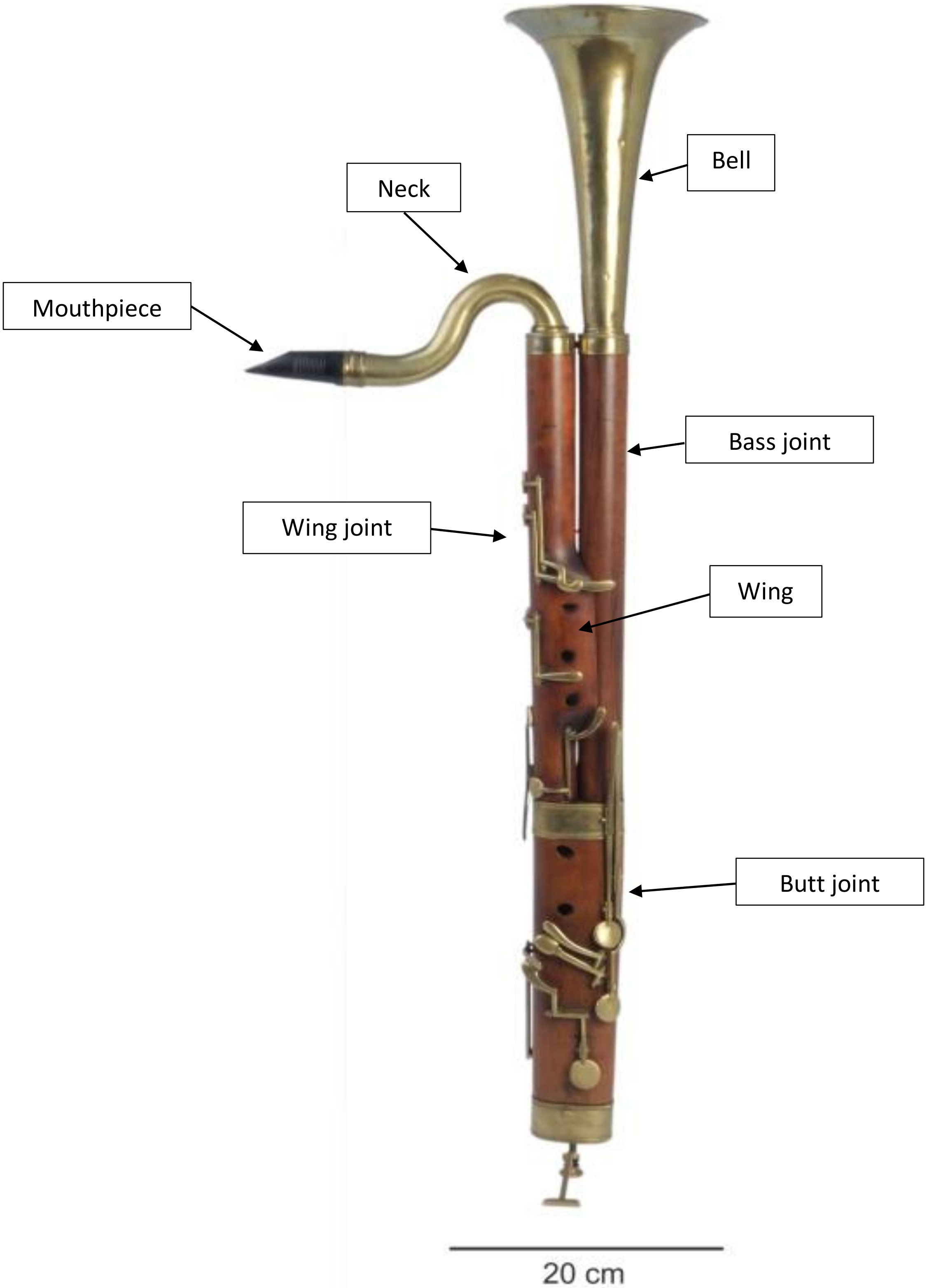

Figure 1.2. A bassoon-form bass clarinet by Streitwolf of Göttingen, 1833/37, D.LE.u.1539 with the principal components labelled. Note that the structure of this instrument is a mirror image of the Grenser shown in Figure 1.1. Image from MIMO.

The form was eventually superseded by the 'straight' form (German *gerade*), which is still in current use. The straight form always has a curved neck to present the mouthpiece at a suitable height and angle to the player. It may or, may not, have an upturned bell. An early example by Adolphe Sax is shown in Figure 1.3. Interestingly, the two forms coexisted for at least seventy years.[17] Chapter 3 investigates their eventually divergent role in the repertoire.

There are relatively few contemporary documentary and iconographic sources on the nineteenth-century bass clarinet that illuminate its development and reception. There are, on the other hand, many secondary sources, dating from the late nineteenth century to the present day. Both primary and secondary sources will now be discussed in order to provide the historical context for this research.

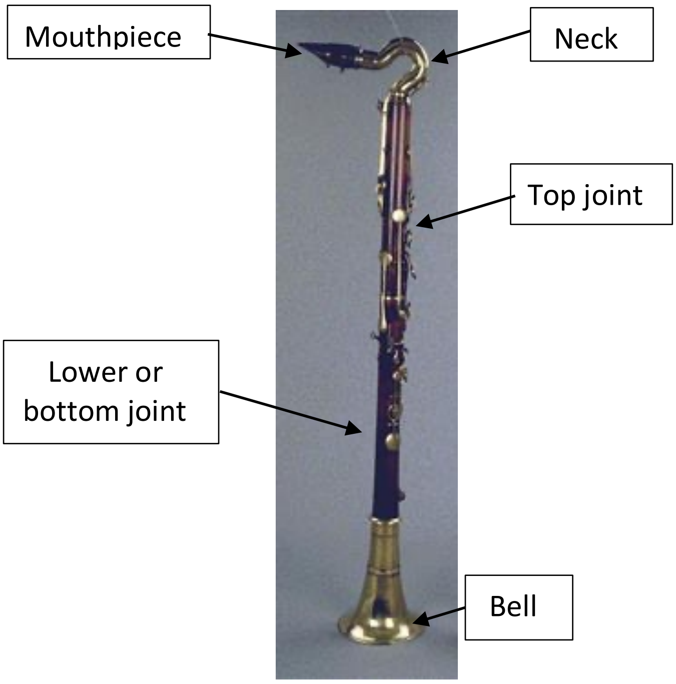

Figure 1.3 Bass clarinet by Adolphe Sax, Paris *c.*1843. F.P.cm.E.1223 C1337. Image from MIMO.

The bass clarinet in the literature

Encyclopaedias of music

Bass clarinets appear briefly in the first edition of the *Grove Dictionary of Music and Musicians* in a rather dismissive article, which includes:

> **Bass clarinets**. The commonest of these is in B♭, the octave of the ordinary instrument, but the writer has a C basso of Italian make, and Wagner has written for an A basso. They are none of them very satisfactory instruments; the characteristic tone of the clarinet seeming to end with the corno di bassetto.
>
> … They are all slow-speaking, hollow-toned instruments, rather wanting in power. … Although occasionally of value for producing exceptional effects [the bass clarinet] does not present any great advantages for orchestral use.[18]

[17] A typology and chronology is given in Chapter 2, *The development and typology of the bass clarinet*.
[18] W. H. Stone, 'Bass Clarinet,' in *Grove Dictionary of Music and Musicians, 1st. Edition*, vol. I . London: Macmillan, 1879, I:362.

This is surprising; by this time (1879) all of Wagner's operas had been performed, with prominent bass clarinet parts, as well as significant compositions by Liszt (*Dante Symphony*, 1856) and others using bass clarinets. No mention is made of the form of the instrument. In the second edition (1877-1889), in an entry by the same author, the second part of the quotation has been removed from an otherwise unchanged entry.[19] By this time the first four symphonies by Mahler had been written and even in England the instrument had been used in a major work by Sir Arthur Sullivan (*The Golden Legend*, 1886). Not until the fifth edition, is there a significant section on the bass clarinet, written by Rendall.[20] The material is also contained, in more detail, in Rendall's monograph.[21]

Musik in Geschichte und Gegenwart (*MGG*) discusses the clarinet family briefly in the 1958 edition, with a picture of a bassoon-form contrabass instrument[22] but the article makes no comment on either the design or the evolution of the instrument.[23] *MGG* does not discuss the clarinet family in detail until the 1996 edition but even here the historical development of the bass instrument is discussed very sparsely. Riehm also states in this article:

> Many early bass clarinets were in C, here they were used as customary bass instruments (in place of bassoon). As, after Meyerbeer's *Les Huguenots*, the bass clarinet took its place in the proper instruments of the orchestra, so it was built in A and B♭, similarly to the normal clarinets. Today, only instruments in B♭ are used.[24]

Shackleton, in *Grove Music Online* remarks that (excluding chalumeau) the earliest extant bass clarinet is probably that by Anton and Michael Mayrhofer of Passau (D.M.sm.52.50), then goes on to discuss the Heinrich and Augustin Grenser instruments:[25]

> These finely made instruments are pitched in B♭, with nine keys, and descend to written B♭1 (sounding A♭1). The keywork is diatonic from E2 down and there are two thumb-holes, in the manner of the bassoon of that period.[26]

The acoustic analysis in Chapter 8 shows that the bottom note is in fact B♮. Shackleton continues:

> It seems not unlikely that the instrument was intended to replace the bassoon in military bands

but gives no source for this suggestion. He goes on to mention early bass clarinets, or designs, by Louis Nicolas Victor Humont-Desfontenelles, Alexandre Dumas, the French patent by

[19] W. H. Stone, 'Bass Clarinet,' in *Grove Dictionary of Music and Musicians, 2nd. Edition*, vol. I. London: Macmillan, 1877-89 reprinted with corrections 1902, I:149–50.
[20] F. G. Rendall, 'Clarinet,' in *Grove Dictionary of Music and Musicians, 5th. Edition*, vol. I. Oxford: OUP, 1954.
[21] F. Geoffrey Rendall, *The Clarinet: Some Notes on Its History and Construction*. Third edition revised by Philip Bate. London: Ernest Benn, 1971.
[22] The instrument is by Wiepricht and Skorra, D.B.ga.120TD, *c*.1840.
[23] Heinz Becker, 'Klarinette. C. Die Europäische Klarinette.' in *Musik in Geschichte Und Gegenwart. I. Allgemeine Geschichte.* Kassel: Bärenreiter, 1958, 1006–27.
[24] Diethard Riehm (Ed.). 'Klarinetten. Abschnitt II'. In *Musik in Geschichte Und Gegenwart, Sachteil. Bd. 5.2. Neubearbeitete Auflage.* Ed. Ludwig Fischer. Kassel: Bärenreiter, 1996, 1005–27.
[25] S.S.m.M2653 and D.DS.hi.KG67:133 respectively.
[26] Nicholas Shackleton, "Bass clarinet." *Grove Music Online*. 2001; Accessed 9 Nov. 2021. https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000002236

François-Antoine Sautermeister[27] George Catlin, Johann Heinrich Gottlieb Streitwolf and Catterino Catterini, dating between 1807 and 1833. These makers all have significant roles in the history of the bass clarinet and their work is discussed in Chapter 2, *Bass clarinet development and typology*.

Monographs

There are several important monographs on the clarinet: Geoffrey Rendall,[28] Oskar Kroll,[29] Jack Brymer,[30] Johan van Kalker,[31] Günter Dullat,[32] Eric Hoeprich[33] and three volumes on historical clarinets by Rice[34] along with Anthony Baines' book on woodwind instruments.[35] Brymer's book, written mainly with the player in mind, mentions the bass clarinet only in passing, and Baines gives attention only to bass clarinets from and after Adolphe Sax, referring the reader to Rendall for further history. Rendall does give a detailed account of the history of the bass clarinet. He includes Lot's basse-tube (only known from documents), the Grenser and Catterini inventions of the bassoon-form instrument, the innovations of Streitwolf and the work of the contemporary but secretive Dumas, who reinvented the bassoon form but was unwilling to show it to others until on his deathbed.[36] He discusses Desfontenelle's first experimental straight-form instrument of 1807, the experiments of Dacosta and Buffet Jeune on the straight form, and finally the dominance of the new Adolphe Sax design of 1838. Since his book was published in 1954, some more instruments have been discovered, such as the original Heinrich Grenser instrument in Stockholm[37] and documents such as the patent of Françoise-Antoine Sautermeister for a bassoon-form instrument.[38] Rendall erroneously attributes the Grenser instrument in Darmstadt[39] to Heinrich, whereas it is stamped with the mark of his uncle Augustin. Rendall also makes an interesting remark on a disadvantage of the bassoon-form instrument:

> They all have one serious defect, the great difficulty of drying out the bore both during and after use.[40]

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[27] Françoise-Antoine Sautermeister, *Instrument à vent nommé bass-orgue*, French patent No. 755, filed August 12, 1812, and issued 1812.
[28] Rendall, *The Clarinet: Some Notes on Its History and Construction*. 1954
[29] Kroll, *The Clarinet*, 1968.
[30] Jack Brymer, *Clarinet*. London: MacDonald and Jane's, 1976.
[31] Johan van Kalker, *Die Geschichte Der Klarinetten*: *Eine Dokumentation.* Oberems: Verlag Textilwerkstatt 1997. *Die Geschichte der Klarinette: Eine Dokumentation*, Zweite überarbeitete und vermehrte Ausgabe, Munich: Katzbichler, 2020.
[32] Günter Dullat, *Klarinetten: Grundzüge Ihrer Entwicklung : Systeme, Modelle, Patente : Verwandte Instrumente : Biographische Skizzen Ausgewählter Klarinettenbauer (Fachbuchreihe Das Musikinstrument)*. Frankfurt am Main: E. Bochinsky, 2001.
[33] Eric Hoeprich, *The Clarinet*. London: Yale University Press, 2008.
[34] Albert R. Rice, *The Baroque Clarinet*. Oxford: Clarendon Press, 1992; *The Clarinet in the Classical Period.* Oxford: Oxford University Press, 2003; *From the Clarinet D'amour to the Contra Bass*, 2009.
[35] Anthony Baines, *Woodwind Instruments and Their History, Toronto: General Publishing* 1967.
[36] François-Joseph Fétis, 'Instrumens Nouveau. Clarinette-Basse,' *Revue Musicale* 7 (May 1833) 122-123.
[37] S.S.m.M2653
[38] Sautermeister, *Instrument à vent nommé bass-orgue*, filed August 12, 1812, and issued 1812.
[39] D.DS.hl.KG67:133
[40] Rendall, *The Clarinet: Some Notes on Its History and Construction*, 1954, 143.

Indeed, some of the bassoon-form instruments from the late nineteenth century, for example two soprano basset clarinets from Italy and a bass by Stengel[41], are fitted with keys that open drain holes ('spit keys') at the bottoms of the bores. These are distinguishable from tone holes as they are in the wrong positions for any notes in the chromatic scale and usually cannot be reached when fingers are in the playing position. An extended period of playing, which would be inappropriate on a museum instrument, would be necessary to test Rendall's suggestion. However, the presence of drain holes on some instruments does indicate the recognition and solution of a problem.

Kroll gives a summary of the history of the bass clarinet and its music, but it is much less detailed than Rendall, for example omitting mention of the Grensers. Van Kalker's book differs from the others in that he sets out purely to document the history of the instrument, the makers and what has been published about them. The book is particularly useful in citing and quoting original sources, and has an excellent classified bibliography.

Dullat is mainly concerned with descriptions of clarinets and the families of clarinet makers, and has a significant entry on bass clarinets and their history. He illustrates nine bassoon-form bass clarinets, though does not mention that these comprise only a small proportion of those known in museums. He also discusses the typology, perhaps in more sub-categories than is useful; for example, one of his classes, the 'V-shaped form', contains only one example and is not very different from his 'ophicleide' form.[42]

Hoeprich gives a narrative of the evolution of the bass clarinet and its music, classified by country, which lends a different perspective.[43] Hoeprich is not only a professional player but has also learned to make his own instruments, including some copies from his own large collection of historical instruments, which informs his discussion. His illustration of Sautermeister's patent[44] unfortunately appears to have been taken from a secondary source (as has that in Rice[45]) and is a line drawing rather than an engraving. The original shows considerably more detail, including inset drawings of all the keys, as discussed in the next section and shown in Figure 1.4.

Rice presents the most comprehensive account of the development of the bass clarinet, and its music, up to 1860.[46] He discusses a large number of makers, instruments, composers and music and provides much technical detail (especially on the keywork) and many original sources.

In addition, a number of doctoral theses, mainly from the USA, present information on the early bass clarinet. These have been partly, but not completely, summarized in the above books and encyclopedia articles. Charles Roeckle presents the first useful historical survey of

[41] I.R.ms.740 by Tedesco Chiesara, 1889, Verona, Italy; I.R.ms.631 by Alessandro Ghirlanda, *c.*1868, Verona, I.R.ms.631; I.F.ga.1988/170 by Johann Simon Stengel
[42] Günter Dullat, *Klarinetten*, 73–95.
[43] Hoeprich, *The Clarinet*, 2008, 259ff.
[44] Hoeprich, Ibid. 261.
[45] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 264.
[46] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 249-386.

the bass clarinets and their music that was known at the time of writing.[47] David Kalina discusses the structural development of the bass clarinet.[48] Thomas Aber presents a history of the bass clarinet and its use in the nineteenth century orchestra.[49] Eric Wachmann discusses the woodworking tools used by contemporary makers in the period 1775-1843.[50] Finally, Philip McLeod from New Zealand developed new mathematical and computational tools for the rapid analysis of musical pitch by an autocorrelation algorithm, which is of use in analysing the sounds made by the instruments.[51] A similar, but more developed method, by Alain de Cheveigné and Hideki Kawahara has in fact been used in the present work.[52] However, while the theses contain much useful information, many of them rely heavily on secondary sources and written communications from museums, with little or no direct access to the instruments.

In summary, the above secondary sources between them give an accurate historical description of the development of the bass clarinet, with a number of examples. There is little attempt other than in Rice[53] to classify them into types, to relate them to other types or examples, or to examine regional differences. This may be because these sources deal mostly with only a few important examples rather than viewing the body of data as a whole. None of them lists as many as half of the extant examples given in Chapter 4, *Extant bassoon-form bass clarinets*. The reasons for instruments being constructed in bassoon form and the later dominance of the straight form has been little explored.

We can only get a glimpse of the musical uses of the instrument from the relatively few musical examples cited in most of the secondary literature. The main exception is again Rice, who discusses twenty-six works for bass clarinets in stage and opera music and one arrangement for wind band, giving a number of musical extracts, for works up to 1860.[54] He has also written an article on the earliest bass clarinet music.[55] Kroll gives a useful critical assessment of the clarinet and bass clarinet tutors available in the nineteenth century. The only one of these that includes the bass clarinet is that of Robert Stark, in which no differentiation is made between exercises for clarinet and those for basset horn and bass

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[47] Charles Albert Roeckle, 'The Bass Clarinet – an Historical Survey'. Master's thesis, University of Texas, Austin, 1966.
[48] David Kalina, 'The Structural Development of the Bass Clarinet'. Ed.D. thesis, Columbia University, New York, 1972.
[49] Thomas Carr Aber, 'A History of the Bass Clarinet as an Orchestral and Solo Instrument in the Nineteenth and Early Twentieth Centuries and an Annotated, Chronological List of Solo Repertoire for the Bass Clarinet from before 1945'. DMA thesis, University of Missouri, Kansas City, MO, 1990.
[50] Eric Wachmann, 'Clarinet Woodworking: The Tools Used in the Construction of the Clarinet between 1775 and 1843'. DMA thesis, University of North Carolina, Greensboro NC, 1997.
[51] Philip McLeod, 'Fast, Accurate Pitch Detection Tools for Music Analysis'. PhD thesis, University of Otago, Dunedin, 2008.
[52] Alain de Cheveigné and Hideki Kawahara, 'YIN, a Fundamental Frequency Estimator for Speech and Music,' . *J. Acoust. Soc. Am.*. 111 (2002) 1917–30. https://doi.org/10.1121/1.1458024
[53] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009.
[54] Rice, 339–86.
[55] Albert R. Rice, "The Earliest Bass Clarinet Music (1794) and the Bass Clarinets by Heinrich and August Grenser." *The Clarinet* 38 (2011) 54–58.

clarinet.[56] However, Kroll omits the tutor by Kappey that discusses the bass clarinet,[57] including the skill of transposition from bass parts in C to substitute for bassoon, as well as the first dedicated bass clarinet tutor by A.P. Sainte-Marie.[58] Kroll also gives a repertoire list which includes the bass clarinet, but with no historical perspective (e.g. the dates of composition are not noted).

The repertoire for the bass clarinet is discussed in Chapter 3, *The bassoon-form bass clarinet in the nineteenth-century repertoire*, where it is examined in particular for evidence for the usage of the different types of instruments in operas, orchestras and bands.

Contemporary publications and documents

There are a number of contemporary references to bass clarinet design, innovation and sound from the musical journals of the period, for example *Harmonicon* (1823-1833), *The Musical Times (1844 -), Revue musicale* (Paris, 1827 - 1835) which merged with *Gazette musicale de Paris* (Paris 1834-1880), *Allgemeine musikalische Zeitung* (Leipzig, 1798-1848 and 1866 - 1882), *Berliner allgemeine musikalische Zeitung*, (Berlin, 1824-1830), and *Wiener allgemeine musikalische Zeitung* (Vienna, Jan.-Dec.1813). Information on French instruments and comments by Hector Berlioz were found in *Journal des Débats* (1789-1944). These and other sources have been searched through RILM and RIPM,[59] and are summarised below.

Little iconography exists on the bass clarinet until the 20th century. It consists of illustrations in manuals and tutors (of which only four are known), patent documentation (only two are known specifically for the bassoon-form bass clarinet) and occasional illustrations in books. This is not such a disadvantage for understanding the form and design of the instrument, since many actual instruments are available in museums. However the occasional engraving or image can serve to confirm the type of instrument used in a tutor or the use of an instrument in an ensemble such as a town or military band.[60]

There is an important patent by Sautermeister showing the 'invention' of a bassoon-form bass clarinet in 1812 (note that the Grenser instrument shown in Figure 1.1 displays a date of 1793). No instruments by Sautermeister are known to have survived, but the patent contains clear drawings, shown in Figure 1.4. Besides illustrations of the body and keywork, the drawing clearly shows the mouthpiece in reed-up position; this may also be indicated by the flat mouthpiece angle. Unfortunately the accompanying text does not help resolve this issue; it merely states in the description section that it is essentially a cylindrical tube:

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[56] Robert Stark, *Grosse Theoretische-Praktische Clarinett-Schule Nebst Anweisung Zur Erlernung Des Bassetthorns Und Der Baßclarinette.* Heilbronn: C.F. Schmidt, 1892.

[57] Jacob Adam Kappey, *Tutor for the Bass and Alto Clarinets; Designed with Special Reference to Their Uses as Substitutes for the Bassoon and the Requirements of Military Bands; With Scales and Exercises In the Bass and Tenor Clefs and Numerous Advanced Studies.* London: Boosey & Co, 1888.

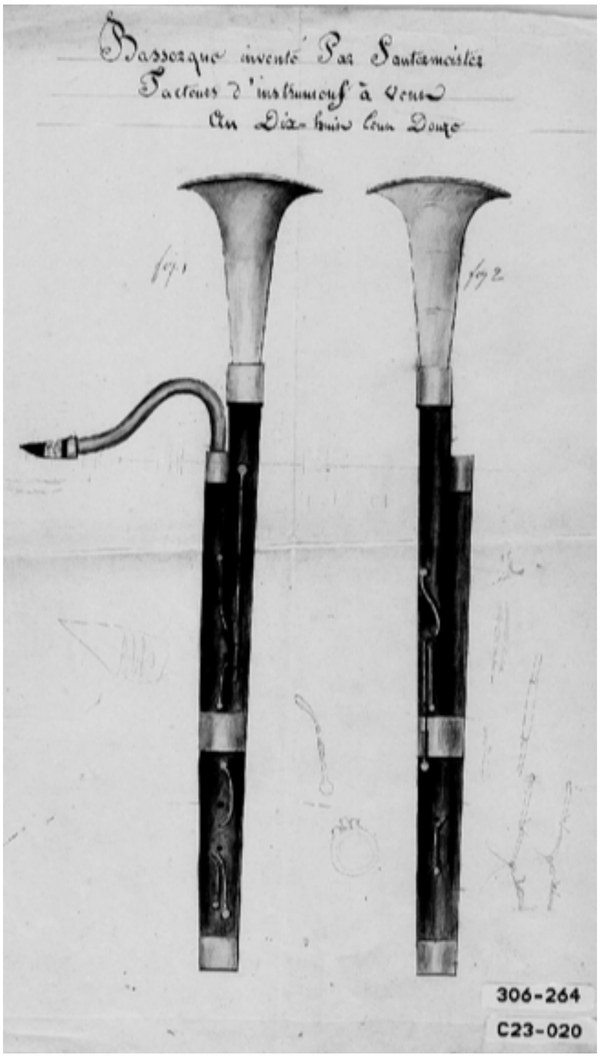
[58] A.P. Sainte-Marie, *Méthode Pour La Clarinette-Basse à L'Usage Des Artistes Clarinettistes, Avec l'indications Des Doigté Pratiqués.* (Paris: Evette et Schaeffer, 1898); Thomas Carr Aber, 'The First Published Method for the Bass Clarinet - A. P. Sainte-Marie's Mèthode Pour La Clarinette-Basse... of 1898 - and a Brief Survey of Subsequent Didactic Works for the Bass Clarinet,' *The Clarinet* 42, no. 3 (2015) 76–79.

[59] 'RIPM - Retrospective Index to Music Periodicals accessed March 27, 2019; 'RILM - Répertoire International de Littérature Musicale'. https://www.rilm.org/ accessed March 28, 2019

[60] e.g. Kappey, *Tutor for the Bass and Alto Clarinets* 1888.

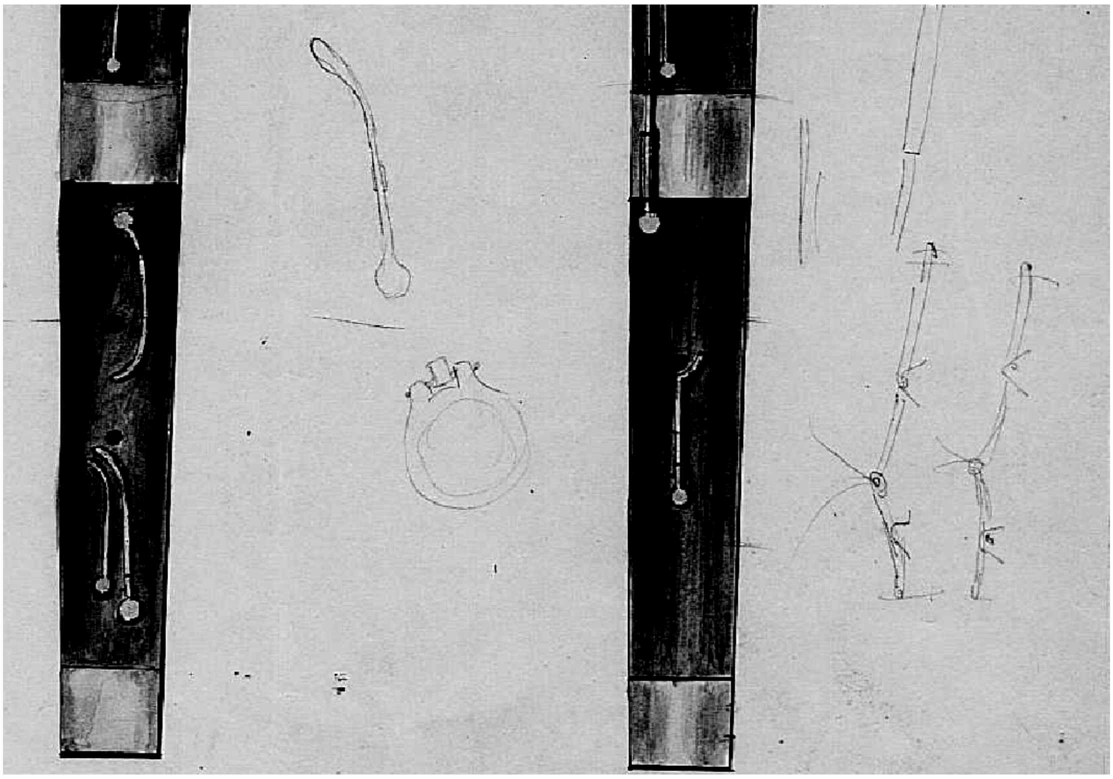
> Know that, This instrument is bored straight. That is to say, that the opening of the hole in the interior is of equal width from the embouchure to the bell. It is folded back on itself in the form of a bassoon, having a bell at its extremity. The mouthpiece is a 'beak' which is fixed on to the bocal [neck]. The instrument is called a Bassorgue. It has three full octaves plus a few notes, with complete facility to form tones and semitones. I can curve the bell or replace it by a globe or equally by a tube pierced from one side to the other. I can change the fingering and the placement of the keys and similarly I could add three [keys]; if the artist judges it useful. ...The essence of the instrument is a straight tube, more or less wide.[61]

The weakness of patents as a source is that they do not in themselves constitute proof that the invention had ever been made. For example, the Belgian patent of 1838 by Adolphe Sax for the bass clarinet[62] indicates that it could be provided with an extension to low C2, but no such instruments or documentary descriptions have ever been found. In the absence of surviving instruments, one can only make a subjective judgement based on the quality and realism of the drawings and descriptions. Those by Sautermeister do look realistic and convincing to me, but they could possibly be a paper design by an experienced woodwind maker. The patent is also an early indication of the willingness of a maker to cooperate with a player.



(a)

[61] Françoie-Antoine Sautermeister, Instrument à vent nommé bass-orgue.
[62] Belgian patent No. 1051 approved 1 July 1838



(b)

Figure 1.4. Sautermeister (1812) patent for a 'bass-orgue', (a) overall sketches, (b) detail showing keywork drawings. The writing at the top of the drawing translates as: Bassorgue invented by Sautermeister/Wind Instrument Maker/ Year 1812. From the French patent office website.[63]

A similar situation holds for the Louis Müller patent of 1846, since no instruments to this specification have survived, but Pontécoulant, in referring to the patent, does state that it was constructed:[64]

> Müller constructed a bass clarinet. The form and arrangement which the inventor gave to this clarinet allowed him to enrich the instrument by four extra notes that complete the lower range, making it descend to C.[65]

Müller was the nephew of Sautermeister and succeeded to his workshop[66]. It is interesting that Müller went back to the Grenser arrangement with the bell on the player's right, rather than Sautermeister's 'new' arrangement with the bell on the player's left (Figure 1.5). The patent is largely concerned with the fingering and keywork for ease of playing, which does seem to be somewhat innovative, and this may be why he was granted a patent for fifteen years rather than five or ten. Although the body form is shown as largely solid (cf. Catterini's bassoon-form, made like a dulcian), one suspects from the tubular shape of the upper parts that there were actually joints, at least above finger hole I. The finger holes are located

[63] Sautermeister, Instrument à vent nommé bass-orgue, filed August 12, 1812, and issued 1812.
[64] French patent No. 3,192
[65] Pontécoulant, *Organographie; essai sur la facture instrumentale, art, industrie et commerce;* 2 vols. Paris: Castel, 1861, vol. 2, 449.

[66] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 280.

centrally. This implies quite long chimneys to all the finger holes, which would affect the sound (as discussed extensively in Chapter 8).

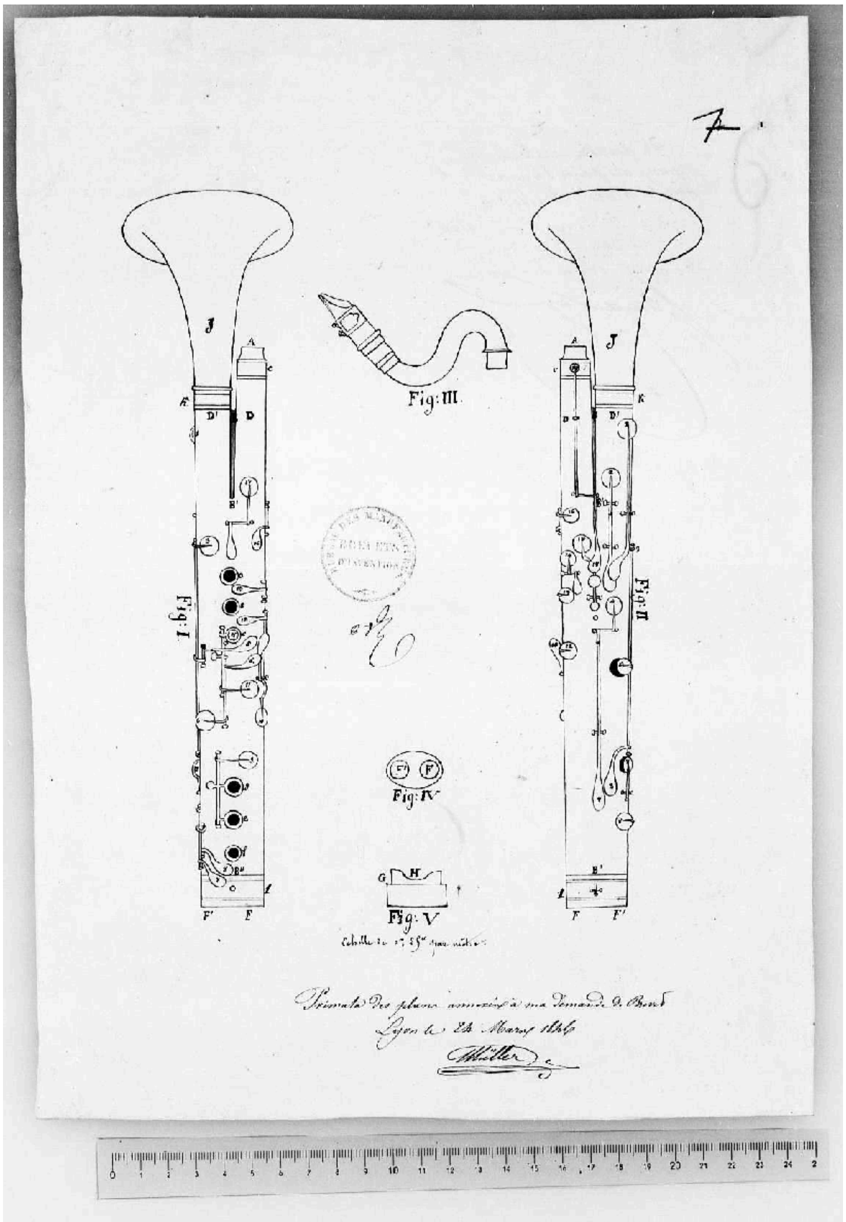


Figure 1.5. The picture accompanying Louis Müller's fifteen-year patent of 1846.

Three nineteenth-century tutors that deal with the bass clarinet are known, plus a fingering chart by Wood.[67] Streitwolf published a tutor to accompany his bassoon form instrument and included a fingering chart.[68] Wood's scale is shown in Figure 1.6. It is clear from the range, down to B♭1, and the reference to use of the thumbs, that it was for a bassoon-form instrument. Unfortunately, no instrument by Wood has survived.

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[67] George Wood, "A Scale of the Bass Clarinet Invented and Mfred by George Wood" (1833), British Library GB-Lbl.e.108[19].

[68] Johann Heinrich Gottlieb Streitwolf, *Anweisung, Die Bass-Clarinettekennen Und Blasen Zu Lernen*. Mainz: Fils de B. Schott, 1833. This chart is used in the acoustic analysis in Chapter 8, *Acoustic Spectra of Historical Bass Clarinets.*

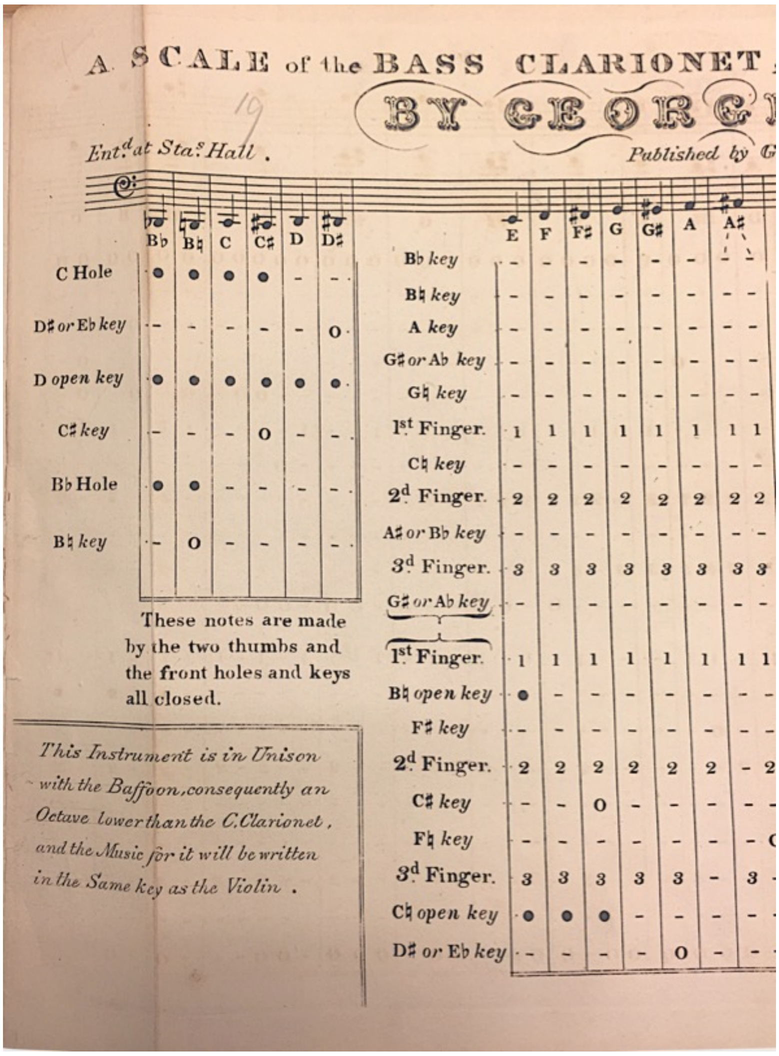

Figure 1.6. Scale for the Bass Clarinet by George Wood, left-hand side. The text makes it clear that a bassoon-form instrument in C is being described. Image by author with permission of the British Library, British Library GB-Lbl.e.108[19].

Jacob Adam Kappey remarks in the title that his 1888 *Tutor for the Bass and Alto Clarinets*, (Figure 1.7) is

> Designed with special reference to their uses as substitutes for the bassoon and the requirements of Military Bands...[69]

This is an important indication of one common use of bass clarinets at the time. Kappey's book is one of a set of tutors for all main band instruments. It is intended for players who have to double at short notice, in particular those taking the parts of bassoon on either bass or alto clarinets (since the bassoon takes longer to learn from scratch). Accordingly, there is a fingering chart and tables of transpositions into sounding tone in bass, tenor and (for alto) the alto clef. There is a picture of a straight-form bass clarinet, with Müller-type system (with *brille* on RH1 and 2) down to E2, as is the fingering chart.

[69] Jacob Adam Kappey, *Tutor for the Bass and Alto Clarinets*. Title page.

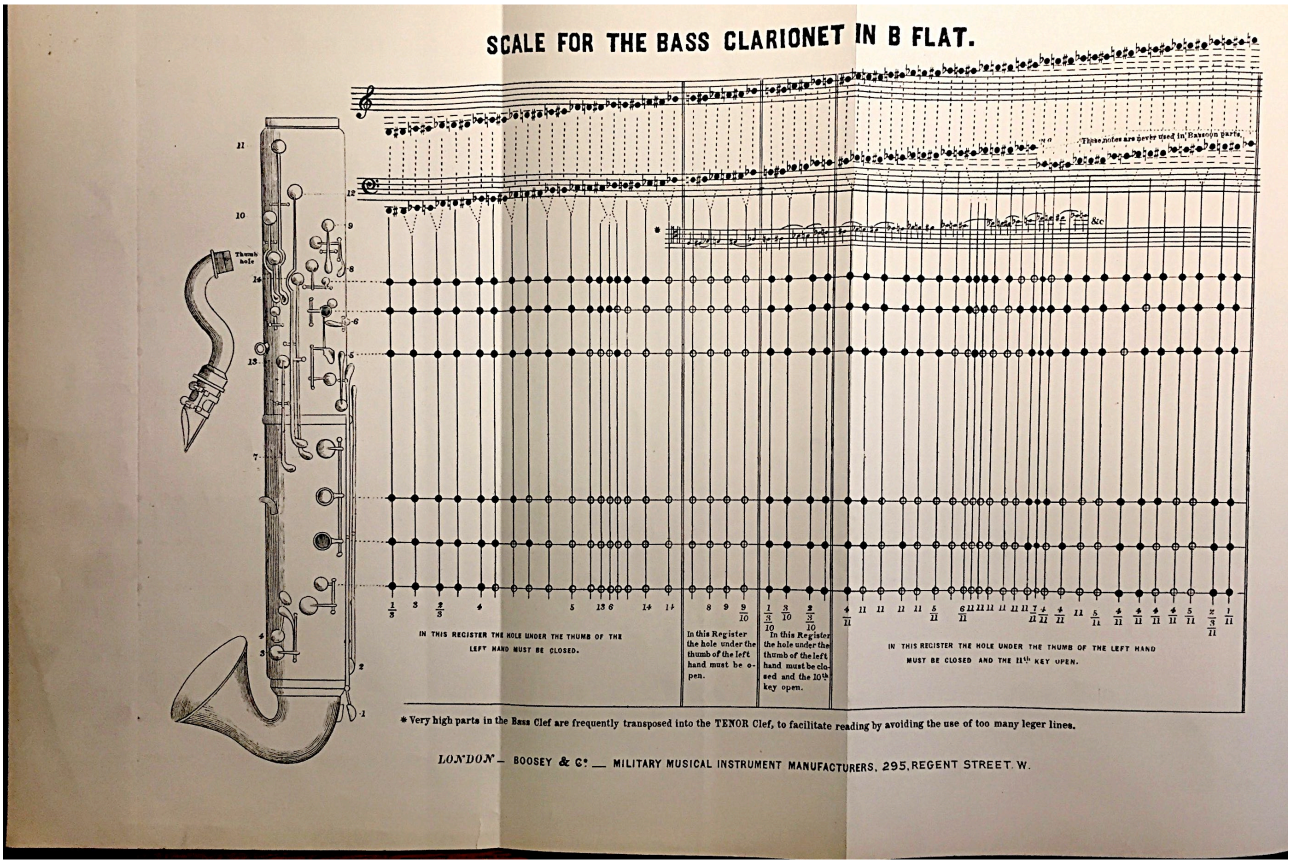

Figure 1.7. From Kappey's tutor, showing the design of bass clarinet used. Image by author with permission of the British Library.

The text makes clear that the mouthpiece is placed so that the reed contacts the lower lip. There are two pages of brief instruction then exercises, labelled 'Ivan Muller', which are quite extensive with scales, arpeggios and grace notes. The alto volume is similar but has very few exercises. There is nothing on history or choice of instruments. At the end of the century Stark (1892) and Sainte-Marie (1898) each published a tutor for basset horn and bass clarinet.[70] The Stark tutor is aimed almost exclusively at achievement of a technical facility in fingering and articulation.

The early nineteenth century was a time of rapid development in the arts and sciences, and accounts of new instruments appear in the musical journals of the period, especially *Revues Musicales*, to which François-Joseph Fétis regularly contributed articles on new instrument designs.[71] These included brief descriptions and comments on instruments by Dumas, Streitwolf, Dacosta and Buffet. A short history of Dumas and his instrument is given by Fétis. Its dimension of about a metre, and his comment that

> This clarinet, of which the analogue was made in Germany in 1830, is an old French invention of M. Dumas, formerly chief of the goldsmiths to the Emperor Napoléon[72]

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[70] Stark, *Grosse Theoretische-Praktische Clarinett-Schule;* Aber, 'The First Published Method for the Bass Clarinet; Sainte-Marie, *Méthode Pour Las Clarinette.*

[71] e.g. François-Joseph Fétis, 'Instrumens Nouveau. Clarinette-Basse; Fétis, 'Exposition Des Produits de l'industrie,' *Industrie. Instrumens à Vent* 8 no. 22 (1 June 1834) 171–72.

[72] Fétis, 'Instrumens Nouveau. Clarinette-Basse'.

make it most probable that the instrument was bassoon shape; the only 'analogue' instruments made in Germany in the 1830s were of bassoon shape, and Streitwolf's bassoon-shape instrument was definitely known to Fétis.[73] This is confirmed by Adolphe Le Doucet Pontécoulant, writing in 1851:

> Dacosta showed a bass clarinet that he had inherited from Dumas: it has a tube curved in the manner of a bassoon, with a mouthpiece adapted to fit at one end.[74]

Fétis states that the bassoon-type bass clarinet of Dumas was well received by audiences, and he also reports

> I should not forget to state that the fingering of the bass clarinet only differs from the ordinary clarinet in three or four notes. […] Two or three hours of work suffice to acquire the skills.[75]

As mentioned above, Hoeprich discusses the Dumas instrument as straight, citing Fétis (1834), but this is a misinterpretation. Fétis actually makes it clear in this article that Dacosta is now playing on the new Dacosta-Buffet (*jeune*) straight instrument and comments on the bassoon form instruments:

> In order that the new instruments conserve as much as possible of the analogy that exists with the soprano clarinet, it is necessary not to alter the form at all; I think therefore that Messrs. Dacosta and Buffet have better achieved this end than Mr. Streitwolf in not curving the tube of their bass clarinette, and in facilitating the playing of the instrument by means of an inclined bocal to which the mouthpiece is adapted.[76]

The instruments of Streitwolf (bassoon-form) and Buffet 'Jeune' (straight), both in about 1833, attracted praise from Fétis for their sound. However, a major innovation occurred in about 1838 with the introduction and patenting of a new design of straight form bass clarinet by Adolphe Sax, following his earlier work on the soprano clarinet and his pioneering work on acoustics.[77] Berlioz commented very favourably on Sax's attention to acoustic detail such as the larger bore, improved mouthpiece, the precise positioning and larger diameter of the tone holes, and also the use of a second speaker key to improve the upper register.[78] The last was actually first used in the second oldest bassoon-type bass clarinet known, by Augustin Grenser (uncle of Heinrich) dated 1795 but not copied on all bassoon-type instruments.

Sax also adopted plateau keys to operate the tone holes. Berlioz comments on the musical effects of these improvements as follows:

> M. Adolphe Sax's new bass clarinet is still more improved. It has 22 keys. That which especially distinguishes it from the old one is its perfect precision of intonation, an equalized temperament throughout the chromatic scale, and a greater intensity of tone.[79]

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[73] Fétis, 'Exposition Des Produits de l'industrie.'
[74] Pontécoulant, *Organographie; essai sur la facture instrumentale,* vol. 2, 366.
[75] Fétis (1833)
[76] Fétis (1834).
[77] François-Joseph Fétis, *Biographie Universelle Des Musiciens Et Bibliographie Générale De La Musique Par F.j. Fétis.* (Paris: Librairie de Firmin-Didot et Cie. 1837), 415.
[78] Berlioz, H. quoted in L. Kochnitzky, *Adolphe Sax and His Saxophone* (New York: Belgian Information Center, 1949); Hector Berlioz, ''Instrumens de Musique. M. Ad. Sax.' *Journal Des Débats*, June 12, 1842.
[79] Berlioz, 'Instrumens de Musique.' 1842. Hector Berlioz, *Traite de l'instrumentation*. Paris: Schonenberger, 1843. [English tr.] *Treatise on Instrumentation*, Mary Cowden Clarke. London: Novello, 1856. Quotations are from the English translation.

There is no doubt that Sax's bass clarinet had a major influence on the development of both the orchestral and band instruments. While it later diverged into the French (Buffet) and German (Albert and Oehler) systems, it has been the basis of all bass clarinets for 180 years. Clearly it was excellent technically and musically. The question remains whether it was (acoustically and musically) substantially superior for certain purposes to the bassoon form instrument, or whether Sax's undoubted skills at performance, manufacturing and sales were the deciding factors in its widespread adoption in opera and orchestral music.

Its merits were certainly hotly contested at the time, primarily by rival instrument makers and their proponents, in particular Wilhelm Friedrich Wieprecht of Berlin, who championed German[80] instruments, in particular those of Streitwolf and an unnamed maker of the bassoon-form contrabass clarinet called the batyphone by its inventor Skorra. Pontécoulant documents much of the arguments (made in front of luminaries such as Liszt) and lively correspondence, for example Sax's remark:

> My bass clarinet shows no similarity with those of Germany, neither in the sound, nor in the mechanism nor in the form; I have played it in the presence of Messieurs Savart, Dacosta (of Paris) and others in 1839, with a skill that supposes at least two years of study, and of which besides I have already given proofs, notably in Belgium, in solos in concerts of the Court and at those of Mr Fétis, and many times in the meetings of the Grand Royal Harmonie of Brussels, and also at the Société Philharmonique where I played the solo bass clarinet part.[81]

Sax also adopted plateau keys to operate the tone holes, though he was not the first to do so (for example, the slightly earlier Catterini instrument). According to a report in 1843, Sax and Dacosta held a play-off in 1839 in front of Mme. Dacosta, who remarked

> My friend, I am sad to say this, but since Monsieur [Sax] has played, your instrument has the effect on me of a mirliton.[82]

This is clearly a disparaging comment; a mirliton was a short covered-double-reed pipe rather like a toy 'trumpet'. Some can be seen in CZ.P.cmm nos. E1741, 1733, 1707 and 2404. Encyclopaedia Britannica describes it as a 'pseudomusical instrument or device' with a buzzing tone.[83] This is probably the least partisan of the comments available on the sound of the instruments. However, the comments by 'E.G.' are making a comparison between the Sax and Dacosta instruments, not with, for example, Streitwolf's bassoon-form instrument. Soon after, Dacosta adopted a Sax instrument, and eventually the design of the Buffet and Sax instruments converged, with the adoption of the Boehm system hole layout and keywork from 1855.[84] German instruments retained the Müller keywork, which eventually became the Albert and then the Oehler system, as in German soprano instruments.

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[80] Strictly, Prussian, Saxon etc at this period, but Sax's correspondence refers to 'l'Allemagne'.
[81] Pontécoulant, *Organographie Essai Sur La Facture Instrumentale*, vol. 2, 307
[82] E.G. 'Adolphe Sax,' *Le Patriot Belge*, September 23, 1843.
[83] 'Mirliton'. *Encyclopaedia Brittanica.* Accessed 3 November 2021. http://www.britannica.com/EBchecked/topic/384986/mirliton
[84] Our Story - Buffet Crampon,' Buffet Crampon - Paris, May 12, 2016,. https://www.buffet-crampon.com/en/our-story/. Consulted 2 August 2021.

By the mid-century, comprehensive and useful historical treatises on instruments were published in France, by Pontécoulant and by Kastner.[85] These include instruments in the military bands, which were very important in post-revolutionary France and will be discussed in Chapter 3.

The evidence of the instruments

As stated above, the central aim of this thesis is to emphasise the empirical evidence as provided by the instruments themselves and their repertoire. In the final part of this chapter I discuss the various ways in which this might be achieved.

Playing an original instrument

The obvious way in which to discover the behaviour of an early instrument would appear to be to play a historical instrument or a good copy. But both methods require critical analysis. The question of what consitutes 'a good copy' is discussed in the next section. And as Libin re-iterates

> The pure original state of an old instrument cannot be recovered by any means and may not be knowable.[86]

Sometimes, an historical instrument has been kept unaltered and in good enough condition throughout its life, by regular playing and periodic overhauls. But this is rare. More common are the large numbers of instruments in museums which are kept, for conservation reasons, at controlled humidities, normally between 40% and 60% relative humidity (often at about 55%).[87] In contrast, the average humidity in an uncontrolled environment may be much greater. Data available from the World Data Center for Meteorology show that, in the United Kingdom, the average annual relative humidity ranges from 70% to 80%; of course climates in some other countries are much drier.[88] And when an instrument is played, the relative humidity inside the instrument rapidly leaps to 100%, leading to moisture absorption in the wood from the inside.[89] The lower average level of humidity found in museum environments leads to some shrinkage of the bore, which is detectable by the bore becoming slightly or even

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[85] Pontécoulant, *Organographie; essai sur la facture instrumentale.* In 2 volumes, totaling 1008 pp.; Georges Kastner, *Traité Générale d'instrumentation* (Paris: Prilipp, 1837). 413 pp.; Georges Kastner, *Supplément Au Traité Générale d'instrumentation* (Paris: Prilipp, 1844); Georges Kastner, *Manuel Général de Musique Militaire A l'Usage des Armées Françaises*. Paris: Typographie de Firmin Didot Frères, 1848, 410 pp.

[86] Laurence Libin, 'Materials from Endangered Species in Musical Instruments' in 'Copies of Historical Musical Instruments', CIMCIM Publications, 3 (1994) 27. http://cimcim.mini.icom.museum/wp-content/uploads/sites/7/2019/01/Publication_No._3__1994__Copies_of_Historic_Musical_Instruments.pdf accessed 17 October 2021.

[87] Robert Barclay, 'The Care of Historic Musical Instruments,' *The Galpin Society Journal* 52 (1999) 374. https://doi.org/10.2307/842551; Patricia Andrew, *Standards in the Museum Care of Musical Instruments*, Revised. London: Museums and Galleries Commission and Museums, Libraries and Archives Council (2005); Cary Karp, 'Storage Climates for Musical Instruments,' *Early Music* 10, issue 4 (1982) 469–76. https://doi.org/10.1093/earlyj/10.4.469

[88] 'Average Humidity in the United Kingdom - Current Results,'. https://www.currentresults.com/Weather/United-Kingdom/humidity-annual.php accessed 3 November 2020.

[89] Christina R. T. Young and Gabriele Rossi Rognoni, 'Playing Historical Clarinets: Quantifying the Risk'. In Rossi Rognoni, Gabriele and Anna Maria Barry (Eds.), *COST FP1302 Woodmusick: Second Annual Conference Effects of Playing on Early and Modern Musical Instruments September 9-10, 2015*, London: Royal College of Music, COST, 2017

very noticeably elliptical.[90] Whilst the effect may be calculated quite well if the species of wood is known, and could be corrected by careful reaming, this is not a procedure that is permitted on a musem instrument. Even slow rehumidification is unlikely to restore the bore, since there is evidence that after a substantial period at low humidity, the contraction of the wood becomes irreversible.[91]

In addition, the pads in museum instruments may have gone brittle with age and consquently do not seal well, they bores may have cracks causing further leakage, and their key mechanisms may have corroded so that they do not operate correctly. One can tell very little about the original sound of such an instrument by attempting to play it. Even the slightest leak in an instrument changes its acoustic properties drastically.[92]

Occasionally, a museum owning an instrument that is in sufficiently good condition will permit a skilled technician to overhaul an instrument for special demonstrations. Examples are the Brussels Museé des Instruments de Musique, where an Adolphe Sax instrument was partially overhauled to play in the Sax bicentenary celebrations in 2014,[93] and the Robert Schumann School in Düsseldorf, where a Stengel bass clarinet in A, originally owned by the Bayreuth Theatre, was restored for a demonstration concert and for future use.[94] More frequently however, woodwind instruments in museums may not be played, for reasons of conservation and risk of damage, especially for the relatively rare instruments that are the subject of this thesis.[95] There are thousands of soprano clarinets in the world's museums, but fewer than 90 bassoon-form clarinets of all types.[96] Furthermore, if only a few selected instruments can be played, the conclusions are necessarily incomplete. One does not know if a particular instrument is typical of its class, or is a particularly good or particularly bad one.

It is indeed worth attempting to play historical instruments even very briefly, since the results can contradict prior assumptions and indicate new lines of enquiry. This occurred in the present project as will be described in Chapter 7: for example, the construction of the butt joint had much less influence, and the long fingerholes on the top joint had much more influence, than I initially expected. But such results must be regarded as pointers only; as aids to formulating a hypothesis which must then be tested by other means.

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[90] Cary Karp, 'Woodwind Instrument Bore Measurement,' *The Galpin Society Journal* 31 (1978) 9–28,. https://doi.org/10.2307/841187

[91] Luis Esteban et al. 'Reduction of Wood Hygroscopicity and Associated Dimensional Response by Repeated Humidity Cycles,' *Ann. For. Sci.* 62 (March 22, 2005),. https://doi.org/10.1051/forest:2005020

[92] D. Keith Bowen et al. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played,' *Applied Acoustics* 143 (2019) 84–99. https://doi.org/10.1016/j.apacoust.2018.08.028

[93] A recording of a short performance on this instrument was kindly provided to me by Géry Dumoulin of the Museé des Instruments de Musique, Brussels, with permission to include the recording with this thesis.

[94] Keith Bowen, 'Vergessene Klänge Und Kommende Sounds', *Rohrblatt*, 'Wagners Bassklarinette: Klang und Zeit' – Symposium an der Robert Schumann Hochschule in Düsseldorf 15. Juni 2013. 4 (2013) 181–82.

[95] Cary Karp, 'Restoration, Conservation, Repair and Maintenance: Some Considerations on the Care of Musical Instruments,' *Early Music* 7 issue 1 (1979) 79–84. https://doi.org/10.1093/earlyj/7.1.79

[96] Phillip T. Young, *4500 Woodwind Instruments* (London: Tony Bingham, 1993).

Making and playing a copy

One of the ways in which a hypothesis about an early instrument may be tested is by making a copy and play-testing that. But this is not itself without problems. These have been discussed by Martin Elste. He distinguishes the five following classes of copies:

1. The historical object.
2. The modern type, or usually called: a reproduction.This category covers those instruments at which the instrument maker has knowingly departed from details of the historical object. In a way, it is as modern and at the same time as false as reproduction furniture.
3. The reconstruction. It is always the more or less speculative result of organological research and covers the re-making of the original state of a historical object as well as the construction of all those instruments, historical copies of which are no longer fully or not at all available for measurements and study.
4. The true copy or exact copy. This term should be used only when the instrument maker has tried to re-create a historical object in every detail. It is a legitimate goal but it is always based on dated knowledge that is quickly superseded by further research.
5. The counterfeit. For this, the instrument maker tries in his new object to imitate the appearance of an old one, possibly by using historical parts. Usually, counterfeits are not true copies, because most historical objects were after all individual objects, and thus there is no financial interest in faking a specific object while the original is known to exist somewhere else. Sometimes specific features of instruments such as violin labels are counterfeits.[97]

We are thus primarily considering reconstructions and reproductions. It is not often that a copy is made *purely* to discover the sound and playing properties of an instrument. More usually, the instrument is to be used for performance as a soloist or in a 'period' ensemble. In this case, the player has a temptation to ask the maker to improve the instrument by using their modern skills, for example by making certain notes sound more clearly or better in tune by undercutting, or even by adding extra keys. For a player, especially a professional who is frequently judged by the quality of their performances or recordings, this is understandable; the listeners will not know that the weak and muffled B in the chalumeau (the lowest register of the clarinet) in early instruments is a feature of the original design that was probably well understood by contemporary composers.

In the historical performance movement there has always been a conflict between two attitudes towards copy making, which can be contrasted as 'measure carefully and make an exact copy' and 'understand the instrument and build it as a skilled maker would'.[98] It is reasonable to characterise these as 'reconstructions' and 'reproductions' respectively. There are still makers who take these opposed positions for making period instruments,[99] though ideally they should converge. Additionally, it must be recognised that an *exact* copy of even a very well-preserved instrument is a chimaera. We do not have control over the detailed properties of the wood or of other natural materials used on a fine scale, indeed they were and are variable; we cannot reproduce every last variation of bore, tone hole position, shape and

[97] Martin Elste, 'Reflections on the 'Authenticity' of Musical Instruments'. In 'Copies of Historical Musical Instruments', CIMCIM Publications, 3 (1994) 3.
[98] John Koster. 'The 'Exact Copy' as a legitimate goal'. In 'Copies of Historical Musical Instruments', CIMCIM Publications, 3 (1994) 7.
[99] Daniel Bangham 2018, private communication.

surface finish to atomic-scale precision, even with CT (computerised tomography) measurement and additive manufacturing (3D printers). Every measurement and manufacturing method has a tolerance, even today. Should we measure and manufacture to 1 mm, to 0.1 mm (the thickness of a human hair) or 0.001 mm or even less? The task is thus seen as getting the tolerances *close enough*. The benefits of learning and thinking like a maker are as much as anything of understanding the tolerances: knowing which factors significantly affect the final instrument, and which can be made to a wider tolerance with impunity. The scientific methods decribed below can help greatly in the development of understanding of this set of tolerances and in verifying the fidelity of copies. Nevertheless, the maker Fred Morgan concludes

> As our knowledge increases, so will the amount of information that we must commit intelligibly to paper.[100]

Further questions arise when an instrument was developed during its original playing life, either through repair or through development by the original or another maker, such as additional keys. The Griesbacher basset horn in the RCM Museum[101] is an example in which keywork has been modified after manufacture. There are many examples of tone holes plugged and moved, or mechanisms added or removed during the life of an instrument, such as the bass clarinets by Kruspe of Leipzig, the Catterini in Oxford and the two anonymous bass clarinets in the Metropolitan Museum, from personal observation.[102] Sometimes these have been done during the original manufacture, and sometimes at a later period. Occasionally one can tell which is which. For example, Figure 1.8 shows a detail from the Kruspe example. A mechanism to improve the throat B♭ note has been added, which involved drilling another tone hole; that it is a post-manufacture addition is shown by it intercepting one of the original makers' marks. In such cases there is no correct answer. The maker must decide which version of the instrument to copy, usually either the original (if deducible) or the last variation of the instrument made or modified by the maker. The period instrument player will often want the last variation of the instrument; it is more likely to play evenly and with good intonation, since these are the main reasons for adjustments to be made during the life of an instrument. The temptation to improve the instrument with the use of modern knowledge must be resisted for the purposes of empirical organology, and the copies must be made to the original dimensions and keywork of the original instrument (including features such as venting and undercutting) so far as these can be determined. Understanding the scientific properties of the wood and other materials used in the instrument can help considerably in assessing the changes that may have occurred since manufacture.[103]

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100 Fred Morgan, 'Making Recorders Based on Historical Models,' *Early Music* 10, issue 1 (1982) 14–29. https://doi.org/10.1093/earlyj/10.1.14

101 GB.L.cm.242

102 D.Le.u.90-43; GB.O.ub.496; US.NY.mma.89.1635 and 1636.

103 Wachmann, 'Clarinet Woodworking: The Tools Used in the Construction of the Clarinet between 1775 and 1843.'; K. Wilson and D.J.B. White, *The Anatomy of Wood*. London: Stobart 1986; F.W. Jane, *The Structure of Wood*, London, Adam and Charles Black, 1956.

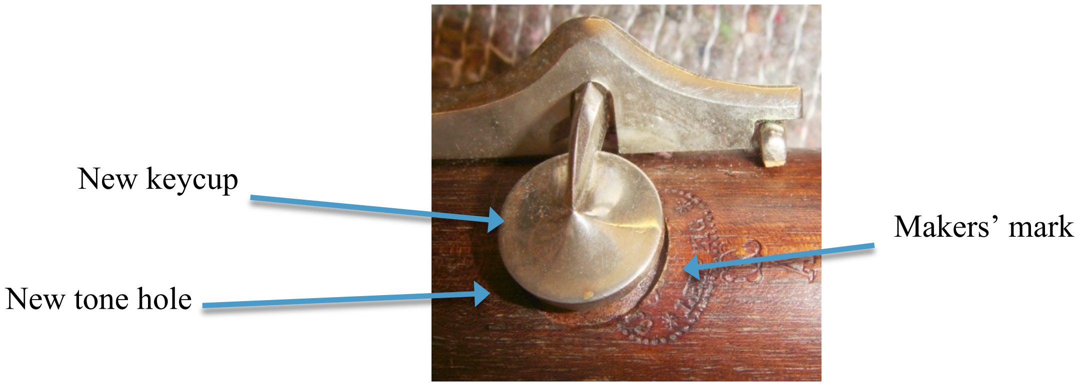

Figure 1.8. Detail of Kruspe (Leipzig) bass clarinet in A, showing a modification intercepting an original maker’s stamp. D.LE.u.90-43

The principle followed in building an acoustic copy of an historical instrument is to use similar materials and to copy the dimensions of the instrument accurately, after allowing for shrinkage due to age. It follows that the maker of such a copy may also have to copy ‘!s’ in the original. For example, the tone holes may not be in optimum positions, especially for a large and complicated instrument such as a bass clarinet. This will affect the intonation, or may have necessitated tuning corrections after manufacture, which would not have been needed with a more accurate acoustic design. In the case of the bassoon-form bass clarinet, the double bores are usually spoken of as parallel and coplanar. But this again is a tolerance. In one example measured, the Catterini in the Bate collection, they converge slightly, by 0.9°, corresponding to about 9 mm over the length of the instrument.[104] This is certainly a design feature and must be copied, though it is unlikely that the maker specified the convergence to better than a few mm over the length of the instrument. Even with current industrial practices and equipment not available until the 21st century a drill ‘wander’ of 0.6 mm in 600 mm is a very close tolerance indeed. The two bores are also slightly skewed (not coplanar) by about 0.1°. This might have made a difference in tone hole chimney lengths and hence affect the sound of the instrument, so a maker would need to copy this feature or compensate for it by tone hole inserts if necessary. It is seen that the copier may even need to work much more precisely than did the original maker. Thus not only is it unnecessary to use contemporary tools and measuring instruments, it is inappropriate; they may not give the accuracy required.

My assessment of the priorities for the manufacture of an acoustic copy of a woodwind is as follows, based upon coaching of a skilled maker[105] and on the computer modelling. Of prime importance are the bore diameter and flare, the positions, diameters and lengths of the tone holes and (usually to a lesser extent) the undercutting of tone holes. Tolerances can be discovered by the computer modelling methods discussed below. The mouthpiece and neck (dimensions and materials) are next in importance. Secondary but still significant are the materials and the positions of the pads and the use of similar wood, similarly treated in terms of seasoning and oiling. Finally, of low importance are the materials for banding, the metal for keys and the metal and threads for pivots and screws.

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[104] GB.O.ub.496. Personal measurements.

[105] I thank in particular Daniel Bangham of Cambridge Woodwind Makers foundation for this period of research.

Originally, it was intended that building a reconstruction of a bassoon-form instrument would be part of this research project and considerable effort was made to research and learn the techniques and skills involved. This was eventually abandoned, partly because of the estimation of the time required. However, we see from the above discussion that there are also a number of uncertainties in this approach. If the copy played badly, was it because it was not made well enough, or because it was a poor original, or because some of the above points were not taken into account? If it played well, would this mean that the class of instruments that it represents would also play well? And even a 'perfect' copy would only tell one about a single instrument, not about the class, and any differences within the class cannot be deduced without making a significant number of copies. The focus of the project therefore shifted to an analytic study of the acoustics of the instruments, which can be applied to any instrument that one can measure geometrically.

Museum collections of musical instruments

These have been a major source of information, and have been used in three ways. First, by means of a comprehensive search through museum catalogues, mostly in the RCM Library. This enabled about 40 instruments to be added to the examples that were listed in the secondary sources discussed in Chapter 1. Secondly, familiarity with the instruments was gained by visits to museums, with prior arrangement with the curators, to examine bass clarinets of the period. On some occasions, it was permitted to play instruments for a short period. The museums and collections visited were RCM (London: GB.L.cm), EUCHMI (Edinburgh: GB.E.u), the Bate collection (Oxford: GM.O.ub), the Horniman Museum (London: GB.L.hm), Musée des Instruments de Musique (Brussels: B.B.mim), Robert Schumann School of Music (Düsseldorf: no sigil), Germanisches Nationalmuseum (Nuremberg: D.N.gnm), Musikinstrumenten-Museum der Universität Leipzig (Grassi Museum), (Leipzig: D.LE.u), Stadtmuseum and Deutsches Museum (Munich: D.M.sm and D.M.dm), Music Museum (Musik- & Teatremuseet, Stockholm: S.S.m), Museum of Czech Music (Prague: CZ.P.nm), Museo Nazionale degli Strumenti Musicali (Rome: I.R.ms), Museo Civico Teatrale 'Carlo Schmidl' (Trieste, I.TS.mt), Conservatorio di Musica San Pietro a Majella (Naples: I.N.c), Galleria dell'Accademia (Collezione del Conservatorio Luigi Cherubini) (Florence: I.F.ga), Metropolitan Museum of Art (New York: US.NY.mma), and Universität Basel, Musikwissenschaftliches Institut (Basel: CH:B:mi). Finally, a number of instruments were selected so as to address key topics:

- the history of the bassoon-form bass clarinet from its invention by Grenser, its implementations by Streitwolf (1828) and Catterini (1833) and its late manifestations by Stengel (1860-75) and Kruspe (*c*.1880);
- the comparison between makers who made surviving instruments in both bassoon and straight form, namely Kruspe and Stengel;
- two straight form Adolphe Sax instruments from 1840 to compare the bassoon-form models with the design that eventually became the standard;
- for reference, a late straight-form German-system instrument in my own possession and in good playable condition, a Heckel bass in A from 1910, whose acoustical properties were studied in detail in order to validate the computer modelling.

Modelling the acoustics of musical instruments

There is an extensive literature on acoustics of musical instruments, including the clarinet, though very little specifically on the bass clarinet. This literature will be introduced in Chapters 5 *The acoustics of woodwind instruments,* and 6, *Acoustic modelling of woodwind instruments* in the context of an introduction to acoustic analysis and the development of computer modelling of the bass clarinet. The purpose of such modelling is to use the instruments themselves as the primary source for discovering their acoustic characteristics. During this work I developed an accurate method of computing the basic resonance properties of a clarinet-like instrument, using my judgement of the best acoustic theories and models available and incorporating them in a new software program for calculation of the resonances.[106] This permits the calculation of absolute pitch, intonation and temperament to an accuracy of a few cents and provides qualitative information on timbre and tone quality. The inputs for the computations are geometric measurements of the instruments: mouthpiece volume, bore diameter and flare, bell shape, tone hole positions and dimensions, pad diameters and heights and tone hole edge rounding. It is normally no problem to carry out such measurements on museum instruments (except for mouthpiece volume), and the measurements and analysis of a selected set of instruments are given in Chapter 8, *Acoustic spectra of historical bass clarinets* and in Appendix B.

Examining the toneholes and the keywork

It is evident from the previous section that the acoustical properties of an instrument are determined by the diameter and shape of the bore, the pattern of tone holes, and the shading of the latter by pads and perhaps keys; and not at all by the keywork systems that are designed to operate them.

There are just two basic variants of the tonal pattern associated with these toneholes in Western Art musical instruments and they apply to all woodwind families.[107] The earliest is shown in Figure 1.9. The labelling is of the tones *emitted* when the labelled hole is open and all those higher up the instrument are closed.[108] Following Voorhees and current English-speaking usage, I shall call this the *simple pattern* of toneholes. This does not imply anything about the keywork used to operate the holes. This pattern is used for five-key clarinets, Müller thirteen-key instruments, variants such as that by Baermann/Ottensteiner, the Albert system and 'simple system' clarinets and even the Oehler system. Additional holes to the basic pattern have been introduced by many makers to adjust alternative fingerings, intonation, venting and resonance on particular notes, all of which are of concern to the player. This Simple pattern was used for *all* of the bass clarinets studied in this thesis.

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[106] Bowen et al. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played.'; Bowen, D. Keith. Assessing the Sound of a Woodwind Instrument That Cannot Be Played'. *In Proceedings of the 11th International Conference of Students of Systematic Musicology.* Belo Horizonte, Brazil, 6 – 8 June 2018. https://doi.org:10.5281/zenodo.1345176

[107] Jerry L. Voorhees, *The Development of Woodwind Fingering Systems in the Nineteenth and Twentieth Centuries*. Hammond (LA, USA) Voorhees Publishing, 2003, 32-33.

[108] Note that this is not the same as the fingering for the note but one finger less than the latter.

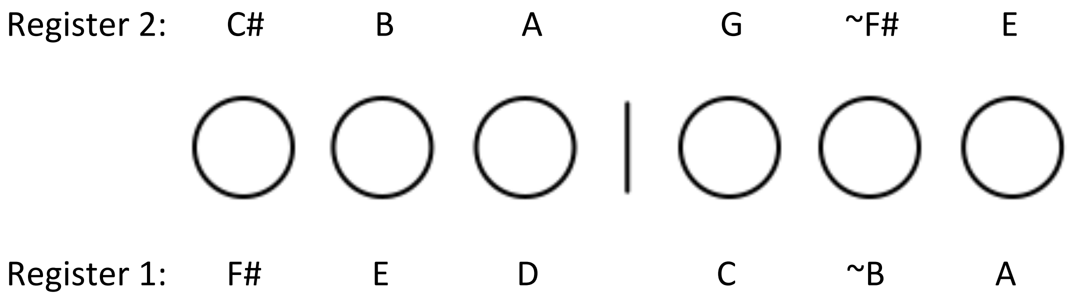

Figure 1.9. Simple or traditional system of tone holes in a clarinet, for Register 1 and Register 2. Register 1 labelling also applies to the bassoon, apart from the left hand tone hole which is F♮ not F#. Register 2 labelling also corresponds to the oboe and (non-Boehm) flute. The ~ symbol means that the tuning is approximate at these notes.

The second pattern is the Boehm pattern, shown in Figure 1.10. The Boehm system is not just a redesign of the keywork but a different acoustical design. Its main purpose is to improve the forked notes of the simple pattern, mainly B♭/F and E♭/B♭, in which it succeeds admirably and is now by far the most popular system except in Germany. However, as seen in the figure, and recalling that L4 and R4 have other keys to operate, it has two more holes than there are available fingers. On the left hand this extra hole, emitting F#, is operated by the thumb. On the right hand, the thumb is occupied by supporting the instrument, and a mechanism is required. This mechanism is the brille (German: spectacles), allowing the C/G hole to be opened or closed automatically by operation of the other fingers. This system was first applied to the flute. It was also tried on the oboe and bassoon but (perhaps due to the way it was implemented) was thought to impair the sound of those instruments.[109]

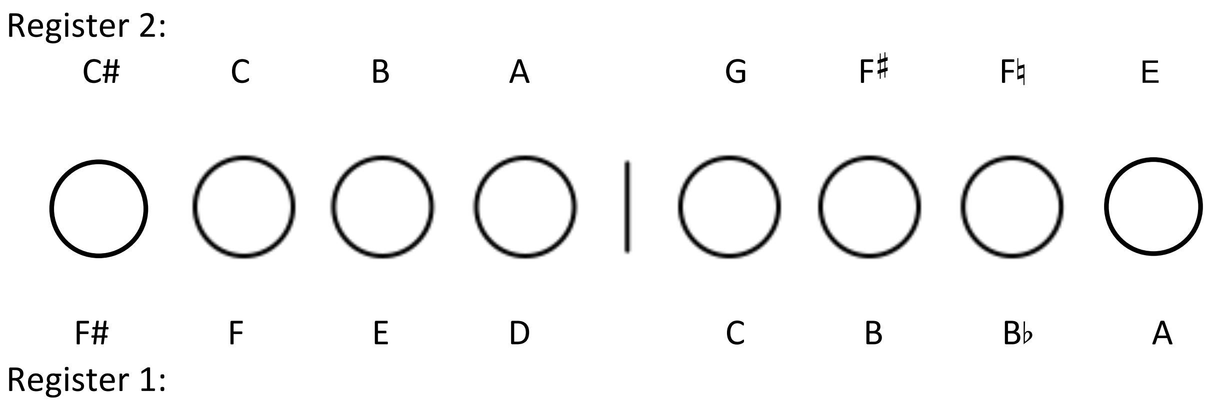

Figure 1.10. Acoustical layout of tone holes in a Boehm-system clarinet. The labelling for register 2 also applies to the Boehm flute.

Most of the instruments examined in this thesis do not have 'systems' *per se*, but a collection of keys operating single holes, as in the Müller thirteen-key soprano clarinet introduced in about 1812, and quickly used in bass clarinets.[110] From this developed the Albert system with but minor variations, such as one or two automatic *brilles* to make some fingerings easier or

[109] Voorhees, *The Development of Woodwind Fingering Systems*, 2003, 10-12.
[110] Iwan Müller, *Gamme Pour La Nouvelle Clarinette, Inventé p. Iwan Müller* (Bonn: Simrock, 1812).

more in tune.[111] None of the instruments described in this thesis use the later Boehm (Klosé), or Oehler systems.[112]

All of the instruments examined, whether bassoon, ophicleide, half-bassoon or straight had very similar keywork systems down to E2: they are almost all based on the Müller system but with a variety of later developments, depending upon the date.[113] The number of keys and the presence of lower- or upper-joint brille mechanisms give a guide to the state of development, and may help in dating an instrument. The only exceptions are the Lempp and Grenser instruments; these precede the Müller 13-key system and are based on the five-key clarinet plus additional keys for the lower notes.

The fingering (or thumbing) below E2 varies considerably between makers. There was, and is still, no standard layout for these notes on modern instruments, whether in Oehler or Boehm systems. Below the note E2, the layout of keys and even whether holes were normally closed or normally open depended completely on the designs of individual makers. The only commonality was that they were operated by one or both thumbs; this is inevitable since all the other fingers are occupied by closing the holes I – VI, F/C and E/B. The notes below E2 are usually called the 'basset' notes, since they were originally developed for the basset horn. The common feature to all cases examined is that these notes are emitted from a single tone hole and that they do not utilise forked or auxiliary holes or brilles (or their equivalent for plateau keys). Inter-key linkages in basset notes are rare, and are confined to the automatic closure of basset tone holes higher in pitch than the note being played (e.g. Schediwa) or to the automatic closure of the normal LT key to free the left thumb to operate basset keys (e.g. Stengel; both cases are illustrated later). But frequently, the operation of more than one key at a time was performed by providing two keys close enough to be simultaneously operated by the right or left thumb.

None of the clarinets examined in museums was a Boehm-system. Predominant world wide except for Austria and Germany, the Boehm system was developed for the soprano clarinet between 1839 and 1843. Makers were slow to introduce the Boehm system to the bass clarinet, and such instruments were not commonly made until *c.*1880. The earliest manufacturer is Buffet-Crampon, who introduced the Boehm system to the soprano clarinet in 1850 and to the bass clarinet in 1855, however, they remained rare (even for those made by Buffet-Crampon) until the twentieth century.[114]

Since the acoustical behaviour of an instrument does not depend upon the keywork (other than through shading effects), and all instruments considered are fairly similar, the details of the keywork have not been considered in this work; the reader is referred to the standard works on the clarinet already cited. There are some relevant observations concerning keywork, however, which include:

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[111] Hoeprich, *The Clarinet*, 171-5.
[112] Jerry L. Voorhees, *The Development of Woodwind Fingering Systems,* 30 ff.
[113] Müller, *Gamme Pour La Nouvelle Clarinette*; Albert R. Rice, 'Müller's 'Gamme De La Clarinette and the Development of the Thirteen-Key Clarinet', *The Galpin Society Journal* 56 (2003) 181–84; Voorhees, *The Development of Woodwind Fingering Systems*, 2003, 161-188.
[114] 'Our Story - Buffet Crampon'.

- understanding the operation of the lower range of an instrument and the extent to which it is fully chromatic;
- considering ergonomic factors, for example in the positioning of the A♭ key for LH1, a difficult design issue for a bassoon-form instrument;
- assigning a date by, for example, using the number of keys or the presence or absence of a brille-type mechanism for the B/F# correction hole;
- observing the design and layout of the key touches and mechanism in order to draw parallels between different makers and to suggest a provenance for unstamped instruments.

Concluding remarks

The bassoon-form bass clarinet and its variants was obviously a thriving form in the nineteenth century. The early literature shows a competition between this and the slightly newer straight form, which the latter eventually won. However, the two types coexisted in mature forms for at least 70 years, so it is clear that the bassoon-form instruments found a substantial niche. It has been speculated that, with a few exceptions, this was in wind and military bands. The acoustical models of bass clarinets of both bassoon and straight form are expected to provide insight into any acoustic differences between these classes of instrument.

Chapter 2

The development and typology of the bass clarinet

This chapter traces the history of the bass clarinets, from precursors that demonstrate the technological capability of makers, through the various forms that did not become established as instrument types, to the two stable types that dominated the nineteenth century: the bassoon-form and the straight form. A temporal chart is provided to summarise this information at the end of the chapter.

The precursors: Racket, dulcian, bassoon, the basset horn 'box'.

The first recorded use of a double bore folded instrument was attributed by Langwill[1] and Kopp[2] to Canon Afranio of Ferrara (1480- *c*.1565), who was reported in 1539 to have constructed, or imported, an instrument that he called the *Phagotum*.[3,4] The name indicates a continuity through to the modern bassoon or Fagott. Continuously since that time, very many folded double-reed instruments of the bassoon class were developed, known in different countries as curtal, curtail, storta, stortito, Stört, sztort etc, referring to its shortened aspect; as dulcian, Dulzian, dolziana, dulcin etc. referring to its sweet sound; bassoon, basson, basoncico, bajón, vajon, bajoncillo, bajca etc. referring to its bass register; or Fagot, Fagott, fagotto, Vagot, Fagoth, facotto, fagottino, fagotiho etc, referring to its resemblance to a bundle of sticks.[5] The purpose of reciting this list of names in many languages is to show that the principle of a folded-tube wind instrument was very well-known to makers in a great number of countries, for at least two hundred years before bass clarinets were made in this form. The ultimate folded instrument was known as the racket or rackett (and several other names) in which the bore is folded in many segments from holes drilled inside a short cylinder, giving a surprisingly low pitch from a small instrument. The instrument has been known since at least the sixteenth century and existed in sizes from soprano to great bass. The latter plays at contrabassoon pitch in an instrument only 30 cm long. The baroque racket, with tapered holes giving a bassoon-like bore, was developed by J.C. Denner in the early eighteenth century (Figure 2.1).[6] Many bassoon-like instruments were developed in the sixteenth, seventeenth and eighteenth centuries. These are treated extensively by Kopp, and just one example will be shown of a dulcian, again by J.C. Denner of Nuremberg (Figure 2.2).[7] It is interesting that this shape, common to many makers of dulcians, is echoed in the monolithic form of the Catterini bass clarinet shown in Figure 2.3.[8]

[1] Lyndesay G. Langwill, *The Bassoon and Contrabassoon*. London: Ernest Benn, 1965, 8
[2] James B. Kopp, *The Bassoon.* New Haven and London: Yale University Press, 2012.
[3] Teseo Albonesi, *Introductio in Chaldaicum Linguam*. Pavia: [n.p.], 1539.
[4] Musurgiana. 'Instructions for Playing the Fagotum. Series I No.4 and II, No. 2.' *Modena*, 1895. This article includes a copy of a manuscript of 1565.
[5] Kopp, *The Bassoon*, 6
[6] Kopp, 53.
[7] D.N.gnm.MIR403
[8] GB.O.ub.496

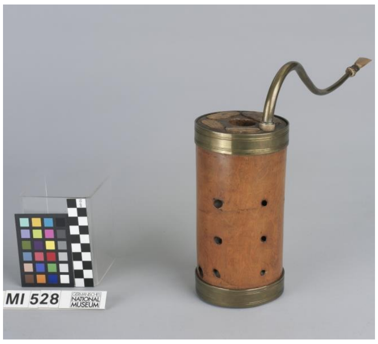		
Figure 2.1. Rackett by J.C.Denner, D.N.gnm.MI528. Image from MIMO	**Figure 2.2. Dulcian by J.C. Denner D.N.gnm.MIR403. Image from MIMO**	**Figure 2.3. Bass clarinet by Catterino Catterini. GB.O.ub.496**

These instruments developed into the baroque and then the classical bassoon by the time that basset horns and bassoon-form clarinets were made. Makers therefore knew that such folded tubes worked perfectly well, and they were very experienced in their (difficult) manufacture.

The earliest use of the folding technique in the clarinet family is the basset horn 'box' or 'Kasten'. When the clarinet was made in the tenor range, it became inconveniently long for a players' fingers and arms, and of course the bass clarinet is still longer. Some makers overcame this problem by making the instruments in sickle or square shape,[9] but more commonly, the instrument was made straight as far as the low written F – that is, as far as fingers unaided by keys can stretch to cover the tone holes – and the lower segment, written F to C, was effected by means of a box in which the bore is folded into three with keys covering holes in the sides of the box. The earliest such instruments known are three anonymous instruments dating from the mid 1750s to 1760.[10] Such instruments were made in quite large quantities from the 1750s.[11] A close-up of the box from the Griesbacher instrument in the RCM museum is shown in Figure 2.4 and an X-ray of a similar instrument is shown in Figure 2.5.

[9] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 100 ff.

[10] Thomas Grass and Dietrich Demus, *Das Bassetthorn: seine Entwicklung und seine Musik*. Vol, *2. Auflage.* Norderstedt: Books on Demand, 2004, 246.

[11] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 115 ff.

Figure 2.4. Close-up of the box (Kasten) on the Griesbacher basset horn.[12] The lower joint enters the box at the top left, then three segments of the bore are contained in the box.

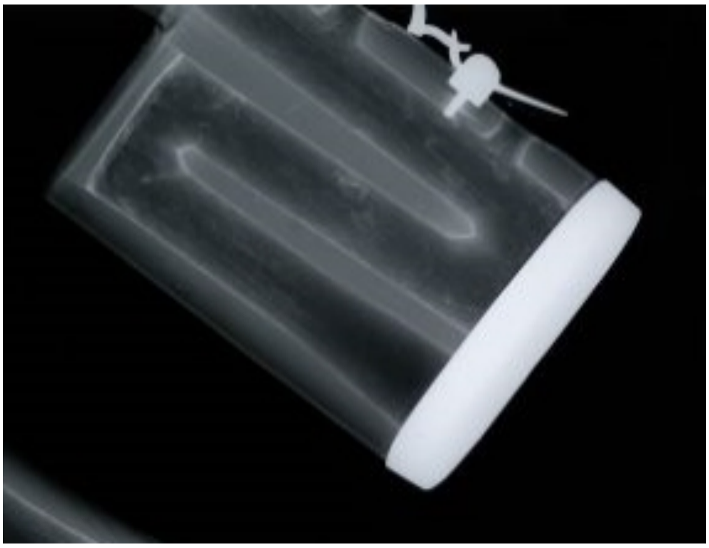

Figure 2.5. X-ray of the box of a basset horn by Mayrhofer, D.N.gnm.MI133.[13]

[12] GB.L.rcm.242

[13] https://objektkatalog.gnm.de/wisski/navigate/46649/view

The typology of the bass clarinet

An outline of the various types, with thumbnail images, is shown in

Table 2.1.

Table 2.1. Outline of classification typology (see main figures for attribution of thumbnails).

Class	Example	Thumbnail
Plank type Long toneholes drilled obliquely in edge of plank	B.B.mim.M939 Anon.	
Basset-horn type	D.M.ms 52-50 Anton & Michael Mayrhofer, Passau.	
Basse-tube type	Gilles Lot, Paris	No examples known, description only.
Serpent type	B.B.mim.940 Papalini, Paravalle.	
Bassoon type:		
True bassoon	D.LE.u.1539-1 Streitwolf, Göttingen	
Bassoon with LH keys	D. Uhingen.reil. Pietro De Azzi, Venice	
Half-bassoon	D.M.sm.79-28 Ottensteiner, Munich	
Ophicleide	US.NY.mma.89.4.2459 Losschmidt, Olomouc	
Straight type	GB.E.u. 4932 Stengel, Bayreuth	

Discussions on bass clarinet typology were commenced by van der Meer (1987)[14] and also appear in Dullat (2001)[15] and Rice (2009)[16]. As discussed and illustrated below, the bass clarinet has been made in many forms, all being attempts to reconcile the necessary acoustic length of the instrument and placement of the toneholes with the limited length and stretch of human fingers and arms. The types are discussed in (roughly) chronological order.

Plank type	**Date range:** *c.*1750 - 1800
Number of examples known:	Three, plus one documented but destroyed in war in 1940s.
Makers:	Probably three or four different but unknown makers.

Figure 2.6. Plank type bass clarinet B.B.mim.M939. Anonymous maker, in A, c.1750. In the image, the neck is absent, and the bell rotated for clarity; the bell and neck may be later replacements. Image from MIMO.

[14] John Henry van der Meer, 'The Typology and History of the Bass Clarinet,' *Journal of the American Musical Instrument Society* 13 (1987) 65–88.
[15] Dullat, *Klarinetten*, 73 ff.
[16] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 250 ff.

The oldest known attempt at making a clarinet sounding in the bass register is the 'plank' type, illustrated in Figure 2.6. The type was named by Rice[17] after an informal description by Young.[18] In this type, fingerholes were drilled through a deep section of wood at an angle, so that the correct pitches could be sounded without an excessive stretch of the fingers. The long, narrow chimneys were similar to those of a bassoon and probably had a similar acoustic effect. The bore is fairly narrow (*c*.18 mm). Historical records are available from V. C.Mahillon, who noted that the instrument in Brussels once belonged to Adolphe Sax. Mahillon was able to play a scale from concert C#2 to G3 plus the notes a twelfth higher with the single register key, corresponding to a bass clarinet in A. He reported that the notes

> are naturally of poor quality, without timbre, without accuracy, because of the defective proportions of the air column.[19]

However, the standard pitch has varied by several semitones over the last two centuries, and no music written specifically for a bass clarinet in A is known until *Lohengrin* in 1845.[20] It is likely that the instrument was made to correspond to some local ensemble or organ pitch.

The instrument shown in Figure 2.6 has been examined. It has been rendered unplayable at an unknown time by having a hole drilled into the bore opposite to one of the finger holes. Two other examples of this type are known, one in Florence[21] and an incomplete one in Switzerland[22]. One also existed in Berlin but was destroyed in WWII; it is known from an entry and photograph in Sachs' 1922 catalogue.[23] Rice also discusses these instruments, whose pitch and playing properties are not recorded.[24] The earlier two (Berlin and Sognono) could be described as bass chalumeaux but the later two clearly have register keys. The latest one, in Florence, dates from about 1780 and none has been identified from a later period. There are no makers' stamps on any of the instruments, and no known documentation or reference to this type in the literature or in musical scores. The country of invention and their uses are therefore unknown.

Basset horn type	**Date range:** c.1765
Number of examples known:	1
Makers:	Anton and Michael Mayrhofer, Passau (Germany)

The sickle shape had already been used by Anton and Michael Mayrhofer, Passau (Germany) and by one or two anonymous makers for their basset horns (for which they claimed

[17] Albert R. Rice, *The Baroque Clarinet*. 1992, 34.
[18] Phillip T. Young, *The Look of Music: Rare Musical Instruments, 1500 – 1900*. Vancouver: Vancouver Museums & Planetarium Association, 1980, 197.
[19] Victor-Charles Mahillon, *Catalogue Descriptif et Analytique Du Musée Instrumental Du Conservatoire Royal de Bruxelles (Deuxième Edition)*, vol. 1–5. Brussels: Gand, 1893, vol 2, 219-221.
[20] D. Keith Bowen, 'The Rise and Fall of the Bass Clarinet in A', 2011: 44–51; Bruce Haynes, *A History of Performing Pitch: The Story of 'A'* (Lanham and Oxford: The Scarecrow Press, 2002).
[21] I.F.ga.109
[22] CH.Sognono
[23] Curt Sachs, *Sammlung Alter Instrumente Bei Der Staatliche Hochschule Für Musik Zu Berlin*. Berlin: Julius Bard, 1922.
[24] Albert R. Rice, *The Baroque Clarinet*. 1992, 35.

invention), from about 1755-60 or possibly earlier.[25] In 1765 the Mayrhofers produced a true bass clarinet, shown in Figure 2.7. It descends chromatically to written E, then has a low C.

Figure 2.7: Bass clarinet in B♭ by Anton and Michael Mayrhofer, c.1765. D.M.ms 52-50

The sickle curve was made by drilling the bore in the octagonal body, sawing wedges out of the inside of the curve, gluing the wood together in the curved shape, then covering the body with a reinforcing wooden strip and with leather. The same procedure was used for the 360° loop but of course with less acute angles with a small lateral offset so that the loop passed over the body. This was a difficult procedure to execute and to make leak-free, and appears to have been very rarely used. This Mayrhofer example is the only bass clarinet example extant, and there is a similarly-made unstamped tenor oboe in Paris, attributed to Antonio Grassi of Milan.[26] Nor would the method lend itself to chromatic basset notes, since the tone holes would be located on the loop itself.

Interestingly, this bass clarinet does not use a box, even though such was used on the Mayrhofers' basset horns.[27] Possibly it was made as an experiment or what we would now call a 'technology demonstrator'. In an historical context, this was a trial attempt that did not lead to further development or use.

[25] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 101.
[26] F.P.cm.E.749
[27] e.g. D.N.gnm.MI133

'Basse-Tube'	**Date range:** c.1772
Number of examples known:	1, by documentation only
Makers:	Gilles Lot

This is included since it is the first documented mention of a bass clarinet, a little later than the Mayrhofers, in an announcement in the Paris newspaper, *L'Avant-Coureur* of 11 May 1772, thus:

> M. G[illes] Lot, the wind instrument maker living in the courtyard of the monks of the Abbey Saint-Germain, next to the fountain, has shown a newly-invented musical instrument under the name *basse-tube* (basso tuba) or bass clarinet. Up to now there has not been seen an instrument of such a large range. It can play three and a half octaves; it descends as low as the bassoon and rises as high as the flute. This instrument, which is of an unusual form, contains several keys for production of semitones, all very artistically arranged and with a very ingenious mechanism. The sounds that it produces are very agreeable, and so perfectly sonorous that the low tones imitate very well the pedal note of an organ. This instrument, when played by a skilful artist, cannot fail to produce a good effect and to gain the approval of the public, whether as a solo instrument or in the orchestra.[28]

This appears to have been quite an advanced model, though it is not certain that it is a bass clarinet. Unfortunately no instrument is known to have survived and no other descriptions are known. The description could suggest a bassoon-form instrument from *d'une forme tout à fait particulière* and the low range matching the bassoon, but the name '*tube*' might more aptly describe a straight form. In either case it could have been an inspiration for future models.

In the chronological sequence we should note here that Anton Stadler announced in 1788 (on a handbill of his Benefit Concert in Vienna) a 'Baß-Klarinet'. From strong iconographic and musical evidence, this was a normal clarinet in bore and tonality (A and B♭) but with extended length and keywork to produce tones down to written C3. Such instruments are now called *basset clarinets*, and do not form a part of the bass clarinet history or typology.[29]

Serpent type	**Date range: :** *c*.1820 – 1829
Number of examples known:	6
Makers:	Nicola Papalini, Chiaravalle, Italy

This innovative design by Nicola Papalini[30] was made by carving half of the serpentine bore in each of two pieces of wood. Precise mirror-image carving and accurate registration is required. The two halves are then glued and pinned together. The serpentine bore allows the instrument to be much shorter, and places most of the fingerholes within easy reach of the fingers. The serpent form was made only by Nicola Papalini, six of which survive, dating from about 1820 to 1829. The later specimens had keywork added, often with touches that ran from one side to the other to preserve the very compact design. The demand for these unusual

[28] '*L'Avant-Coureur* of 11 May 1772. Quoted in Rendall, *The Clarinet*, 1954, 143.

[29] Pamela Poulin, 'Anton Stadler's Basset Clarinet: Recent Discoveries in Riga,' *Journal of the American Musical Instrument Society* 22 (1996) 110–27.

[30] US.NY.mma.89.4.2545. This instrument is dated c.1810 in the MMA catalogue but Rice (2009) puts it c.1825, which seems likely by comparison with B.B.mim.940.

instruments clearly persisted for about ten years, but no other maker appears to have attempted this very difficult technique for making bass clarinets.

Two examples are shown, Figures 2.8 and 2.9, both *c*.1825. The other Papalini instruments are in Leipzig, Boston, Paris and Rome (this last being an alto in F rather than a bass clarinet).[31]

Figure 2.8 (left). Serpent-form bass clarinet in C by Nicola Papalini. c.1825. D.M.ms 52-50. Image courtesy A. Rice

Figure 2.9 (right). Serpent-form bass clarinet in C by Nicola Papalini. c.1825. US.NY.mma.89.4.2545.

Bassoon type	**Date range: : 1793 – c.1914**
Number of examples known:	c.70
Makers:	At least 35 including Heinrich Grenser, Augustin Grenser, Johann Streitwolf, Georg Ottensteiner and others (Germany), George Catlin and others (USA), Paolo Maino, Giacinto Riva and others (Italy), Ludwig & Martinka (Bohemia).

This compact type is constructed similarly to a bassoon, with similarly named joints (see Figure 1.2 for nomenclature). The butt joint contains both 'down' and 'up' tubes, joined by a transverse hole near the bottom end (see Figure 2.18). The free ends of the holes are plugged with corks, which can be adjusted for tuning the two halves of the instrument relative to each other.

[31] D.LE.u.1538; US.B.mfa.17.1879 (unstamped); F.P.cm.E.760, C.550; I.R.ms.617

The continuous history of the bass clarinet began in 1793 with this instrument, invented and made by Heinrich Grenser of Dresden. It is in a bassoon form, with of course a cylindrical bore, and descends to C2, B♮1 or B♭1. It was possibly an improvement on existing models that have not survived.[32] Heinrich advertised his invention in *K.K. Prager Oberpostamtszeitung.*[33] The instrument itself survives and is now in Stockholm; its original customer was the King of Sweden.[34,35] It is referred to in Pontécoulant's history of musical instrument makers:

> In 1793, Grenser, maker of the court of Dresden made, it is said, the first model of the bass clarinet.[36]

Figure 2.10. Heinrich Grenser's original (dated) bassoon-form bass clarinet. S.S.m.M2653 Image courtesy Scenkonstmuseet/Swedish Museum of Performing Arts, Stockholm. Photograph Sofi Sykfont.

It inspired a large number of instruments by many makers. Heinrich Grenser was thus the first inventor of bass clarinets whose work was then emulated by many others, and should be regarded as the founder of this class of instruments (see Figure 2.10). Heinrich was a woodwind maker apprenticed to his then more famous uncle, Augustin Grenser, who soon

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[32] Albert R. Rice, "The Earliest Bass Clarinet Music (1794) and the Bass Clarinets by Heinrich and August Grenser." *The Clarinet* 38 (2011) 54–58.
[33] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 258.
[34] S.S.m.M2653
[35] Rice, "The Earliest Bass Clarinet Music (1794) and the Bass Clarinets by Heinrich and August Grenser".
[36] Pontécoulant, *Organographie; essai sur la facture instrumentale,* vol. 2, 80

emulated his nephew in making a bassoon-form bass clarinet, now in Darmstadt, in 1795.[37] Many of the later makers were also very distinguished, such as Johann Heinrich Gottlieb Streitwolf of Göttingen, Catterino Catterini of Italy, Georg Ottensteiner of Munich and Johann Simon Stengel of Bayreuth.[38] The excellence of the workmanship of Streitwolf from 1828 onwards is a notable milestone.[39]

Keys could operate pads on either the down or up tubes, and thumbs were used to operate the holes or keys for notes below written E2 or E♭2. The design is compact and convenient for marching bands. Instruments were made originally in B♭ but soon after also in C. No instruments in A are known. Almost all bassoon-form bass clarinets known have a range at least to low written C2 or one or two semitones lower, and such notes are normal rather than an 'extension' on these instruments.[40]

The bassoon-form instrument was reinvented in France by Dumas in about 1807, when it was presented at the Conservatoire.[41] The last known maker was one of the Schediwa family, who relocated from Bohemia to Kyiv, Ukraine (then in the Russian Empire) in the late nineteenth century; he produced excellent quality instruments with chromatic range to low C2. An example is shown in Figure 2.15.[42]

It is also likely that the instruments made by George Catlin and his associates in the USA from 1810, Catterino Catterini in Italy from 1834 and Johan Heinrich Gottlieb Streitwolf in Germany from 1828 were independent or at least semi-independent inventions. These makers (as well as Sautermeister) claimed invention, or invention was claimed for them (by Kastner[43] in the case of Streitwolf) but they may have been using the term loosely, as 'improvement' or 'development' rather than a completely original design.

Communications between makers, musicians and performers in the eighteenth century must have been generally good across Europe; for example, Grenser's first bass clarinet was made for the King of Sweden's orchestra. Communications to the fledgling USA must have been slower, and - if they occurred at all - information about the design of the instruments may have been verbal or descriptive from press reports, rather than technically accurate. This idea is supported by the fact that Catlin's instrument is built in the mirror image of Grenser's.[44,45] Grenser placed the bell on the right-hand tube viewed from the player, rather than on the left hand as with bassoons and all subsequent bassoon-form bass clarinets other than Augustin Grenser's, who was master of the workshop in which his nephew Heinrich worked.[46] The bore of Catlin's clarinets, varying from 17.3 to 19 mm is also much larger than Grenser's (which at

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[37] D.DS.hl.KG67:133. This instrument had the significant improvement of an extra register key (see Chapter 8).
[38] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009.
[39] Rice. 268
[40] Exceptions are a few ophicleide forms made by e.g. Widemann (GB.L.hm. 14.5.47/301b which descend to E♭2.
[41] Rice. 261
[42] GB.O.ub.401
[43] Kastner, *Supplément Au Traité Générale d'instrumentation*.
[44] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 265
[45] Robert E. Eliason, 'George Catlin: Hartford Musical Instrument Maker Part II,' *Journal of the American Musical Instrument Society* 9 (1983) 21–52.
[46] I have personally verified the 'handedness' of Heinrich Grenser's instrument in the Stockholm museum.

15.2 mm is really that of a basset horn) and similar to later European instruments. Eliason[47] usefully lists the differences between Heinrich Grenser's instrument and the nine American bass clarinets made by Catlin and his known or probable students or associates. He points out that this is the largest set of bass clarinets (that we know of) made anywhere in the world before about 1825. We have no evidence of any communication between the American and European makers. At present we can only conclude that they independently produced similar solutions to the same design problem, possibly inspired by verbal descriptions by travellers or emigrants. For example, a strong Moravian community that maintained Harmoniemusik traditions is well known in the early USA from the mid-eighteenth century.[48] One of Catlin's instruments, a bassoon-form alto clarinet, is shown in Figure 2.11.[49] Sadly, no further examples are known to have been made after the retirement or death of Catlin and his associates, and no ongoing American tradition was established in this field.

Figure 2.11. Catlin, alto clarinet, US.NY.mma.1994.365.1

A number of other examples of early and late 'folded' clarinets are shown for familiarity in Figures 2.12 to 2.17. These are catalogued in Chapter 4.

[47] Eliason, 'George Catlin: Hartford Musical Instrument Maker Part II.'

[48] Roger Hellyer, "The Harmoniemusik of the Moravian Communities in America," *Fontes Artis Musicae* 27, (1980) 95–108.

[49] US.NY.mma.1994.365.1

Figure 2.12. 'Bassoon-type' bass clarinet by Streitwolf. In B♭. D.LE.u.1539-1. Image from MIMO.

Figure 2.13 'Bassoon-type' bass clarinet by Ludwig & Martinka, *c.*1865, in C. CZ.P.cmm.E135

Figure 2.14. 'Bassoon' type bass clarinet by Georg Ottensteiner, *c.*1855, in B♭. D.M.sm.79-28

		
Figure 2.15. 'Bassoon' type bass clarinet in B♭ by Schediwa from the Ukraine. U.O.ub.401	**Figure 2.16. 'Ophicleide' type bass clarinet, attributed to Giovacchino Bimboni, 1845-50, in B♭. D.N.gnm.MIR-482. Image from MIMO.**	**Figure 2.17. 'Bassoon-form' type basset clarinets in B♭ from Verona, Italy. Left: Chiesara, 1889, I.R.ms.740. Right: Ghirlanda, *c.*1868. I.R.ms.631**

The classifications noted in the captions above are the broad classes proposed by van der Meer and are based upon the method of construction: all bassoon types have folded tubes that reverse at the butt joint and are clearly distinct from plank, basset horn and straight types.[50] Van der Meer distinguished sub-classes of the bassoon types again based upon structure, but these are in my view less useful. For example, his V-type has only one member, [51] and the sub-classes do not tell us much about the important musical properties of the class. It is easy to miss important details, such as the type of tone hole (long, thin, diagonal, open or short, wide and covered), which has not been considered in previous classifications. Moreover, the various 'types' overlap in date and there is no simple succession.

I prefer to regard all the folded instruments as 'bassoon-type', as a useful shorthand that is widely used in the literature and in museum classifications. But there are a number of distinctions within this class that it is important to recognise in order to understand the possible acoustic differences. I therefore suggest the following sub-classification of the

[50] Meer, 'The Typology and History of the Bass Clarinet.'
[51] D.N.gnm.MI338 attributed to Stengel.

bassoon type according to the potential acoustic differences. There are three ways in which acoustic effects may show themselves:

- by the structure of the fold at the butt joint
- by the long, thin tone holes that can occur in the top joint.
- by the relatively massive construction of the butt joint, again necessitating longer tone holes

In other respects there are no systematic or acoustically-significant differences between the bassoon form and the straight form.

Sub-class: True Bassoon Type

The original Grenser instrument and those made by many makers such as those illustrated above are very close parallels structurally with bassoons, in two respects. The most obvious is that they have a butt joint with a double bore, connected by a hole, as shown in Figure 2.18. The lower ends of the tubes (the bottom end of the instrument) were plugged by corks, which could be adjusted so as to tune the two halves with respect to each other. This feature persisted throughout the lifetime of the form, even being found on the Schediwa instruments in the early twentieth century.[52] In some cases in the second half of the century this was replaced by a metal U-tube, making it into the ophicleide type discussed later.

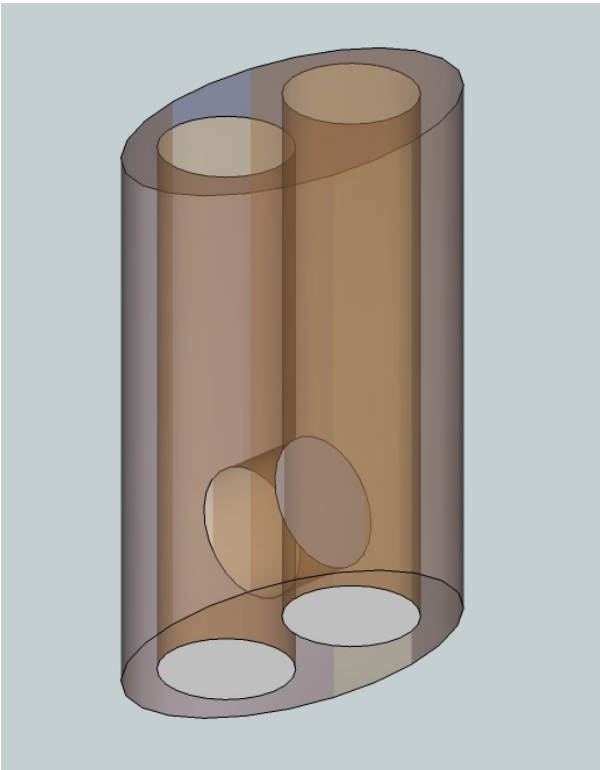

Figure 2.18. The butt joint in a bassoon-form bass clarinet, copied from that in contemporary bassoons.

The second major parallel is the structure of the wing joint. The early bassoon-type instruments and many subsequent models had wing joints that were similar to those of a bassoon, that is, they had a protruding 'wing' through which long holes were drilled diagonally for fingerholes I, II and sometimes III, in order to allow the fingers to reach the tone holes.

[52] Personal inspection of the instrument in the Bate Collection, U.O.ub.401.

Some examples that can be dated with reasonable certainty are shown in Figures 2.19 to 2.22, showing that this feature persisted at least until 1860.

Figure 2.19. Heinrich Grenser, S.S.m.M2653 dated 1793. Wing joint. Image courtesy Scenkonstmuseet/Swedish Museum of Performing Arts, Stockholm. Photograph Sofi Sykfont.

Figure 2.20. Streitwolf D.LE.u 1539-1, dated 1833-37 by the Grassi Museum. Wing joint.

Figure 2.21. Giacinto Riva, US.NY.mma-89.4.3124, dated by the MMA and Rice at c.1860. Wing joint.

Figure 2.22. Stengel, I.F.ga-1988-170 Cherubini, c.1850 – 1860. Wing joint.

It is seen that with the wing-joint construction the tone holes are not only long and diagonal but relatively small in diameter. These factors are necessitated by clarinet acoustics and by human anatomy; in order to cover the holes one has to stretch the fingers, and the fingers must be wide enough. Acoustically, any clarinet must have a largely cylindrical bore, and in a folded instrument this should be at least 20 mm (only the very early Grensers are any less); the overall width is doubled in a folding instrument, plus the widths of the walls. It is therefore very difficult for the fingers to reach the centre of the top and bottom of the tube of the bore on the opposite side to the wrist. Examination of many bassoon form bass clarinets in museums, holding them in their playing positions, has shown me that there are only a few practical ways to make such a folded instrument:

- by use of the extended wing joint as discussed above;
- by the use of keys to extend the range of the fingers, as on the Catterini and Pietro De Azzi discussed below and on ophicleide-type instruments;
- by use of a standard tubular top joint and kinks in the crook and bell to allow the up tube to avoid the down tube near the positions of the left hand fingers, as on the Franz Karl Kruspe instrument in Basel, discussed in Chapter 7;[53]
- by using a straight tubular top joint and extending the butt joint so that more tone holes are carried on the butt; the bell then comes directly off the butt joint and there is no long bass joint to interfere with the fingers. This is the half-bassoon type, discussed below and made by e.g. Georg Ottensteiner and Josef Josefovitch Schediwa.[54]

Furthermore, the player's finger size limits the size of open tonehole that can be employed. This in turn limits the acoustic emission of the tonehole and therefore the dynamic level attainable[55], and does not allow the maker to compensate for a long 'chimney' by enlarging the hole. It is clear that early bass clarinet makers realised this limitation. From the 1830s we see mechanisms introduced that allow an easier reach and much larger holes, for example by Catterino Catterini (Figure 2.23) and Pietro De Azzi (Figure 2.24). The acoustic effect of long, narrow chimneys will be studied in Chapters 7 and 8. This observation gives rise to the next sub-classes.

[53] CH.B.hm.1999-136

[54] D.M.sm.79-28 (Ottensteiner) and GB.O.ub.401 and GB.E.u.4819 (Schediwa).

[55] And less obviously but very importantly, the cutoff frequency, discussed in Chapter 8.

Sub-class : Bassoon Type with LH Keys

The keys allow tone hole to be placed centrally on the down tube, but to be operated by the left hand fingers without an undue stretch. These may be made either in one piece like a dulcian (e.g. Catterini[56]) or, more commonly, in bassoon construction with the extended wings supporting the keys rather than being used for long, diagonal holes (e.g. De Azzi, discussed below[57]).

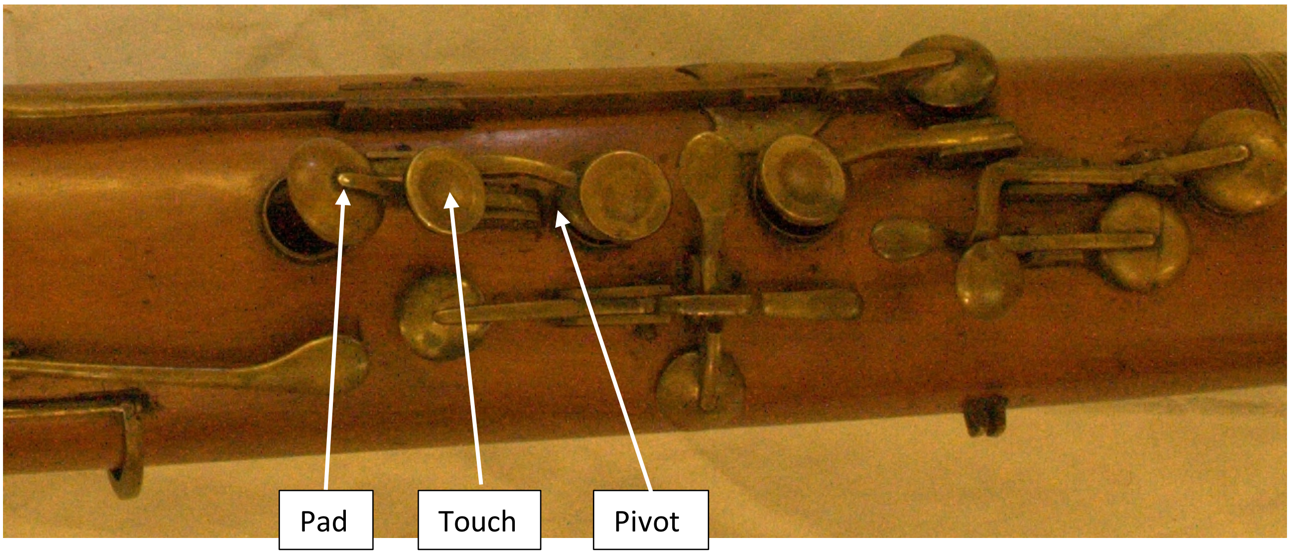

Figure 2.23. GB.O.ub-496, Catterino Catterini, stamped 1833. The touches operate holes too large to be covered with a finger.

This sub-class began with Catterini in 1833 and continues at least as far as dulcian-shaped basset clarinets made by Tedesco Chiesara in 1889.[58] By that time the bassoon-form bass instruments themselves were made in one of the other forms.

The instrument by Catterino Catterini of Padua, which he called a *polifono* or *glicibarifono*, is of particular interest. It is in dulcian shape, and is dated by the award of a gold medal at an exhibition of the Imperiale Regio Istituto del Regno Lombardo-Veneto, Venice, 4 October 1833.[59] It is described as having fourteen keys, but it is not known whether the six plateaux keys for holes I - VI were included in this total. The instrument was most likely played by Catterini himself in the première of the first orchestral/operatic solo for bass clarinet, *Emma d'Antioch* in La Fenice theatre of Venice on 8 March 1834 (credited as *glicibarifono* in the programme), and several other performances in the region are documented[60] He made at least

[56] GB.O.ub.496
[57] D.Uhingen.reil.De Azzi
[58] I.R.ms.3254
[59] Gabriele Rocchetti and Gabriele Rossi Rognoni, 'Gli Strumenti Musicale Premiati Dall'Istituto Lombardo Di Scienze, Lettere Ed Arti Nell'Ottocento. Ed. R. Meucci,' in *Liuteria Musica e Cultura*, vol. 1998, 1998, 3–17; Anon. 'Nuovo Strumento Di Fiato, Di Catterino Catterini Di Monselice,' *Giornale Di Belle Arti e Tecnologia* 1 (1833) S.292; Anon. 'Nachrichten. [News from] Lombardisch-Venetianisches Königreich,' *Allgemeine Musikalische Zeitung* 36, no. 34 (August 20, 1834) 570–71.
[60] Fabrizio Della Seta, 'From The Glicibarifono To The Bass Clarinet: A Chapter In The History Of Orchestration In Italy'. In Niels Martin Jensen and Franco Piperno (Eds.). *The Opera Orchestra in the 18th- and*

three instruments, one of which still exists in the Bate Collection at Oxford.[61] The latter instrument has twenty keys (including plateaux keys) and is stamped 'No. 3" so is probably a later model. It is not quite clear who actually made the instrument. The sparse documentation about Catterini, listed in Della Seta indicates that he was a clarinettist and inventor, and it was stated by Waterhouse that the instruments were reportedly made by Riva.[62,63] No source is given by Waterhouse for this remark, which has been repeated.[64] Although Riva was undoubtedly a skilled maker, as testified by the bassoon-form instrument bearing his stamp in New York.[65] I know as yet no evidence for the suggestion that the instruments were not made by Catterini himself. The instruments bear his mark in the location at which one would expect a makers' mark.[66] The research notes and documentation of the Waterhouse Collection have not been generally available to scholars since the passing of William Waterhouse in 2007.

The instrument by De Azzi is an early but particularly good example of this subclass. Figure 2.24 shows the elegant and practical arrangement of the left-hand keys.

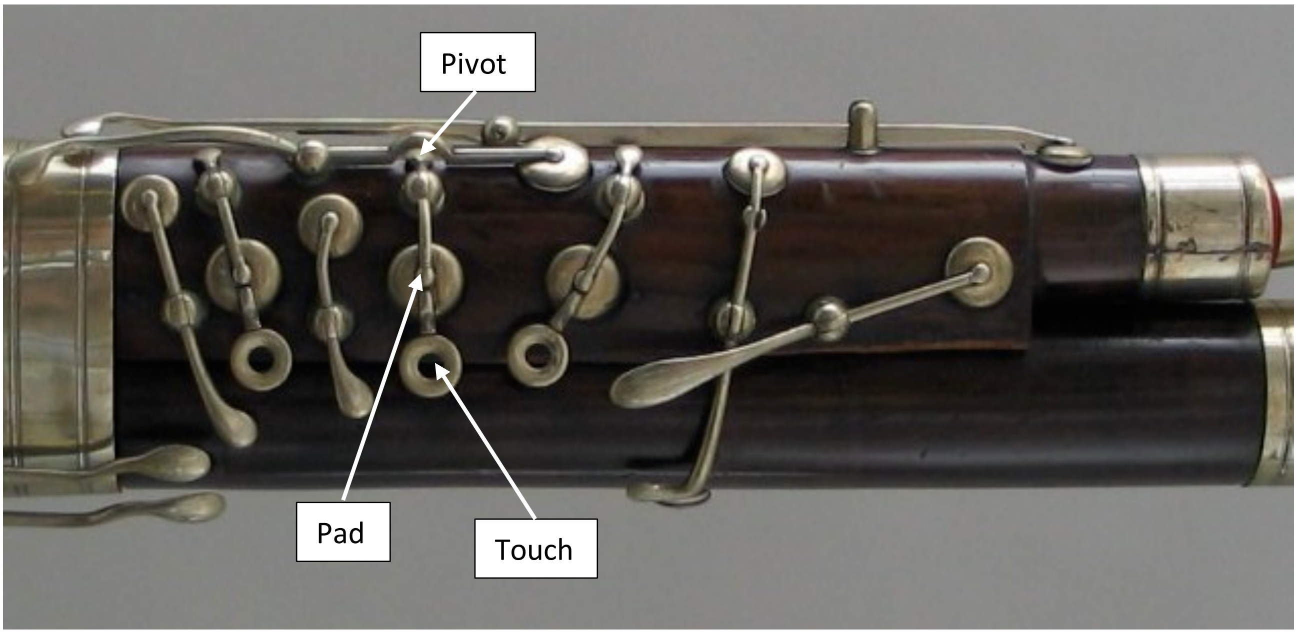

Figure 2.24. Bass clarinet, D.Uhingen.reil, Pietro De Azzi, dated c.1848 by Rice. The key touches for I, II and III operate pads that are located much more centrally on the down bore. The details of pad/hole II are labelled. The down tube is the upper one in this image. Image courtesy Thomas Reil.

19th- Century Europe, II: The Orchestra in the Theatre - Composers, Works, and Performances. Berlin: Berliner Wissenschafts-Verlag, 2008, 331–52.

[61] GB.O.ub.496, illustrated in Figure 2.3. It is also stamped No. 3.

[62] Della Seta, `From The Glicibarifono To The Bass Clarinet'

[63] William Waterhouse, *The New Langwill Index: A Dictionary of Musical Wind Instrument Makers and Inventors.* London: Tony Bingham, 1993, 59 and 330. This attribution also appears in earlier editions.

[64] e.g. Rice, *From the Clarinet D'amour to the Contra Bass*, 2009.

[65] US.NY.mma.89.4.3124

[66] Herbert Heyde, *Makers Marks* (London: In Waterhouse, William (1993). The New Langwill Index, xiii.

Sub-class: Half-bassoon type

Date range: 1850 – *c.*1914

Number of examples known: *c.*10

Makers: Ottensteiner, Buffet, Schediwa and others

It is probable that makers realised the problem with the wing joint, and eventually abandoned this method of manufacture, but retained the compact butt joint. In these instruments the top joint does not differ from that in a straight-form instrument. One would therefore expect little acoustic difference between these and a straight instrument. Examples (already shown) are Ottensteiner (Figure 2.14) and Schediwa (Figure 2.15).

There are now three joints (plus the neck and bell) rather than four. The wing (now simply the upper joint) and butt joints are elongated and the bass joint omitted. These instruments normally descend to written C2. The keywork for the notes from C2 to E2 is operated by the right thumb. Its tone holes are on the up tube of the butt joint, as opposed to tone holes on the long bass joint operated by right and left thumbs as in most bassoon forms.

Sub-class: Ophicleide type

Date range: *c.*1845 – *c.*1870

Number of examples known: Six before *c.*1850 ; a very large number of contra-alto and contrabass instruments to modern times.

Makers: Bimboni, Losschmidt, Skorra, Widemann, Wieprecht, Sax, Martin Frères, Uhlmann, Leblanc

A natural development of the bassoon form was to make it entirely of metal (very occasionally wood), with a U-bend rather than transverse hole in the butt joint. These instruments play and sound very well (see Chapter 7). Rice named this class by analogy with the ophicleide, a conical folded instrument with brass mouthpiece but fingerholes like a woodwind. The Sax is a contra-alto and the Skorra, and Skorra & Wieprecht instruments are contrabass clarinets, and these lower clarinets are still normally made in ophicleide ('paperclip') form. An ophicleide of 1840 by Henry Smith of Wolverhampton, is shown in Figure 2.25 to illustrate the derivation of the name. The material is normally brass or nickel silver (occasionally wood), and the bottom joint is made with a 'bow', a U-shaped reinforced tube, rather than the complicated structure of a bassoon-type butt joint.

In the mid-nineteenth century, several makers constructed folded instruments in the shape of an ophicleide: Widemann of Paris, Louis Auguste Buffet of Paris, Martin Frères of La Couture, Losschmidt of Olomouc, Nechwalsky and Uhlmann of Vienna and Carl Kruspe of Erfurt, hence they appeared in widely separated countries within a few years of 1850. The instruments were all well made, and quickly gathered good reputations. The type still exists for contra-alto and contrabass clarinets. Many of them are of metal construction, and have short tone hole chimneys and keys to operate all the tone hole pads. An example by Bimboni is shown in Figure 2.16, and a Losschmidt example is examined in Chapter 7.

Figure 2.25. Ophicleide, Henry Smith Wolverhampton, *c.*1840. GB.E.u.3096. Image from MIMO.

In summary, the bassoon-form clarinets, of which the bass was the most important, started with the basset horn in 1789 in Vienna and the bass clarinet in Saxony no later than 1793, and ran through to the early years of the twentieth century. It was re-invented or redesigned in New England, USA in 1810, in Saxony again in 1828 and the Venice region of Italy in 1833 and these three regions produced instruments of distinctive form and keywork.

Far more bassoon-type instruments were made than any of the other types that preceded the straight form. The catalogue in Chapter 4 of the thesis lists over eighty that are extant in museums and collections. These folded instruments are compact and convenient to play and to transport and thus offer a number of apparent advantages over the 'straight' form that is now universal.[67] There is the report by Fétis that the bassoon-type bass clarinet of Dumas was well received by audiences.[68] But the bassoon-form instrument has completely disappeared from manufacturers' catalogues other than for contra-alto and lower instruments; it has not been an available option from any maker for more than a century.

Straight type	**Date range:** 1807 - present
Number of examples known:	Very large indeed.
Makers:	Desfontenelles, Buffet 'jeune', Adolphe Sax, followed by Kruspe, Stengel, Buffet, Nechwalsky and a very large number of others to modern times, including all current makers of bass clarinets such as Buffet, Selmer, Wurlitzer, Yamaha and many others.

[67] following the German usage: *gerade*, as opposed to *fagottform*.
[68] Fétis, 'Instrumens Nouveau. Clarinette-Basse,' May 1833.

The modern 'straight' type is defined as one in which the tone holes lie essentially in line, as in a soprano clarinet. The neck is curved for the convenience of the player, and the bell section may either point downwards or curve upwards. Straight-form instruments were developed in parallel with the bassoon-form from the early nineteenth century,[69] the earliest claim being made by Desfontenelles in 1807.[70] His instrument survives, as shown in Figure 2.26, from which it appears to have been a well-made instrument, but it did not immediately achieve critical or commercial success, or displace the bassoon-form instruments. After originally working with Dumas on his bassoon-form instrument (see Chapter 1) the straight model developed by Dacosta in collaboration with Louise Auguste Buffet ('Buffet jeune') was later used successfully in the Act V bass clarinet *obbligato* in Meyerbeer, *Les Huguenots,*[71].

Figure 2.26. Bass clarinet by Desfontenelles of Lisieux. F.P.cm.E.1055. Image from MIMO.

From 1838 a major competitor emerged, in the new, patented design of Adolphe Sax, who was also a large-scale manufacturer and moreover possessed excellent marketing skills. Sax's design was quite different from previous bass clarinets of either form. He enlarged the tone holes and placed them in acoustically correct positions, which he determined by his discovery of the 'law of proportions':

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[69] Or possibly from 1772 if Gilles Lot's *basse-tube* was straight.
[70] The instrument F.P.cm.E1055.C.1136 has a dated stamp by Desfontenelles
[71] There is somewhat conflicting evidence concerning the player and instrument used in the first performance in 1836 (see discussion in Rice 2009, footnote 177 p. 287) but this is not germane to the development of the instrument.

> The timbre of an instrument is determined by the proportion of the columns of air rather than by the substance from which the instrument is made[72]

Earlier Sax instruments had a downward-facing bell fitted with a reflector to project the sound towards the audience. This was eventually replaced by an upward-facing saxophone-type bell. The latter may be regressive in sound quality[73] but significantly lowers the height of the instrument so that it can be played in a normal-height chair. It has not formerly been noted that the bore of Sax's instruments was exceptionally large. The two instruments in Brussels[74] have minimum bore 28 – 29 mm, and this design was followed in the earlier instruments by Buffet; for example an instrument in Nuremberg dated about 1850, where the one-piece middle bore is approximately 28.8 mm.[75]

Berlioz himself remarks, after a discussion of Sax's improvements to the soprano clarinet[76]

> M. Adolphe Sax's new bass clarinet is still more improved. It has 22 keys. That which especially distinguishes it from the old one is its perfect precision of intonation, an equalised temperament throughout the chromatic scale, and a greater intensity of tone.

And, from the context of his earlier remarks on the bass clarinet[77]

> As it is always the same instrument, - constructed on larger dimensions,- as the ordinary clarinet ....

it appears that Berlioz was familiar with the straight form, not the bassoon form instrument.

The quality and innovation of Sax's instruments may also have been one cause of the eventual disappearance of the bassoon-type instruments. The excellent playability of Sax's instruments must have been a factor, against which the lack of notes below E2 was not perceived as a disadvantage for orchestral playing.[78]

Sax's design strongly influenced those of Buffet-Crampon, the firm established in Paris in 1836 by Jean-Louis Buffet (a competitor of Buffet-jeune), which is still a dominant force in clarinet and bass clarinet manufacture. Buffet-Crampon exhibited their new Boehm system bass clarinet at the Exhibition in Paris in 1855, which gradually supplanted the Sax design based on Müller's original layout in France and is now current for the two major present-day manufacturers, Buffet-Crampon and Selmer. The bore has now settled at approximately 24 mm for French-style instruments. In Germany, the Sax keywork design, with some additional features such as brilles, persisted largely through to the early twentieth century. The German makers retained the preference for the 'German bore', usually slightly narrower (about 20 – 22 mm) and parallel almost to the end of the clarinet, rather than the wider, more flaring

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72 Oscar Comettant, *Histoire d'un Inventeur Au XIXe Siècle. Adolphe Sax, Ses Ouvrages et Ses Luttes*. Paris: Morris, 1860.

73 S. Fox, private communication 2018.

74 B.B.mim.0175 and 2601; D.N.gnm.MIR478

75 D.N.gnm.MIR478; Frank P. Bär, *Verzeichnis Der Europäischen Musikinstrumente in Germanischen Nationalmuseum Nürnberg. Band 6: Liebesklarinetten, Bassetthörner, Bassklarinetten, Metallklarinetten*. Wilhelmshaven: Florian Neutzel, 2006, 241.

76 Berlioz, *Treatise on Instrumentation*, 116.

77 Berlioz, 114; Crouch, 'The Contributions of Adolphe Sax to the Wind Band'; Berlioz, 'Instrumens de musique.', 1842.

78 Sax's patent refers to the possibility of adding notes down to low C, but no such instrument has been found.

French design.[79] This can be seen even in the external shapes of Figures 2.27 and 2.28. Oskar Oehler applied his clarinet system to the bass clarinet around the end of the nineteenth century. Such designs are still current in Germany, by manufacturers such as Wurlitzer, Schwenk & Seggelke and Leitner & Kraus. The Schmidt Reform Boehm system, a combination of keywork and hole layout of the Boehm system with an Oehler-type long cylindrical bore, and some keywork modifications giving improved venting and resonance control, is also manufactured by Herbert Wurlitzer in bass clarinet form. Straight form bass clarinets, from the Sax invention to present-day instruments, are shown below in Figures 2.27 to 2.30.

	
Figure 2.27. Adolphe Sax, Paris *c.*1843. F.P.cm.E.1223 C1337. Image from MIMO.	**Figure 2.28. Carl Kruspe (senior) of Erfurt. Left (D.LE.u.4478): in A. *c.*1880. Right (D.LE.u.4479): in B♭, *c.*1870.**

[79] See for example, the Heckel (1910) instrument analysed acoustically in Chapter 6.

Figure 2.29. Selmer Privilege bass clarinet in B♭ (Boehm system) to C2 with custom neck and bell, with the soloist Sarah Watts. Courtesy Sarah Watts, photograph by Emma Ledworth.

Figure 2.30. Fritz Wurlitzer Reform Boehm bass clarinet in B♭ with extension to C2, from the Sir Nicholas Shackleton collection. GB.E.u.4923. Image from MINIM.

Timeline of developments in the design of bass clarinets

We may illustrate the development of bass clarinets by the timeline shown in Figure 2.31. In this chart the principal inventions are shown, including both the first of every type and significant stages within the type. For example, the bassoon-form instrument was invented by Heinrich Grenser, but significant improvements were made by Augustin Grenser, George Catlin, Catterino Catterini and Johann Streitwolf.

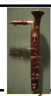
Decade starting	Maker	Form	Location	Thumbnail
1750	Anon.	Plank	unknown	
1760	Mayrhofers	Basset horn	Passau	
1770	Lot	Straight?	Paris	
1780	Experiments by H. Grenser and others			
1790	H. Grenser A. Grenser	Bassoon	Dresden	
1800	Desfontenelles	Straight	Paris	
1810	Catlin	Bassoon	Hartford, CT	
1820	Papalini Streitwolf	Serpent Bassoon	Chiaravalle Göttingen	 
1830	Catterini Sax	Dulcian Straight	Padua Brussels	 
1840	Bimboni Losschmidt	Ophicleide	Florence Olomouc	 
1860	Ottensteiner	Half-bassoon	Munich	
1870	Many bassoon, ophicleide and half-bassoon models produced in this period			
1880				
1890				
1900				
1910	Schediwa End of line of bassoon-form	Half-bassoon	Odessa	

Figure 2.31. Timeline of the development of bass clarinets (see figures for attribution of thumbnails).

Concluding remarks

The development of the bass clarinet has been characterised and illustrated, from the earliest attempts to modern times. The two forms that have been outstandingly successful and made in large numbers have been the bassoon form and the straight form. The straight form has now displaced all rivals, and is the only one that is still made. The bassoon form and its variants, however, was made in significant quantities from the late eighteenth to the early twentieth centuries. Its variants have structural differences that will affect the acoustical properties, and a new sub-classification has been proposed.

Chapter 3

The bassoon-form bass clarinet in the nineteenth-century repertoire

During the century before 1850 the bass clarinet slowly but steadily became established as an obbligato and orchestral instrument, in chamber recitals (especially together with singers) and in both civil and military bands. Until the late 1830s, almost the only choice of instrument was the bassoon form, with instruments known from multiple makers, catalogued in Chapter 4.[1] Until the advent of the straight-form instrument by Adolphe Sax in 1838, therefore, any call for a bass clarinet was almost certain to have been met by a bassoon-form instrument. Geographically, the bassoon-form instrument was invented in Dresden, Saxony and developed or re-invented in the German States and in the Austrian Empire, notably in Lombardy (North Italy), the USA, and the Czech lands of Bohemia and Moravia. In contrast, the straight form was developed first in France and spread later to Germany, England and other countries, though the French and subsequently English bore design was, and remains, different from the German models.

Composers did not generally specify the form of the instrument in the score, except possibly in Italy; there the use of the term 'glicibarifono', invented by Catterino Catterini, appears to be reserved for bassoon-form instruments based loosely on his dulcian-form design. Bimboni named his ophicleide design the 'Bimboclarino', and the term 'clarone', used widely (e.g. by Puccini), may have implied the straight form but this is not certain. It is more likely that the terms referred to the name of the instrument available in the opera house for which the music was written. The form of the bass clarinet is not specified at all in German or French scores and there are no musical clues to indicate which instrument was intended, other than the range. Importantly, the range extends to at least C2, sometimes as low as B♭1, in almost every bassoon-form bass instrument examined or reported in the literature. In contrast, straight-form instruments do not descend below E2 until the second half of the century, beginning with Nechwalsky in 1853[2] and were rare (even to E♭2) until late in the century. The range is therefore a very good indication of the type of instrument used.

Meyerbeer and Wagner began to use the straight form in their operas, as discussed below, and later art composers follow suit, even when the music appears to require lower notes. A very clear example is in *Nirwana*, by Hans von Bülow, Figure 3.1.[3] It is apparent from the scoring of bassoon, first clarinet and second oboe that the passage would preferably start on D2 in the bass and D3 in the second clarinet. These notes have been transposed up an octave. This indicates that written D2 was unavailable on the bass clarinet (in A) as well as on the

[1] The serpent form of Nicola Papalini, of Chiaravalle nr. Ancona, made from about 1820 – 1830 was not followed by any other maker and is not known to have influenced the music written by any composer.

[2] Anton Nechwalsky, Austrian Patent Application, Bass clarinet, filed 22 July 1853, and Addendum (stating that it can be made in A, B♭ or C) filed 3 October 1853. Dullat, *Klarinetten* reproduces this application but does not indicate whether the patent was granted. An instrument to the description in the patent is at US.W.si.65.0613.

[3] Hans von Bülow, *Nirwana*. Leipzig: Gustav Heinze, 1866.

soprano instrument, and implies that the straight form down to E2 was the composer's expectation in 1870.

1850 has been chosen as the approximate cut-off year for the use of the bassoon-form bass clarinet in Art music, since by that time the straight-form bass clarinet had become established in such ensembles. Whilst there is a little evidence of the use of the bassoon-form instrument in opera after that date (see the reminiscences of J.H. Maycock quoted below), there is no evidence that it was required by composers or needed for their music. The bassoon-form instrument itself, however, was still flourishing after 1850, with many successful makers in both the German States and the Austrian Empire (see Chapter 4) and was used in military, church, civic band and other outdoor music. This chapter therefore considers repertoire for band music up to the end of the nineteenth century.

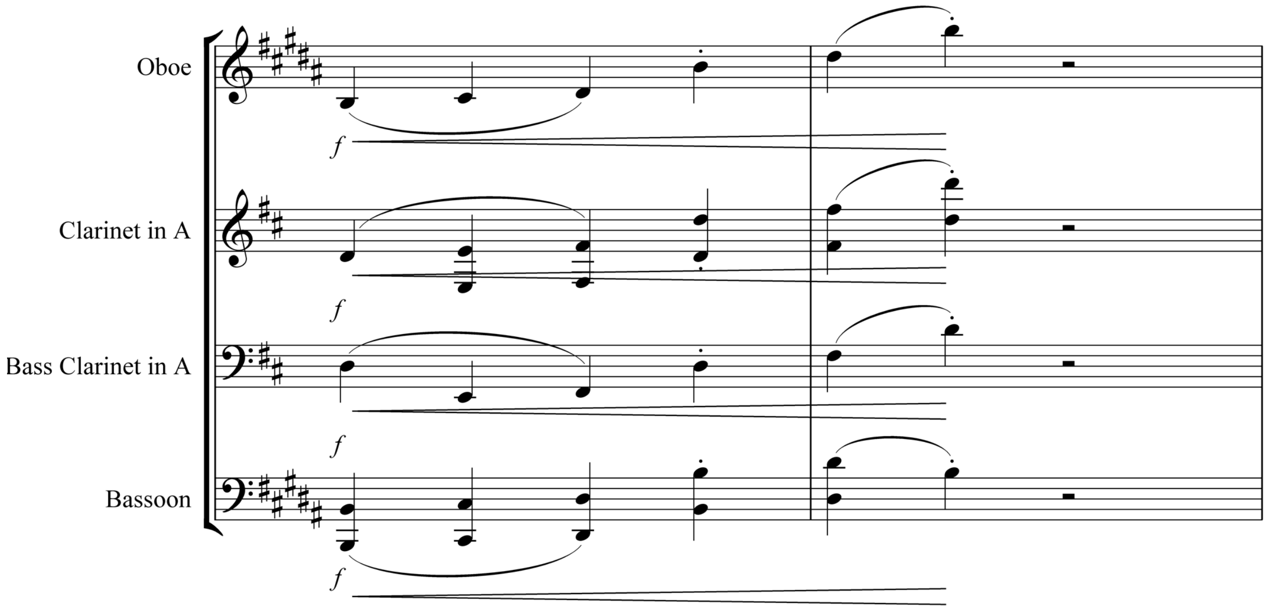



Figure 3.1. The passage from von Bülow, Nirwana, containing the lowest notes used in the bass clarinet part.

Bassoon-form bass clarinets were built in B♭ from 1793 and also in C from the second quarter of the century (see Chapter 4) but no examples pitched in A are known. The first music for the bass in A was Wagner's *Lohengrin*, in 1848, and a number of examples of straight forms in A are known. The choice of bass clarinet tonality in Art music, with very few exceptions, follows the practice of soprano clarinets as outlined by Berlioz:[4] composers follow the tonality so as not to put the clarinet into extreme keys, but since each has a slightly different tonal quality (paralleling that in soprano instruments but less strongly) that must be taken account of in the writing.[5]

[4] Berlioz, *Treatise on Instrumentation*, 114.
[5] Bowen, 'The Rise and Fall of the Bass Clarinet in A,' 2011.

Art music

Table 3.2 at the end of the chapter lists all the known Art music repertoire for the bass clarinet in chamber music and opera and other (predominantly court) orchestras up to 1850.[6,7]

The earliest performance known that involves a bass clarinet dates from 1794, when the Swedish court clarinettist, Johann Stranensky, gave a concert on 16 February 1794 playing works that were probably of his own composition. They were entitled *Romance* with a *Rondo à la Polonaise* for Clarinette Fagotte; the second, *Quintet with two flutes, two horns, and Clarinette-Fagotte*; and the third, *Terzette* from André Grétry's opera *Zémire et Azor* (1772) arranged for two horns and Clarinette Fagotte. These arrangements have not been found but the name, Clarinette-Fagotte makes it clear that a bassoon-form instrument was used and it is virtually certain that it was the then brand-new Heinrich Grenser instrument, which was sold to Duke Carl of Sweden and is still in Stockholm, S.S.m.M2653 (Figure 1.1). The evidence is in the form of a concert programme, the purchase receipt for the instrument and the instrument itself, which is preserved in Stockholm Music Museum (S.S.m.M2653).[8] Note that this instrument is definitely in B♭, as proven by the acoustic calculations in Chapter 8.

The likely candidate for the *Terzetto* by André Erneste Modeste Grétry[9] is the *Terzetto, Act II Scene I* between the three sisters Zemire, Falmé and Lisbé (Figure 3.2). There are other instances of three-part harmony in the opera but none that is a trio between three singers. The sisters are eagerly awaiting their father Sander's return from a voyage, and wondering what presents he will bring them, so the mood is frivolous. It would clearly fit well into a trio with two horns and a bass clarinet, though we learn little about the capabilities of the bass clarinet from this movement and it would not have demonstrated Stranensky's virtuosity. The instrument simply plays a walking bass throughout, largely in the lower register, while the melodic interest representing the vocal parts is in the horns. Presumably the Grenser instrument continued to be used at the Swedish court in the following years.

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[6] The table is based upon the list compiled by Rice, *From the Clarinet D'amour to the Contra* Bass, 2009, 379. with a few additions.

[7] 'Home - RISM,' accessed March 27, 2019, http://www.rism.info/home.html. About 100 searches were performed; 'C.I.R.C.B. - International Bass Clarinet Research Center,' http://www.circb.info/ accessed March 27, 2019.

[8] Rice, "The Earliest Bass Clarinet Music (1794) and the Bass Clarinets by Heinrich and August Grenser." June 2011; Rice, *From the Clarinet D'amour to the Contra Bass*, 2009; Patrik Vretblad, *Konsertlivet i Stockholm under 1700-Talet* (Stockholm: P.A. Norstedt & Söners, 1918).

[9] André Ernest Modeste Grétry, *Zémire et Azor*. Paris: J. Frey, 1772.
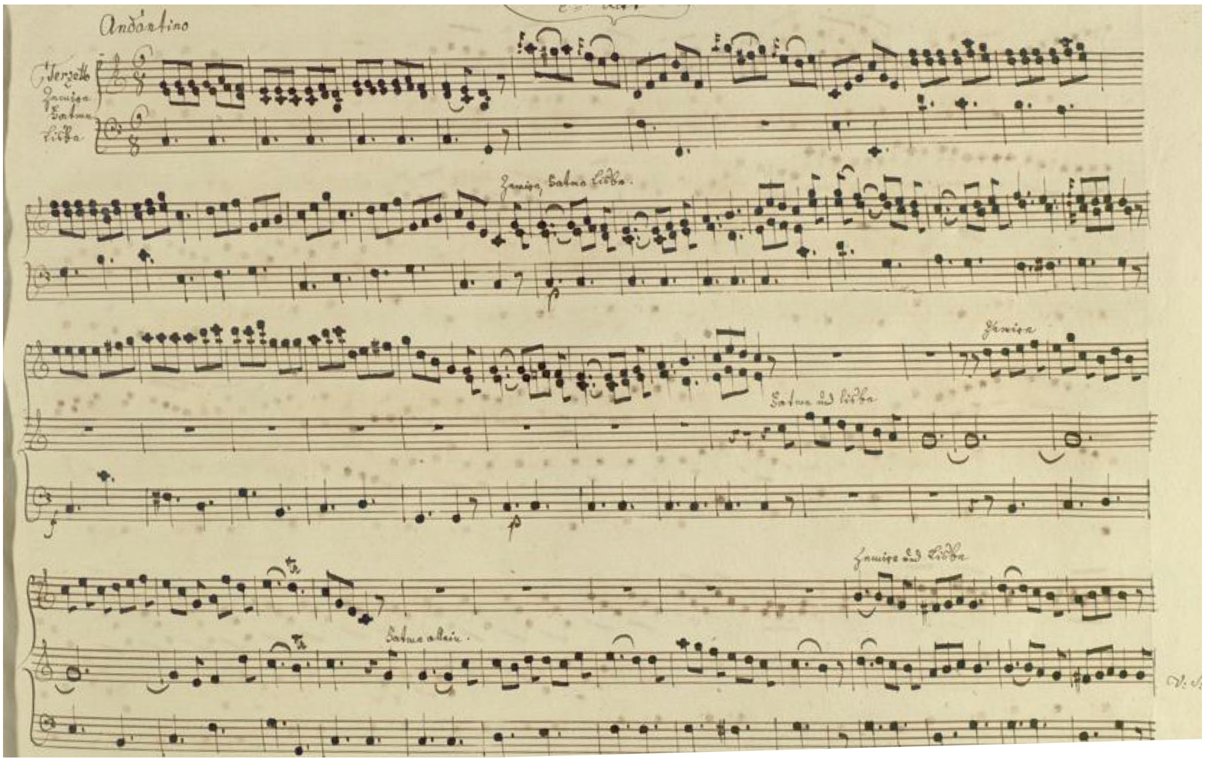
Figure 3.2. Manuscript reduced score of *Terzetto* from *Zémir et Azore* (Act II scene 1) by André Erneste Modeste Grétry, first page (out of three).

I also suggest that another instrument by one of the Grensers was available in Mannheim. The celebrated Mannheim orchestra was large and well-established, including clarinets, well before the end of the eighteenth century, according to Mozart's famous visit in 1777 ('Ah. If we had only clarionets too!').[10] A player named Ahl is listed as a clarinettist in the Mannheim orchestra in 1809[11] and a review of recent music in Mannheim in 1815 reports that

> Ahl the Younger proved himself to be the darling of the public on the clarinet and bass clarinet.[12]

Unfortunately neither the instrument nor the music played were noted, but it is fair to assume that he must have played bass clarinet as well as clarinet in recitals or small ensembles. It is unlikely that he would have gained such a public reputation from orchestral playing alone. The only plausible candidates for the instrument at that time were the Grensers' bassoon-form instruments, so it is probable that one of these was used; possibly even the one by Augustin Grenser now in nearby Darmstadt.[13] The Darmstadt instrument is reported to be in C,[14] but since acoustic analysis (Chapter 8) has shown that the Heinrich Grenser instrument is in B♭, the Darmstadt instrument should be re-examined.

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[10] Wolfgang Amadeus Mozart, 'The Letters of Wolfgang Amadeus Mozart. (1769-1791.), by Wolfgang Amadeus Mozart.' 1791-1769. Letter 119, Mannheim, Dec.3 1778.. https://www.gutenberg.org/files/5307/5307-h/5307-h.htm#link2H_4_0003. Accessed 21 October 2021.

[11] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 340, quoting Adam von Ahn Carse, *The Orchestra from Beethoven to Berlioz*. Cambridge: Heffer and Sons, 1948, 153. Ahl the Elder also played in the Mannheim Orchestra (on horn), but we do not know the relationship between the Ahls, nor their first names.

[12] Anon. 'Nachrichten, Mannheim . Uebersicht der Monate Januar , Febr. Marz.' *Allgemeine musikalische Zeitung* 16, (1815) 331.

[13] D.DS.hl.KG67:133

[14] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 260.

A revealing source for early bass clarinet usage is a manuscript in the library of the Moscow Conservatory, found by Larissa Kirillina, a professor at the Conservatory.[15] It is an arrangement of Beethoven's string quartet *Opus 18, Nos. 1 and 5* for clarinet quartet, and might be the earliest appearance of the clarinet quartet ensemble. It shows the use of bass and alto as well as soprano instruments. Before the beginning of the *Quartet Op. 18 N 1* is written 'Quartette Beedhoben [sic]. Instruments: Cl 1, 2, 3 in B; Cl-Basse'. Titles of movements: *Allegro von brio; Adagio e appasionato [sic]; Scherzo. Allegro molto; Allegro*. Before the beginning of the *Quartet Op. 18 N 5*: Quartetto N 5. Op. 16 [sic]. Instruments: Cl 1, 2 in B; Cl-Alt; Cl-Basse'. Since the original string quartet utilises the lowest note of the cello (sounding C2) it is plausible from this and the suggested date that a bassoon-form instrument with its range to this note would have been used. Unfortunately the manuscript of the arrangement cannot at present be examined due to closure of the Moscow Conservatory Library Department of Rarities since 2012 and consequent storage of the material.[16]

Kirillina suggests that it was handwritten before 1829, since that was the date of the first printed score, and this manuscript appears to have been made from a handwritten score or set of parts. The André score was indeed printed in 1829, but the first edition was actually printed by Artaria in 1796 and another (probably revised) by Mollo in 1801, so we cannot at present be certain of the date.[17] Interestingly, the earliest manuscript of the original string quartet was in Russia until the early 20th century, having been gifted by Beethoven to his friend Karl Amenda soon after its composition. On July 1, 1801 the composer wrote to Amenda stating that he had made drastic alterations to the quartet, presumably for the Mollo edition. The Amenda manuscript is now in the Beethovenhaus in Bonn, and has been published by Henle.[18] The method of stemmatic filiation using this source and the three published editions might enable the source(s) of the Moscow arrangement for clarinets to be deduced and dated more accurately.[19] It will certainly be worth enquiring whether this clarinet arrangement was made directly from the Amenda manuscript.

Kirillina comments that this arrangement could possibly have been made by an amateur, given the erroneous transcription of the author's name, the wrong opus number of the second quartet and some other inexactitudes. Such arrangements might have been popular, and this manuscript appears to be the only evidence available for the use of the bass clarinet in Russia

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[15] Larissa Kirillina, 'A New List of Beethoven Sources in Russia,' *The Beethoven Journal* 14 (1999) 16–26; Larissa Kirillina, 'Ludwig van Beethoven. Manuscripts and Early Printed Sources in the Libraries of Moscow and St-Petersburg (in Russian),' ISBN 987-5-89698-200-6, 2008; Ludwig van Beethoven, *String Quartet Opus 18 No.1 & 5, Arranged for Clarinet Quartet*, Early 19th century, Moscow Conservatory Library, RUS.Mk.B5755 (V.F.Odoevsky Collection).

[16] Professor Larissa Kirillina, emails of October 27 2012 and 17 July 2021. Professor Irina Brezhneva (Head Librarian at the Moscow Conservatory) email of 21 July 2021.

[17] Ludwig van Beethoven, *String Quartet Opus 18 No.1*. Offenbach: Jean André, 1829, Ludwig van Beethoven, *String Quartet Opus 18 No.1*. Vienna: Mollo, 1801; Ludwig van Beethoven, *String Quartet Opus 18 No.1*. Vienna: Mollo, 1801.

[18] Beethoven, Ludwig van, Joseph Schmidt-Görg, Paul Mies, Ernst Herttrich. *Werke: Streichquartette I. Abteilung VI, Band 3 Abteilung VI, Band 3*. Beethoven-Archivs Bonn. Munich: G. Henle, 1962.

[19] Flinders Petrie, 'Sequences in Prehistoric Remains,' *Journal of the Anthropological Institute of Great Britain and Ireland* 29 (1899) 295–301; Colin Renfrew and P Bahn, *Archaeology. Theories, Methods and Practice*. 5th edition. London: Thames and Hudson, 2008, 126-127.

at this time. This long predates the first published use of the bass clarinet by a Russian composer; the earliest appears to be Rimsky-Korsakov, *The Maid of Pskov*. This was composed and extensively revised between 1871 and 1906; from the different editions it can be said that the bass clarinet was introduced in this work between 1877 and 1892.[20] Tchaikovsky's Manfred Symphony was written in 1885, so this is the latest possible date for its Russian debut.[21]

The emergence of the clarinet quartet in the early decades of the nineteenth century, and of the quality of the bassoon-form bass instrument is reinforced by the next item on the list, the advance notice of a concert tour by Hebestreit of Göttingen which would show off the new Streitwolf instrument. Streitwolf's instruments show excellent workmanship and are certainly a very substantial advance musically on those of the Grensers, as discussed in detail in Chapters 7 and 8.

> Currently, Mr. Streitwolf presents us anew with a beautiful instrument, the bass clarinet. In shape it resembles the bassoons … This instrument is much more comfortable to use than the bassoon and has the same characteristics as the clarinet. Its tone range goes from the Contra-B through four octaves, probably a few tones higher. The tone itself is even fuller than the basset horn, it has something indescribably pleasant about it, and resembles the most beautiful trombone tone in depth. Although the bassoon will not be displaced from our orchestras by the bass clarinet, since both instruments have a peculiar tone color, the bass clarinette will still effectively assist the bassoons and win over them in those orchestras in which good bassoonists are lacking. In the church this instrument is more filling than the bassoon. An excellent clarinetist, Mr. Hebestreit, will soon embark on a musical journey and introduce the friends of musical art to this new instrument. Anyone who hears the bass clarinet will certainly thank Mr. Streitwolf for this new orchestral gift.[22]

A characteristic emphasised by Johann Streitwolf in his own sales literature was that

> … the new instrument excels as both a bass and solo instrument. … it therefore completes the clarinet quartet.[23]

This is confirmed by the glowing report by A. Wendt, a regular correspondent of the *Berliner Allgemeine Musikalische Zeiting*:[24]

> … and even surpasses the bassoon as a bass and solo instrument; it could almost serve as a double bassoon alongside the bassoon. Compared to the Bb clarinet and the bassethorn or the alto clarinet, it is precisely what the violoncello is compared to the violin and the viola, and it now makes the clarinet quartet complete.[25]

Wendt also makes clear that the new Streitwolf instrument was pitched in C, though B♭ instruments followed from Streitwolf soon after. We thus have evidence of the early use of

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[20] Gerald Abraham, 'Pskovityanka: The Original Version of Rimsky-Korsakov's First Opera,' *The Musical Quarterly* 54, no. 1 (1968) 58–73; Rimsky-Korsakov, Nikolai, The Maid of Pskov (1872 - 1892). Final edition, St. Petersburg: Bessel n.d. c.1897.

[21] Pyotr Ilyich Tchaikovsky, *Manfred Symphony.* Moscow: P. Jurgenson, 1885).

[22] Johann Gottfried Heinroth, 'Neue Erfindungen,' *Eutonia, eine hauptsächlich pädagogische Musik-Zeitschrift* 1 (1829) 203–4.

[23] Johann Heinrich Gottlieb Streitwolf, *Beschreibung Der von Mir Neu Erfundenen Bass-Clarinette*, 1828.

[24] There is no definite identification of A. Wendt, but it is quite likely that it is (Johann) Amadeus Wendt (1783 – 1836), professor of philosophy at Leipzig and (from 1829) Göttingen, who wrote extensively on music in scholarly journals and in contemporary musical journals, including from cities where he resided. He was responsible for coining the term 'Classical Period' to describe Haydn, Mozart and Beethoven.

[25] A. Wendt, 'Anzeiger Über Die Neu Erfundene Bass-Klarinette Und Kontrabass-Klarinette,' *Berliner Allgemeine Musikalische Zeitung* 7, no. 21 (1830) 167.

the bassoon-form bass clarinet in the formation of the clarinet quartet – at least as a consort of instruments if not as a recognised chamber ensemble - in both Germany and Russia.

Soon after, Wilhelm Deichert and J.C.Bänder, who were members of the court orchestra at Kassel, gave a concert in that city:

> The reviewer could no longer stay at the concert, so he did not have the pleasure of hearing … the following pieces. These were 6) an *Adagio mit variationen* for the newly invented bass clarinet, played by Mr. Deichert, and 7) *Volkslied für Bass- und Contrabass-Klarinette,* a folk song for bass and double bass clarinet!!, which he did not sing but played with Mr. Bänder. The effect is said to have been very positive. …[26]

This was most likely on Streitwolf bass and contrabass clarinets, since these were the only models that had recently been invented.[27] The review tells us little but the date. Deichert was himself a composer, as was J.C. Bänder's son Heinrich, so these works may be by either of them, but the scores have not survived.[28]

Thomas Lindsay Willman gave the first performances of Neukomm's setting of verses from Psalm 70 for 'a counter-tenor-Lady's voice, with the 'bass clarone' in London in 1836. The instrument was plausibly that made by George Wood,[29] though it could also possibly have been a Streitwolf, whose bassoon-form bass clarinet was available in London at this time. His performances and the tonal properties of the instrument were praised in contemporary reviews. Willman accompanied Miss K. Robson in a concert at the Hanover Square rooms reported on 15 April 1836, and Mrs. Arthur Shaw in a concert at Willis's rooms reported on 21 May 1836. They also appeared at the Manchester Musical Festival, as reported on 16 September 1836.[30]

The part ranges from C2 to D5, and is marked in the score for bass clarinet in C; thus it is the same tonality as the early Streitwolfs, the Catterini instrument and the scale and fingering chart by George Wood. In common with the early operatic *obbligati* discussed below, the long introductory concertante part uses a large part of the bassoon-form instrument's range, including the low C2. Although no specimen of Wood's bass clarinet is known, his published fingering chart for the instrument shows it to have been a bassoon-shaped model pitched in C with a claimed chromatic range of four octaves and (at least) a whole tone (B♭1 to C5+). A

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[26] 'Chronik der Opern des Hoftheaters und der Concerte zu Cassel 1830.' *Allgemeine musikalische Zeitung* 1, no. 12 (March 24, 1830) 188–92.

[27] Rendall, *The Clarinet: Some Notes on Its History and Construction*, 149.

[28] Aber, 'A History of the Bass Clarinet as an Orchestral and Solo Instrument,' 74.

[29] George Wood, "A Scale of the Bass Clarinet Invented and Mfred by George Wood" (1833), GB.L.BL.e.108.[19], British Library.

[30] Anon. 'Bass Clarone,' *Musical World* 1, no. 3 (April 1836) 47; Anon. 'Mrs A. Shaw's Concert,' *Musical World* 1, no. 11 (May 21, 1836) 174–75; Anon. 'Manchester Music Festival,' *Musical World* 3, no. 27 (September 16, 1836); F. Geoffrey Rendall, *The Clarinet: Some Notes on Its History and Construction* (London: Williams and Norgate. Third edition revised by Philip Bate (1971). London: Ernest Benn, 1954) 144. Rendall gives the first performance as that by Mrs Shaw, and refers to the instrument part as 'bass clarionet concertant' but does not cite a reference for this name. The Musical World reviews and the score itself refer to it as a 'bass clarone'; Pamela Weston, *More Clarinet Virtuosi of the Past* (London: Author, 1977); Pamela Weston, 'Yesterday's Clarinettists: A Sequel' (York: Emerson, 2002).

short musical example (Figure 3.3) shows the virtuosity expected of the player, even on this early example of the bass clarinet.[31] It is remarkable that within the decade 1834 - 1844 this work, the bass clarinet *obbligati* in Mercadante, *Emma d'Antiochia,* that in Meyerbeer, *Les Huguenots* and probably also Balfe, *The Daughter of St. Mark* all appeared, requiring a degree of virtuosity on the instrument not demanded again until the following century. These works are discussed below. The Neukomm text is based on verses 1, 2, 4 and 5 of Psalm 70, whose theme is the psalmist rejoicing in the greatness of God. As with religious choral music generally, in which the singer representing God is usually a bass voice, Neukomm could have felt that the new bass voice in the woodwind, playing a spectacular *obbligato*, would be both musically novel and religiously appropriate. The accompaniment is a string quartet with double bass, forming, together with the female voice, a powerful and attractive ensemble.
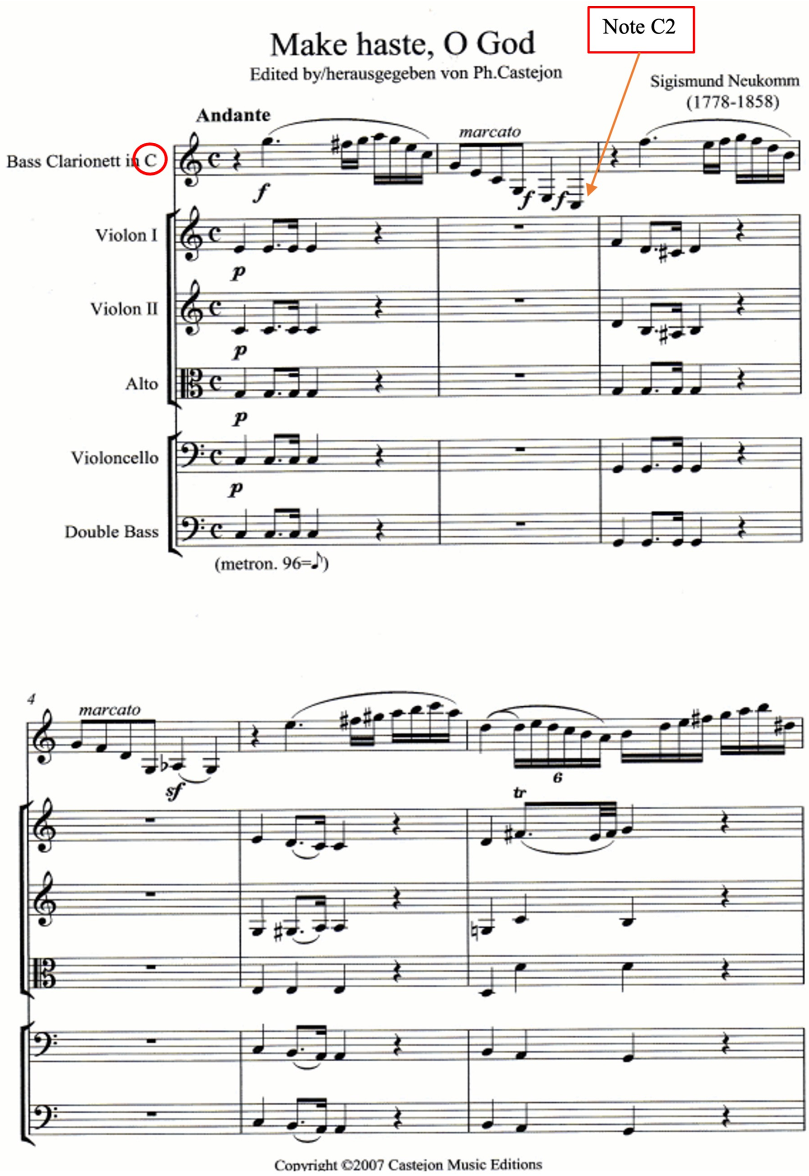
Figure 3.3 Excerpt from Neukomm, 'Make Haste, O God' for contralto voice, solo clarinet and string quintet. Reproduced with the kind permission of Philippe Castejon.

[31] Ph. Castejon, *Neukomm: Make Haste, O God. for Alto Voice, Solo Bass Clarinet and String Quintet.* Köln: Castejon Music editions, 2007.

Composed between 1840 and 1860,[32,33] we find the *Romanza* by Johann Friedrich Diethe, for solo bass clarinet and pairs of oboes, clarinets, bassoons and horns, in manuscript, and an alternate version for bass clarinet and piano co-published in 1898.[34] Diethe (1811-1891) was thought by Aber to have a military band connection, but is now known to have been an oboist in the Leipzig Gewandhaus Orchestra from 1836-1866, as can be found from his caricature and its legend by the artist Christian Reimers.[35] Nothing else appears to be known about him; he does not appear in Grove Online or MGG or any online searches apart from the book of caricatures. In the version for which there is a (copy) manuscript, the accompaniment is the classical Harmoniemusik octet and presumably it was the first to be composed. The solo bass clarinet part is not unlike that of the Neukomm discussed above, with first an ostentatious recitative, involving dramatic arpeggios and runs up and down the instrument (e.g. Figure 3.4), followed by a slow lyrical melody.
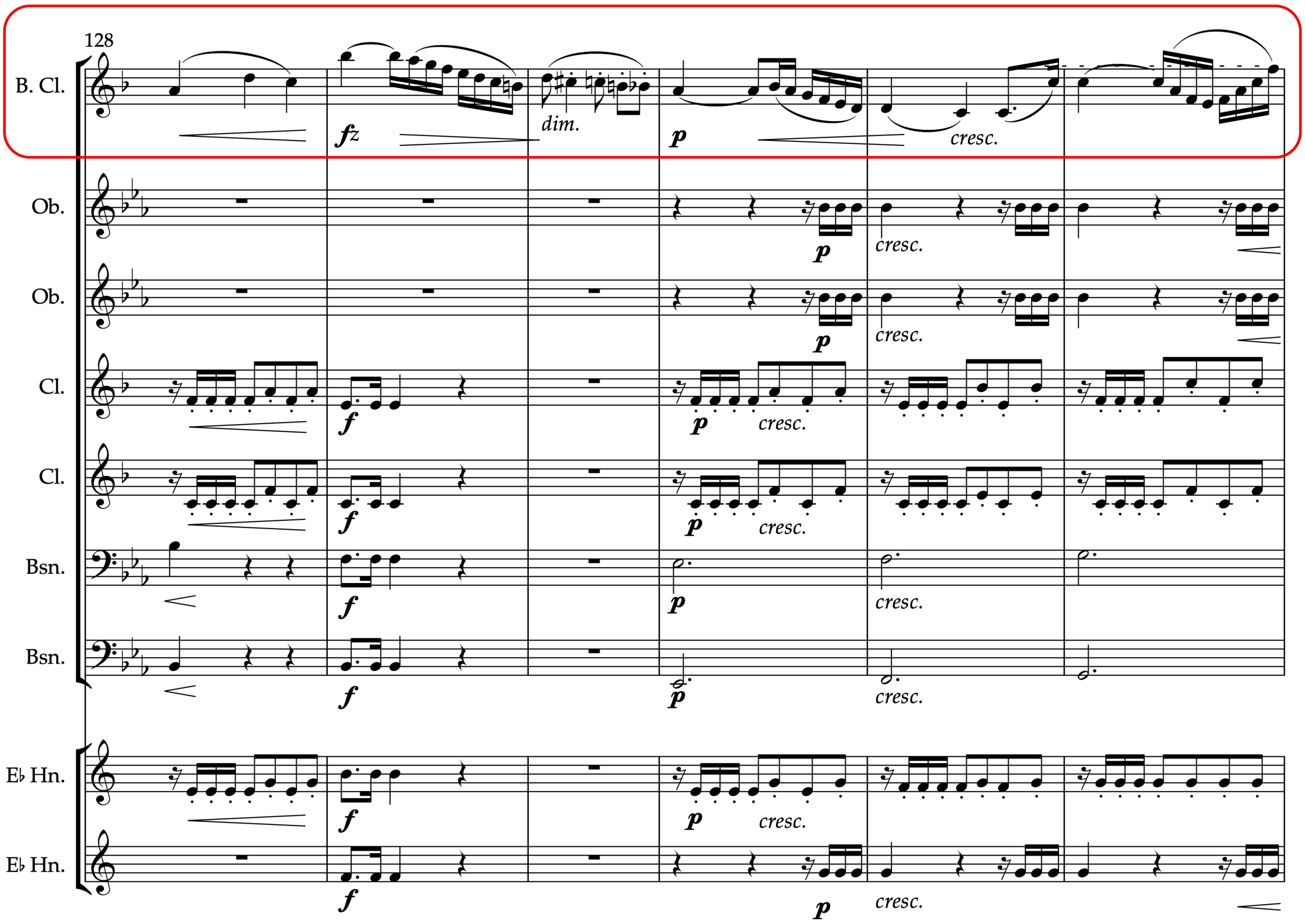
Figure 3.4. Bars 128 – 133 of Diethe's Romanza, showing the lyrical bass clarinet writing and the strong rhythmic accompaniment. After I-Baf.Fondo antico FA1 – 3531 with permission. See Appendix D.

Towards the end, the highest note used is D♭5, again for dramatic effect. The accompaniment is subsidiary, with broken chords in various rhythms which set the harmonic and dynamic

32 Aber, 'A History of the Bass Clarinet as an Orchestral and Solo Instrument' 83.
33 Friedrich Diethe, *Romanza per Clarinetto Basso Si♭*, Bologna, Accademia Filarmonica, Archivio Biblioteca. Music manuscripts, 1860-1840. I-Baf.Fondo antico FA1 – 3531.
34 Johann Friedrich Diethe, *Romanze Für Bass-Klarinette in B* (Leipzig: Carl Merseburger, 1898),
35 Christian Reimers: *Das Leipziger Gewandhausorchester im Lichte der Satire*, 19 Karikaturen, lithography. Leipzig: von Blau & Co. *c*.1850. Meininger Museum D.MEI.sm.Max-Reger-Archiv.

context, but also with well-written solos for the principal wind instruments which utilise their characteristic tone colours (e.g. Figure 3.5). The range used, from E2 to D♭5, make it likely that it was written with a straight instrument in mind.
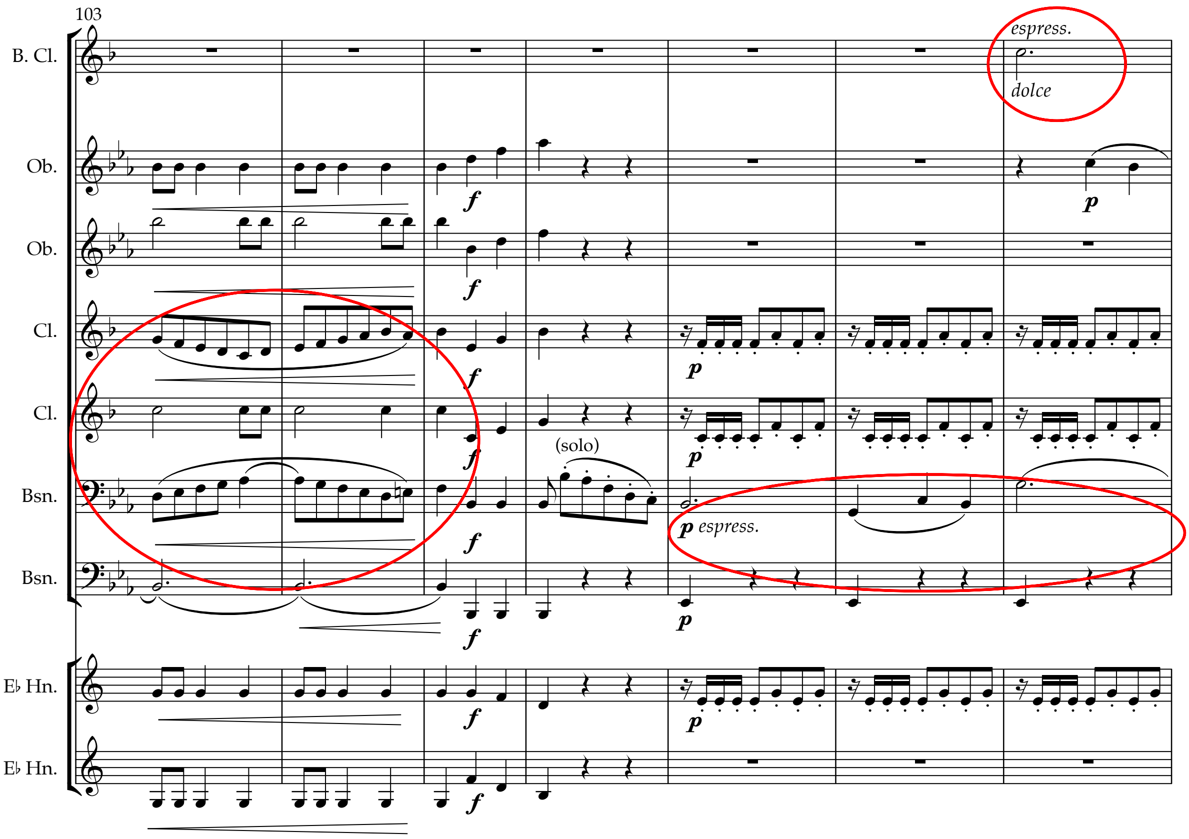
Figure 3.5. Bars 103 – 109 of Diethe's Romanze, showing the contrapuntal melodic figure in the first clarinet and first bassoon, followed by the melodic subject in the bassoon. See Appendix D.

In the second version, for bass clarinet and piano (included only in the Merseberger publication), the accompaniment has been rewritten for piano. The part is not merely a transliteration of the wind ensemble, but is now well-adapted to a pianistic style, while preserving the harmonic and rhythmic structure. Its absence from the copy manuscript may imply that it was undertaken much later, on behalf of Merseberger, by an unknown arranger.

The musical examples of the Diethe chamber music piece are taken from a new edition of the score that I have compiled from the Merseberger parts, using the copy manuscript and the piano version to correct some misplaced bars and notes in the parts. The edition is given in full with critical notes in Appendix D.

The earliest orchestral use of the bass in opera houses appears to be that in Italy by Mercadante in *Emma d'Antiochia* on 8 March 1834, in Venice at the Teatro La Fenice. Reports in the contemporary press suggest that the clarinettist on this occasion was Catterino Catterini, who was most likely performing on an instrument of his design and manufacture.[36] Catterini's bass clarinet (which he named *glicibarifono*) was a bassoon-form instrument made like a dulcian with the body in one piece, such as the stamped specimen in Oxford.[37] The

[36] Anon. 'Nuovo Strumento Di Fiato, Di Catterino Catterini Di Monselice.'
[37] GB.O.ub.496

instrument, called a Contro Clarinetto in this score, is introduced in an orchestral context in one scene and the finale of Act I, is given a major *obbligato* solo at the opening of Act II and plays in two choruses in Act III. The *obbligato* uses the full range of the instrument from C2 to G6 and is technically quite demanding, with rapid scalar and broken chord passages, large leaps and declamatory sections, against a background of either quiet harmonic chords, or of silence (Figure 3.6).
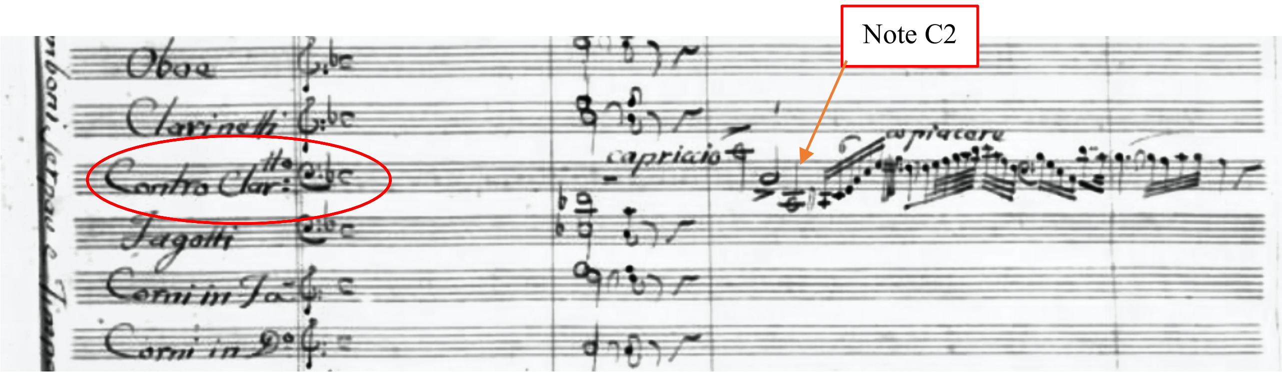
Figure 3.6. The opening of Act II of Saverio Mercadante's *Emma d'Antiochia* showing the start of the 'Contro Clarinetto' obbligato. Library of Conservatorio di Musica S Pietro a Majella, Biblioteca, Naples (I-Nc). From the 1835 performance at Teatro San Carlo, Naples. Image enhanced by Huw Bowen.

What drove Mercadante to use this novel instrument? Clearly he must have been reasonably familiar with the inventor, but he was also aiming for drama, range and novelty to accompany the range of wild emotions and passion that are contained in the libretto. The story is of a love triangle that ends in despair and suicide for the eponymous Emma. An interesting analysis is given by Jeremy Commons in a booklet accompanying a CD in 2003:

> One of the features which gave the premiere a touch of extra interest and colour was the inclusion in the orchestra of a new instrument, a 'glicibarifono' … played by its inventor, a clarinet-maker by the name of Catterino Catterini. The name of the instrument, derived from Greek, means 'sweet and weighty of sound', and would seem a highly accurate description since it was a type of bass clarinet, combining the notes and tones of a clarinet and a bassoon. … In Act II Mercadante wrote him an extended solo, on this recording played by the glicibarifono's modern equivalent, a bass clarinet. It occurs early in the act, after the chorus, having sung their valedictory chorus to the now-wed Ruggiero and Adelia, leave the stage empty and in darkness – ready for the encounter between Emma and Ruggiero, their decision to elope together and their apprehension by Corrado. It is a moment of transition, therefore – a moment which depicts the sudden solitude and deceptive calm of a Mediterranean night, setting a sombre tone for the dramatic and darkly passionate events to follow. Strangely it is not used as we might expect – as a prelude which then provides phrases to punctuate and bind together the following recitative – but stands as a selfcontained and independent item, 40 bars in length. And since the stage at this point is in darkness, there was nothing, at the premiere of the opera, to distract the attention of the audience from Catterini's performance.[38]

Clearly, Mercadante felt that it was the right instrument to express the emotions leading up to this critical scene, and to set a sombre tone for the encounter to follow. Mercadante's opera was reasonably successful in Italy and occasionally abroad, being frequently performed in

[38] Jeremy Commons, Liner Note to Saverio Mercadante, *Emma d'Antiocha*. London Philharmonic Orchestra, David Parry (Opera Rara) CD ORC26. London: Opera Rara & Peter Moore's Foundation, 2003..

several cities in Italy and in Lisbon and Barcelona in the 1840s, then less often, with the last nineteenth-century performance in Malta in 1861.[39]

From other press reports, it is known that Catterini toured Italy for many years performing on this instrument. The repertoire for these concerts is not known, but appears to have contained themes and variations of his own composition. Reports are found, for example, from Parma in 1837:

> On June 14th, Mr. Catterino Catterini gave a musical academy here, where it was heard with applause on his so-called Glycibariphon … the academy was honoured with the presence of I.M. the duchess.[40]

It did not always meet with complete approval, for example the 1847 recital in Vienna

> Mr Catterino Catterini was heard the day before yesterday in the k. k. Hofoperntheater[41] on the glicibarifono he had invented. This instrument is made of sheet metal, shaped like a snake and funnel, has 4 octaves in range and its tone character is most similar to that of the bassoon. It is not very suitable as a concert instrument, but in our opinion it does not offer any particular enrichment for the orchestra. Mr. Catterini had a fair amount of virtuosity and received applause. But the elegy of his composition which he performed was of no importance.[42]

Soon after, in 1844, Giacomo Meyerbeer introduced the bass clarinet in Paris in an important solo in *Les Huguenots*; the opera became extremely popular and was performed many times. The range of this *obbligato* only extends from E2, so it is playable on a standard straight-form instrument such as made by Buffet (as used by Dacosta in the first performance run) and later by Sax. He subsequently used the bass clarinet in several operas: *Ein Feldlager in Schlesien* (Berlin, 1844), *Le Prophète* (Paris, 1849), *Dinorah* (Paris, 1859) and his last opera, *L'Africaine* (Paris, 1865).[43] He used it as a solo instrument in both *obbligati* and short interjections, and in orchestral harmony.

In Italy again, Donizetti used the bass clarinet (including lyrical solo passages) in 1838 in *Maria de Rudenz*, Mercadante again in *La solitaria delle Asturie*, (1840) and Verdi in *Ernani* (1844). In addition to Catterini, who appears not to have been available as a regular player after 1834, it is known that Pietro Fornari was listed as a bass clarinet member of the Teatro la Fenice for ten years from 1837 to 1846. Fornari also played on a bassoon-form instrument supposedly of his own invention, probably an ophicleide type.[44]

In the 1844 performance of *Ernani*, again at Teatro La Fenice in Venice, where Verdi used the bass clarinet for the first time in his operas, he used it for the solo that introduces the Scena Carlo at the beginning of the third act. This must have been a bassoon or ophicleide form,

[39] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 342.

[40] Anon. 'Nachrichten: Parma,' *Allgemeine Musikalische Zeitung* 41 (October 1, 1837) 668.

[41] k.k. means Kaiserlich-königlich, i.e. this is the Imperial and Royal court theatre, built 1708, rebuilt 1861-69, now the Vienna State Opera, rebuilt 1947-55.

[42] Anon. 'Recital review: Catterino Catterini,' *Allgemeine Wiener Musik-Zeitung* 7, no. 133 (November 6, 1847) 536.

[43] Meyerbeer, Giacomo. Les Huguenots. Paris: Maurice Schlesinger, (1836). Paris: Brandus; c1865; ———. Ein Feldlager in Schlesien (1844). Manuscript copy (1850). Brussel, Conservatoire royal de Bruxelles, Bibliothèque B-Bc.13830; ———. Le Prophète (1849), Paris: Brandus, 1851; ———. Dinorah (1859) or Le Pardon de Ploërmel. Paris: Brandus & Dufour, 1859. (First edition of the full orchestral score with spoken dialogue); ———. L'Africaine, Paris: Brandus, 1865.

[44] Della Seta, '' From The Glicibarifono To The Bass Clarinet',

since it requires a range to C2, and it was probably played by Fornari on his own instrument.[45] The original Verdi score is written for a bass clarinet in C, in the key of E♭. Using an instrument in B♭, playing in the key of F would present no difficulty. The most likely reason for the choice of tonality is that Fornari's instrument would probably have been in C, similar to that of Catterini, for which the theatre would have parts for other operas. This is probably the last operatic work for which the bassoon-form instrument was conceived and required and also the last work in the nineteenth century to call for a written C2 in the part. The critical edition commentary shows that this solo was originally conceived for the trumpet; it is probable that Verdi changed this to bass clarinet when he became aware of the unique opportunity offered by Teatro La Fenice.[46]

One wonders who played the bass clarinet parts outside Venice. It is clear from membership lists of orchestral players, and the efforts, sometimes unsuccessful, to obtain bass clarinets in Rome, La Scala Milan, Florence, Parma etc. that La Fenice was the *only* opera house in Italy with a resident bass clarinettist, and that for a limited period of time.[47] Rather than concentrate on Mercadante, it is more fruitful to follow the performances and reception studies of Meyerbeer's *Les Huguenots* (and some of his other operas) for a number of reasons: this was an acclaimed example of the novel 'grand opera' style, derived from Paris with far greater focus on the scene and production values, and with a greatly enlarged orchestra including novel instruments, such as, in Meyerbeer's case, the bass clarinet.[48] On the other hand, Mercadante represented an older style of opera that was becoming unfashionable. *Huguenots* and Meyerbeer's other operas therefore attracted many more performances, in more venues, drew more reviews and critical attention, and required more preliminary correspondence in preparation for the opening. Much of this has been preserved, and is documented in a major study of European opera orchestras in the eighteenth and nineteenth centuries; conducted by the European Science Foundation; it covers the most important opera houses in Italy, France, Germany, Bohemia, England, Sweden, Denmark, Austria, Moravia, Silesia, Spain, Portugal and Russia.[49,50] The study found that the issues around the bass clarinet are often commented upon in the contemporary documents. Various solutions to Meyerbeer's orchestration were found. Sometimes the solos were played on the soprano clarinet, sometimes on the bassoon, both of which appear as suggestions in Meyerbeer's autographs

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[45] Giuseppe Verdi, *Ernani* (1844), full score critical edition, ed. Claudio Gallico, Chicago & Milan: University of Chicago Press & G. Ricordi, 1985.

[46] Della Seta, 344.

[47] Anna Tedesco, "Queste Opere Eminentemente Sinfoniche e Spettacolose': Giacomo Meyerbeer's Influence on Italian Opera Orchestra.' In Niels Martin Jensen and Franco Piperno (Eds). *The Opera Orchestra in the 18th- and 19th- Century Europe, II: The Orchestra in the Theatre - Composers, Works, and Performances.* Berlin: Berliner Wissenschafts-Verlag, 2008, 205.

[48] Tedesco, "Queste Opere Eminentemente Sinfoniche e Spettacolose'.

[49] Jensen, Niels Martin, and Franco Piperno (Eds.). *The Opera Orchestra in 18th and 19th Century Europe. I: The Orchestra in Society, Volume 1 & 2.* Berlin: Berliner Wissenschafts-Verlag; Der Verlag Für Anspruchsvolle Wissenschaftliche Fachliteratur. Berliner Wissenschafts-Verlag. 2008.

[50] ———. *The Opera Orchestra in 18th and 19th Century Europe. II: The Orchestra in the Theatre - Composers, Works and Performance,* Berlin: Berliner Wissenschafts-Verlag; Der Verlag Für Anspruchsvolle Wissenschaftliche Fachliteratur. 2008.

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and printed scores. Sometimes an external player was brought in for the occasion. The most likely source was a local military band, which may have had a relationship with the local opera anyway; it was customary to use such bands for on stage 'banda' in works that included them, perhaps as a special guest appearance from a local regiment.[51,52] And sometimes a 'problem' instrument was simply omitted, as remarked, for example, by the critic Ambros in Prague, who complained about the lack of harps in a performance of *Huguenots*.[53] The practice of omitting or casually substituting instruments was fairly standard and documented for much of the century. Just because an instrument is in the score does not mean that it was there for every performance. Sometimes the reviewer tried to give the readers some sense of the original orchestration by describing the missing instruments.[54] The critic Ambros also made a comment jokingly purporting to be by Meyerbeer on the performance of *Huguenots* in Prague:

> Formerly, in the fifth act for the blessing of Marcel there was also a decent bass clarinet, instead of the lukewarm basset horn, which is now asthmatic tooting, and for the fourth act a cor anglais etc. Isn't my work worth doing as I wrote it?[55]

The use of a local bandsman to play the bass clarinet part makes it likely that he would have brought along his regular bassoon-form instrument, which was relatively common in military and civic bands, as discussed later in this chapter. It is likely therefore, that the bassoon-form bass clarinet was often used in the performance of grand opera in the middle to late nineteenth century, due to the lack of permanent bass clarinet players in the regular theatre orchestras (provided the local band played at the same pitch as the opera).

This is confirmed for two of the most famous nineteenth-century clarinettists in the UK, John Henry Maycock (1817 – 1907) and Henry Lazarus (1815 – 1895), in a detailed interview reported in *The Musical Herald* towards the end of Maycock's long life. Maycock was himself trained in the band of the Coldstream Guards. Two excerpts are informative. The first is a conversation that must have taken place in about 1843 or 1844 during a time when he was playing in Paris.

> 'I will tell you how it was that I took up the bass clarinet. The theatre was closed, and I was walking on the boulevards in Paris. I met Balfe, and he embraced me in his warm manner. He was writing *The Daughter of St. Mark* at the time. He said, 'If you will get a bass clarinet I will write a solo for you.' I went to Sax, the maker in Paris. He was a great broad-chested man, and played the instrument in a way that impressed me. I thought I should play like that at once. I bought the instrument. A friend said, 'You will never be able to play that big instrument; it will kill you in almost no time. I will take you to some one who has made an instrument that you will be able to manage nicely' I went to Sax next day, but he refused to accept a countermand. I paid a forfeit, and he let me off. I recelved the other instrument, and managed to play fairly well on it by the time when Balfe ought to have been ready for me. On the day before the opera was to be produced, I had not received my bass solo. On the day of the performance, the overture arrived with a tremendous solo in it for the bass clarinet.

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[51] Tedesco, 'Queste Opere Eminentemente Sinfoniche e Spettacolose'.

[52] Marta Ottlová and Milan Pospišil, 'Meyebeer's Operas in Nineteenth Century Prague and Their Impact on Prague Opera Orchestras.' in *The Opera Orchestra in the 18th- and 19th- Century Europe, II,* 262.

[53] August Wilhelm Ambros, 'Giacomo Meyerbeer in Sachen Seiner Huguenotten and Den Davidsbündler Flamin in Prag.' *Bohemia* 42, no. 163 (15 July 1869).

[54] V. [Franz Ulm], 'Giacomo Meyerbeer in Sachen Seiner Huguenotten and Den Davidsbündler Flamin in Prag.' *Bohemia* 23, no. 193 (8 December 1850).

[55] Ambros, 'Giacomo Meyerbeer in Sachen Seiner Huguenotten and Den Davidsbündler Flamin in Prag.'

> … [after refusing to play it on the first night, Maycock played it successfully on subsequent nights.]
>
> It was certainly a difficult solo ; it occurred in solo form in the overture, and also introduced a tenor air in the opera. The instrument was a new invention. The compass extended from F in alt to double B♭ below the staff, and I have played four octaves. Even now, if you listen to me on this old disused instrument, I will play three octaves and a fifth. If I play the C on the third space of the treble staff, it sounds the C below the staff. I introduced the Instrument in England fifty years ago, and I do not think it had been used here before. It was Balfe's idea to introduce both the instruments I have named [the other was the basset horn].[56]

The difficulty with this account is that it is not backed up by Balfe's scores in the British Library. Rice has examined the autograph score and BL staff have checked other manuscripts of Balfe, without finding any score entry or part labelled for bass clarinet.[57,58] The other libraries that have collections of Balfe's music, from the Carl Rosa collection, are Liverpool and Manchester Central Libraries who also found no references to bass clarinet parts in this opera.[59] The study of the overtures is complicated by the fact that their scores became disassociated with the scores for the operas themselves, and were published later when they may have been revised.[60] The BL notes on the holding of the overtures state that there are substantial differences between the full score of the *Daughter of St. Mark* overture and the vocal score originally published. Examination of the manuscript overture[61] full score did not reveal any significant clarinet or bass clarinet introduction to a tenor aria, though some parts of the score were very difficult to read. However, there is a spectacular solo matching Maycock's description marked for the clarinet towards the end of the overture, and this was probably left by Balfe in this form due to the difficulty of ensuring that a bass clarinet was available. It is largely unaccompanied and could easily be played effectively on a bass clarinet.

Balfe was the most successful composer of opera in the UK, occasionally writing in the Grand Opera style but mostly in the English Ballad Style.[62] Two conclusions arising from this quotation are striking. First, that the Sax bass clarinet required great effort to play it, most likely in the air supply needed; this is unsurprising from the fact noted in Chapter 2 that the instrument had an exceptionally large bore, >28 mm (and that Sax had an exceptionally broad chest!). It would have been superb in military bands or in Berlioz' large compositions such as *Symphonie Funèbre et Triomphale*, but Maycock clearly felt it was inappropriate for lighter works. Second, that Maycock's bass clarinet was clearly a bassoon form. B♭1 was a common

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56 Anon. 'Mr. J.H. Maycock,' *The Musical Herald*, December 1, 1900, 355–57.
57 Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 368. Autograph manuscript, 1844. GB-Lbl.
58 Michael William Balfe, 'The Daughter of St. Mark' Autograph manuscript, 1844. GB-Lbl. Add MS 29341; Add MS 29342; Add MS 29343.; Michael William Balfe, 'Overtures' (Autograph manuscripts of opera overtures, 1868), GB-Lbl.Eg. MS 2740 f.258.
59 My thanks to specialist librarian Richard Horrocks of Liverpool Central Library for searching in their Balfe collection during the Covid isolation period.
60 William Tyldesley, *Michael William Balfe: His Life and His English Operas* (Routledge, 2017), 24.
61 My thanks to BL Reference Specialist, (Rare Books and Music) Fiona McHenry for searching Egerton MS 2740 f.258 on my behalf during the Covid lockdown, and to the BL Document Service for a digital copy.
62 Nigel Burton and Ian D. Halligan, 'Balfe, Michael William,' Grove Music Online, 2001; Accessed 9 Nov. 2021. https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000001865

enough low note on such instruments,[63] but did not exist on any known straight-form instrument in the nineteenth century (and possibly not since then either, other than custom modifications: C2 is the usual lowest note on 'extended' bass clarinets). Hence, the Balfe parts that he played then, and also subsequently, must have been on the bassoon-form bass, which was possibly in C from the description. This would also apply to the Trio from *Huguenots* that he is recorded as playing in Dublin 1849.[64] The article also mentions that Maycock influenced Arthur Sullivan to include a bass clarinet in *Light of the World*, including the bottom note of B♭1.[65] Whilst Maycock does not mention the make of his bass clarinet, there were two other quality makers of bass clarinets in Paris, Martin Frères,[66] active from 1840, and Widemann,[67] active 1836-1850, who both produced ophicleide-shaped instruments. The Martin Frères instrument is shown in Figure 3.7,[68] and the instrument in the Horniman Museum in London is shown in Figure 3.8.[69] The latter is unstamped but assigned by Adam Carse by similarity to the Widemann instrument in Berlin.[70] Unfortunately, the London instrument cannot be the one owned by Maycock, since inspection showed that it only descended to E♭2.

The second significant remark concerns the use of this instrument in performances of Meyerbeer's Huguenots at Covent Garden London.[71]

> In speaking of the bass clarinet I might have added that Lazarus was in the habit of piaying one of Sax's big instruments, but it was impossible to produce a good effect on so exhausting an instrument. Previously, for the production of *Les Huguenots* at Covent Garden, I lent Lazarus my bass clarinet for a season or two, as it was the only one in this country, and I was not using it at the time, being at Her Majesty's Theatre. Then I went to Covent Garden myself, and resumed the use of my instrument there, at Costa's request, whenever *Les Huguenots*, *L'Africaine*, and other new operas required it; thus Lazarus had to get a Sax instrument, but our work did not clash, as he went to another theatre.[72]

Both Lazarus and Maycock thus played Meyerbeer's operas on Maycock's bassoon-form (possibly ophicleide-form) bass clarinet.

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[63] I am assuming that Maycock is referring to the written note rather than the sounding note, but if his instrument was indeed in C these are of course the same. The argument is unaltered if the lowest note was the written C2 sounding B♭1.
[64] Anon. 'Jullien in Dublin,' *The Musical World* 14, no. 2 (January 13, 1849).
[65] Arthur Sullivan. *The Light of the World* (1873). Revised edition, New York: Schirmer, n.d. [1905].
[66] Waterhouse, *The New Langwill Index: A Dictionary of Musical Wind Instrument Makers and Inventors*. 253
[67] Waterhouse, 427. Widemann's first name is unknown.
[68] F.P.cm.E.1154
[69] GB.L.hm.14.5.47/301b
[70] D.B.im.2902
[71] Maycock does not mention the date. The mention of Costa as the conductor means that this was after 1847, and possibly was the performance at the opening of the new building in 1858.
[72] Anon. 'Mr. J.H. Maycock.'

Figure 3.7 (left). A bass clarinet by Martin Frères of Paris. Paris, Cité de la Musique, F.P.cm.E.1154. Image from MIMO.

Figure 3.8 (right). An unstamped bass clarinet in the Horniman Museum, attributed to Widemann (Paris 1830-1855). GB.L.hm.14.5.47/301b. Object no: 14.5.47/301b © Horniman Museum and Gardens, reproduced with permission.

As seen in Table 3.2, Berlioz very quickly adopted the bass clarinet and used it in major works from 1838. His earlier training at the Conservatoire, which he entered in 1826, was still in the post-French-Revolution period when music, especially military music, was a civic duty. However, the year 1830 in which he won the Prix de Rome, which helped to launch his career, was also the year of the 'July Revolution' that restored the monarchy. His most notable massed work, the *Symphonie Funèbre and Triomphale* was written as a government commission to celebrate the tenth anniversary of this revolution.[73]

Berlioz was very impressed with the new Sax bass clarinet and appeared to use it exclusively. He makes important remarks on the instrument in his 1843 *Treatise on instrumentation*. After introducing the B♭ and the rarer C instruments he writes:

> The bass clarinet is evidently not destined to replace in the upper notes the high clarinets; but certainly to extend their compass below. Nevertheless, very beautiful effect result from doubling, in the octave below, the high notes of the B♭ clarinet, by a bass clarinet. … The best notes are the lowest ones; but owing to the slowness of the vibrations, they should not be made to follow one another too rapidly. … [a very favourable comment on Meyberbeer's use in *Huguenots* follows] … According to the manner of writing for it and the talent of the performer, this instrument may borrow the wild quality of tone which distinguishes the bass notes of the ordinary clarinet, or the calm, solemn and sacerdotal accent belonging to certain registers of the organ. It is therefore

[73] Hugh Macdonald, 'Berlioz, (Louis-)Hector,' *Grove Music Online*, Accessed 16 Nov. 2021. https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000051424 ; Hector Berlioz, *Symphonie Funèbre et Triomphale* (1844). Leipzig: Breitkopf und Härtel, n.d. [1900 – 1907].

> of frequent and fine application; and moreover, if four or five be employed in unison, it gives a rich and excellent sonority to the wind instruments of the orchestral bass.[74]

He then comments most favourably on Sax's improvements, including its 'perfect precision of intonation, an equalised temperament throughout the chromatic scale and a greater intensity of tone.' An anecdote from J.H. Maycock underlines Berlioz's acute ear for the sounds of the clarinets.

> 'Berlioz,' he says, 'was giving some concerts at the time at Drury Lane on the stage. When we were rehearsing one of his symphonies, Lazarus and I used the B♭ clarinets, although our part was marked for the C instrument, which we did not like, preferring to transpose. It was an extremely noisy movement, but Berlioz stopped the orchestra, and said, ' Will you oblige me by playing this movement on the C clarinets?' We had not brought our C clarinets. but promised to do so at night. Thus we got merely the same sounds, but not such shrill tone.'[75]

It is interesting to compare Berlioz's remarks in his *Treatise* with his actual compositions; his usage of clarinets is listed in Rice.[76] His first work including bass clarinet, the opera *Benvenuto Cellini,* was composed between 1836 and 1838.[77] He must therefore have been in touch with Sax about his instrument at a very early stage, since it was only patented and generally released in 1838. It is used in just one movement, the sextuor, no. 14. In this work he does largely avoid making the bass clarinet (played by the first clarinet) move too quickly, and does use the sound of the bass clarinet an octave below the second clarinet, especially in moments of repose, such as a resolution of a chord containing a diminished fifth in the clarinets onto an octave. An effect that he uses quite extensively but not mentioned in the *Traite* is of having the bass clarinet, still playing in the low register, the solo or prominent element in a chorus of low instruments: bassoons, trombones, ophicleide and low horns; and once as solo in counterpoint with bass soloist and quiet strings.

Whilst he called for doubling pairs of bass clarinets several times (*Symphonie funèbre et triomphale, Chant Sacré, Te Deum*), he only once wrote for as many as four bass clarinets, which was in the 1844 edition of the *Symphonie* (one of several editions between 1842 and 1851), and then only in the *Oraison funèbre* movement. He also indicated in several scores that if the bass clarinets were not available the parts could be substituted with ordinary clarinets. It seems that the reality of finding enough bass clarinets and clarinettists overcame his musical preferences.

Wagner began his use of the bass clarinet when he composed *Tannhäuser* in 1845, which uses the B♭ bass in one number (*Elisabeth's Prayer*) and *Lohengrin* in 1848 in which both B♭ and A basses are used. He continued to use the bass extensively in both B♭ and A in the *Ring* cycle, in *Tristan und Isolde* and *Parsifal*, and was probably the single most important composer in

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[74] Berlioz, *Treatise on Instrumentation*, 114–15. He does not mention the instrument in A, which was probably not built until Wagner demanded it for *Lohengrin* (1848).
[75] Anon. 'Mr. J.H. Maycock.'
[76] Rice, *From the Clarinet D'amour to the Contra Bass*, 359. Hector Berlioz, *Chant Sacré* (1830 – 44). Leipzig: Breitkopf und Härtel, n.d. 1900–07; ———. *Symphonie Funèbre et Triomphale* (1844). ———. *Te Deum* (1848 – 1855). 1855 – Paris: Brandus, Dufour et Cie.
[77] Hector Berlioz. *Benvenuto Cellini* (1838). Paris: Choudens, n.d. [1886].

the establishment of the bass clarinet in the orchestra. [78] In no case in any of his operas did he use notes lower than E2, a good indication that the straight-form instrument was normally used, or that he chose not to use the bassoon-form instrument with its greater range. Note that Wagner's opera orchestras used German bass clarinets from makers such as Kruspe, Stengel, Heckel and Beck, which were much narrower bore than the Sax instruments, with correspondingly mellower sound.[79] The bass clarinet then became part of the standard opera orchestra and is then often found in the symphony orchestra. By this time, however, orchestral instruments appear to be almost exclusively the long-flared form derived from Adolphe Sax or the narrower, short-flared-bore instruments preferred by German makers.[80]

Richard Strauss claimed that Wagner always used the bass clarinet for indicating 'solemn resignation' as indeed he did in Act II of *Lohengrin* and in the solo in *Tristan* accompanying King Mark in Act II Scene 3.[81] Tibor Tallian even suggests that Wagner derived this usage from Meyerbeer's use of the bass clarinet in Huguenots, in Marcel's trio *Interrogatoire* (Act V).[82] Unfortunately there is no information to confirm or refute this suggestion. However, Wagner also used it in many other ways, especially in *The Ring* cycle: in dense, powerful moments with fast passage work, to add bass power and colour to the woodwind harmony, and in solos expressing elevation and hope. An example of the latter is the key moment in *Siegfried* Act III Scene III where Brunnhilde is woken by the hero, accompanied by a solo bass clarinet passage rising from E2 to D5, marked 'very tender'. I would rather say that the solemn aspects are indicated by Wagner in descending passages, and uplifting moments in ascending passages; a compositional trait widely used in orchestration.

Ferenc Liszt conducted the first performance of *Lohengrin* in Weimar in 1850, and was thus very familiar with the bass clarinet; this work calls for bass clarinets in both A and B♭. He was also responsible for obtaining the instruments, as he states in a letter to Richard Wagner:

> We have ordered a bass clarinet, which will be excellently played by Herr Wahlbrul.[83]

There is no explanation why he only ordered one instrument. However, his own first use of the instrument as a composer, in the tone poem *Mazeppa*, written 1851-54 was for neither of these but for the relatively rare bass clarinet in C. It seems that this was a deliberate choice,

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[78] Wagner, Richard. *Tannhäuser* (1845). Leipzig: C.F. Peters, n.d.[1920]; ———. *Lohengrin* (1848). Leipzig: Breitkopf & Härtel, 1906; ———. *Das Rheingold* (1854), Mainz: B. Schott's Söhne, n.d. [1873]; ———. *Die Walküre* (1870), Mainz: B. Schott's Söhne, n.d. [1874]; ———. *Siegfried* (1871), Mainz: B. Schott's Söhne, n.d. [1876]; ———. *Götterdämmerung* (1874), Mainz: B. Schott's Söhne, n.d. [1876]; ———. *Tristan und Isolde* (1859), Leipzig: Breitkopf und Härtel, n.d. [1860]; ———. *Parsifal* (1882), Mainz: B. Schott's Söhne, 1882.

[79] Artur Holde, Arthur Mendel, and Richard Wagner, 'Four Unknown Letters of Richard Wagner: Presented with Comment.' *The Musical Quarterly* 27 (1941) 220–34. The evidence they discuss is in a letter from Wagner to Esser (the conductor of Lohengrin in Vienna) of June 15 1861 containing the quote: 'They wrote to me at the time that they had obtained this A [bass] clarinet from an instrument-maker somewhere on the Rhine'.

[80] Bowen. 'The Rise and Fall of the Bass Clarinet in A', 2009; ———. 'The Rise and Fall of the Bass Clarinet in A,' 2011.

[81] Hector Berlioz and Richard Strauss, *Treatise on Instrumentation.* 223.

[82] Tibor Tallian, 'Opern Dieses Größten Meisters Der Jetztzeit'. Meyerbeer's Reception on the 19th Century Hungarian Opera Stage.' in *The Opera Orchestra in the 18th- and 19th- Century Europe, II: The Orchestra in the Theatre - Composers, Works, and Performances (Eds. Niels Martin Jensen and Franco Piperno).* Berlin: Berliner Wissenschafts-Verlag, 2008, 281.

[83] Richard Wagner and Francis Hueffer, *Correspondence Of Wagner And Liszt; Volume 1 1841 – 1853.* New York: Charles Scribner's Sons, 1871. Letter 62, 1850.

since the work is scored for the very unusual combination of clarinets in D and A and bass in C. This was one of the 'symphonic poems', a form that Liszt largely invented and in which he was presumably aiming, *inter alia*, at distinctive combinations of sounds. The first draft of the orchestration was probably implemented by his assistant Joachim Raff and this may have been Raff's choice; but detailed studies by Peter Raabe, curator of the Liszt Museum in Weimar, demonstrated clearly that Liszt's practice was to review and authorise every note of the final version of his works.[84] (The controversial question of Raff's involvement in Liszt's works is discussed in detail by Alan Walker in 'The Raff Case'[85]). The score shows that the bass clarinet was used mainly to provide a different sonority to the wind ensemble or partial ensemble, with only occasional solo bars. The low chalumeau notes are not used and most of the writing is in the clarion register. Very few straight-form bass clarinets in C have survived, though there is the patent of 1853 by Anton Nechwalsky of Vienna claiming that he can produce them in A, B♭ or C.[86] There are ten extant bassoon-form examples in C, including four by Streitwolf,[87] Catterini[88], De Azzi[89], Maino[90] and Ludwig and Martinka[91] (see chapters 4 and 7); so they must not have been particularly rare. There was also a local maker to Liszt in Weimar, Wilhelm Beck, from whom one instrument (in B♭) is preserved, in Leipzig[92].

It is interesting to note the short but highly virtuosic bass clarinet solo, in the ballet *Il Fausto* by Luigi Maria Viviani, performed in Florence in 1849.[93] It is known that this was written for the ophicleide-form 'bimboclarino' invented by Giovanni Bimboni, also of Florence, from the instrumentation treatise by the contemporary Tosoroni.[94] An unsigned but attributed example of the instrument is in Nuremberg.[95] This bass clarinet is silent in the opera until the fifth act, when it enters with a dramatic arpeggio over the complete four-octave range of the instrument from C2 to C6 then proceeds to interchange both lyrical and dramatic parts with the bimboniphone; the latter is a contrabass ophicleide, made by Giovanni's brother and partner Giovacchino. The full score of this section is given in Rice.[96]

In summary, the use of the bass clarinet in the woodwind section of opera and concert orchestras steadily expanded during the nineteeth century. At first it was used in occasional recitals, perhaps mainly for its novelty and from the promotional efforts of makers, but it did not join the standard wind chamber ensembles until the twentieth century; for example, Arnold Schoenberg *Kammersymphonie No. 1* (1906), Darius Milhaud *Chamber Symphony No.*

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84 Peter Raabe, *Franz Liszt Vol. 2*, rev. ed. 1968, vol. 2 vols. Stuttgart: Cotta, 1931, 71–79.
85 Alan Walker, *Franz Liszt, Volume 2: The Weimar Years: 1848-1861.* New York: Knopf, 1989.
86 I know of only two straight-form bass clarinets in C, both Buffet, and both in private collections in the USA.
87 NL.DH.gm.0840392; NL.DH.gm.0840390; CH.Z.mb.123; D.M.dm.68079;
88 GB.O.ub.496
89 D. Uhingen.Reil
90 B.B.mim.0941
91 CZ.P.cmm.E.135
92 D.LE.U.1540
93 Luigi Maria Viviani, 'Il Fausto (Ballet)' (Florence, 1849), Biblioteca di conservatorio di Musica 'L. Cherubini'. I-Fc.MS.2601.
94 Antonio Tosoroni, *Trattato Pratico Di Instrumentazioni*. Florence: Guidi, 1850.
95 D.N.gnm.MIR482
96 Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 373.

5 (1922), Leon Janaček *Mladi* (1924).[97] It came to the wider attention of audiences and other composers firstly from spectacular obbligati by Mercadante and Meyerbeer, where the audience's focus is on the instrument; in later works, such as Wagner's *Tristan* it is directed alternately between the instrument and the singer. These are strongly reminiscent of the structure of Mozart's arias *Parto, Parto* and *Non Piu di Fiori* from *Clemenza di Tito*, for obbligato basset clarinet and basset horn, respectively.[98] This use continued throughout the century (see Balfe, Wagner and Viviani, above) but even beginning from Mercadante we see the instrument incorporated in the woodwind ensemble, strengthening and supporting it in the bass register and giving a novel tone colour in short wind chorus or solo interjections. This trend was emphasized by Berlioz in massive works, which exploited the undoubted power as well as the good intonation of the Sax instrument.

I have already commented that Richard Strauss' remark, that Wagner always used the bass clarinet to indicate 'solemn resignation', by no means accounts for all his uses. Ensemble tone colour, and sheer weight of sound in fortissimo passages are also important. But it is true that both the solo and harmonic bass clarinet has often been used from its earliest appearances to indicate mystery, resignation, horror and death. There are exceptions, but the solo obbligati in *Emma d'Antiochia*, *Les Huguenots, Lohengrin,* and *Tristan und Isolde* are mentioned above in this context. In an article on *Music and the Uncanny in the 19th Century*, aided by contemporary descriptions of the horrific effect of Faust's gallop into the abyss in Berlioz' *The Damnation of Faust*,[99] Frank Hentschel describes the appearance of the 'hideous roaring monster'

> The emergence of the monster is announced and accompanied by low winds—bass clarinet, bassoon, trombone, and tuba—which become denser at the moment of the explicit mention of the monster ...[100]

Even today, it is almost a convention of film and TV music that if the bass clarinet enters prominently, something sinister or tragic is about to happen. An example is the introductory music from the TV crime series *Midsomer Murders* with music by Jim Parker.[101] The bass clarinet enters first, in prominent sextuplets in a low tessitura that establish a dark tone colour and sombre effect; these gradually fade but remain below in accompaniment as other instruments commence the main theme. Then the murder is revealed.

Military, church and outdoor music

It was Rendall who originally suggested that the bassoon-form bass clarinet would have been used from its inception for military bands. It would have formed a more powerful and more compact instrument than the bassoon for the bass line and an easier instrument to carry on

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[97] Arnold Schoenberg. *Kammersymphonie No. 1* (1906), Vienna: Universal Edition, 1912; Darius Milhaud. *Chamber Symphony No. 5* (1922), In *Cinq symphonies pour petit orchestre.* Vienna: Universal Edition, 1922; Leoš Janaček *Mladi*) (1924), Prague: Hudební Matice, 1925.

[98] Wolfgang Amadeus Mozart,, *Clemenza di Tito* (1791). Leipzig: Breitkopf und Härtel, 1809

[99] Hector Berlioz. *The Damnation of Faust* (1846), Paris: S. Richault, 1854.

[100] Frank Hentschel, 'Musik Und Das Unheimliche Im 19.Jahrhundert,' *Archiv Für Musikwissenschaft* 73 (2016) 9–50. Tr. by author.

[101] Jim Parker, *Midsomer Murders Theme,* https://www.youtube.com/watch?v=dvD73A9eXXk. Accessed 3 January 2021.

the march. I would add that its upward- or forward-facing bell would also have been attractive for outdoor music. These arguments are plausible, but the firm evidence presented has been sparse and a number of sources give this suggestion as no more than a conjecture.[102,103]

Whilst much nineteenth century band music has survived, the bass clarinet is rarely specified, and lists of nineteenth century military bands rarely indicate the use of bass clarinets. Whitwell has reviewed the prevalence, composition and use of military, civil and church bands in the nineteenth century in many countries.[104] A good overall indicator is the table of bands and their instrumentation from the nine Continental European countries entered at the major band event of the century, the 1867 International World Band Competition in Paris. Only the bands of Bavaria, Austria and Russia included bass clarinets in their ensembles; those of France (two bands), Baden, Spain, Netherlands and Belgium did not.[105] The Bavarian and Austrian bands would quite likely have used bassoon-form instruments in this period. Little is known in the secondary literature about bands in Russia, other than that they developed greatly during the nineteenth century. Rimsky-Korsakov himself was Director of Navy Bands for ten years and was deeply involved with them.[106]

This is now discussed in more detail, for countries for which secondary literature referencing the bass clarinet is available.

United Kingdom

As far as the UK[107] is concerned, the bass clarinet is not mentioned at all in the parts of the music discovered in the vast collection to 1837 of the Duke of Cumberland.[108] Nor does it appear in the many ensemble listings compiled by Herbert and Barlow,[109] until the publication by Boosey in 1848 when it appears as an alternative to the bassoon.[110] In 1888, Jacob Kappey's tutor shows that bands in England were using bass clarinets, and often using them as substitutes for the bassoon. Instructions are given for transposing such parts. Kappey (himself a noted Marine bandmaster) only illustrates the straight form and does not mention the bassoon form.[111]

Useful insight on the situation in the UK is given in the treatise by Charles Mandel, published in London in *c*.1859, which contains a section on bass clarinet. As one of the founding Professors of the Military Music Class at Kneller Hall (which became the Royal Military School

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102 Nicholas Shackleton, 'Bass Clarinet,' *Grove Music Online*. Accessed 9 Nov. 2021. https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000002236

103 Hoeprich, *The Clarinet*, 2008.

104 David Whitwell. *The History and Literature of the Wind Band and Wind Ensemble. Vol. 5. The Nineteenth-Century Wind Band and Wind Ensemble*. Edited by Craig Dabelstein. 2nd ed. Austin, TX: Whitwell Publishing, 2012. Lists of bands throughout, with chapters classified by country.

105 David Whitwell. *The History and Literature of the Wind Band and Wind Ensemble. Vol. 5,* 116.

106 Nikolay Rimsky-Korsakov, My Musical Life, New York: Tudor, 1936, 118

107 The United Kingdom of Great Britain and Ireland was formally constituted in 1801. Many references refer to England and English which should properly refer to UK and British, as is used here unless it is a direct quote.

108 Karen Spicher, 'Guide to the Hanover Royal Music Archive,' n.d. 133.

109 Trevor Herbert and Helen Barlow. *Music and the British Military in the Long Nineteenth Century*. New York: OUP, 2013, 302-318.

110 'Boosey's Military Journal' 5th Series (1848). GB-Lbl.h.1549

111 Kappey, *Tutor for the Bass and Alto Clarinets*, 1888.

of Music) in 1857, he was both very well informed and influential. First, he was clearly aware of the difference between French and German bass clarinets:

> The French B♭ bass-clarionet is exactly an octave lower than the ordinary B♭ clarinet, and like it, is noted in the treble clef, sounding naturally an octave lower.
>
> The German B♭ bass-clarionet and the low tones that can be produced on the instrument, are alone sufficient to prove it is best calculated to take the principal bass part.[112]

The German instruments must be bassoon-form from the reference to the lower notes.[113] He is disparaging about their sound – in contrast to reports of concerts on Catterini and Streitwolf instruments, above – and perhaps had only experienced instruments of lesser quality, or was basing his comparison on the very powerful Sax instruments:

> Unfortunately, it has always a nasal sound, even when played by the greatest proficients, while its tone is, compared with that of the other bass instruments, too weak to take effectively, when unsupported, even the violoncello-parts, more especially the solos.

After remarking on the disadvantage of the complexity of the instrument he continues with a useful insight into the employment of the bass clarinet in wind bands:

> In spite of this, however, it ought not to be so much neglected as it is; for, on account of the ease with which it is played, it imparts to the invariably and awkward-sounding bass-passages upon the F, and still more upon the E flat bass-bombardon, — when it is employed to support them, —roundness and volume, and that to a far greater extent than the ophicleides, bass-horns, serpents, euphonions, and other bass instruments. Furthermore, as a substitute, in the higher notes and passages, for the violoncello, it produces, when supported by bassoons or even bassett horns, a characteristic expression, never attainable by any other bass instrument.

And the next remark may explain why there are so few surviving band parts for the bass clarinet, at least from the UK:

> Since, however, it cannot, in reed bands, produce by itself any grand effect, there is no separate part written for it. The bass-clarionetist has, consequently, to play his notes not according to the system adopted for other clarionetists, but as they really sound, —that is to say, a tone lower …

[here follows an explanation about transposition at sight] …

> In all cases where there is a bass-clarionetist, we should, -- bearing in mind the compass of his instrument, and its effect,—denote his part by writing over the bass-bombardon, ophicleide, bass-horn, or serpent parts, 'et B bass-clarionet,' and inserting, separately, the few passages intended for the bass-clarionetist alone, when supporting the bassoons or bassett horns.

Mandel is clearly regarding the bass clarinet as a harmonic instrument to be used primarily in ensembles rather than as a solo instrument. This is in interesting contrast to its use in the early operas, discussed above, where the particular atmosphere it could evoke when played solo was important for the dramatic context. This may offer a partial explanation for the survival of the bassoon-form instrument in bands; its harmonic rôle was important, but its solo rôle was not.

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[112] Charles Mandel, *A Treatise on the Instrumentation of Military Bands: Describing the Character and Proper Employment of Every Musical Instrument Used in Reed Bands*. London: Boosey & Sons. [1859], 18.

[113] Straight-form instruments with extended low range are not known in museums or documents from the period considered, with the exception of the Nechwalsky patent of 1853 and his instrument in Washington DC (US.W.si.65.0613).

It is relevant to point out that the use of an instrument that was not specified in the score was not, in the eighteenth and nineteenth centuries, as anomalous as it has appeared for the last century. A parallel may be drawn with the use of the double bass or contrabassoon (a so-called 'sixteen-foot bass'[114]) in Harmoniemusik to double the second bassoon. Such parts were explicitly added to some well-known compositions and arrangements of Harmoniemusik, for example those by Johann Nepomuk Went (1745 – 1801). The extra parts, in another hand, were added to editions produced after Went's death. This indicates that the use of a sixteen-foot bass to double the lowest part an octave lower was nothing unusual, and of course made explicit in works such as the Mozart's *Serenade in B♭ major* (c.1784) and Dvořák's *Serenade for Wind Instruments Opus 44* (1878).[115] Anton Stadler also wrote, in his *Music Plan* (1800):

> … the contrabassoon (or the double bass), however, which plays nothing but the fundamental or thorough bass is very effective … it not only reinforces and completes, but also relieves and assists the wind players. If it is used throughout a piece as in the large scale compositions of Haydn and some other great composers, it can be employed as opportune in suitably adapted solo passages and also as a reinforcement in the main tutti with good effect.[116]

Stoneman et al. suggest that the addition of the double bass or contrabassoon would have been particularly effective in outdoor concerts.

Mandel's recommendations on band instrumentation for various ensemble sizes are given in his publication of 1869[117]. Here he recommends the inclusion of at least one bass clarinet, for ensembles of 30 upwards. It is not clear how much these recommendations were put into practice. An enquiry to the Kneller Hall Archives produced the response:

> The bass clarinet has never been part of the official instrumentation of an army band, rather something of a luxury occasionally played (usually by a third clarinet player) in certain pieces as appropriate. As far as I know it was never used on parade.[118]

The roles played by the military bands in the UK and their repertoire have been discussed in detail by Herbert and Barlow.[119] Briefly, they were used for:

- Signalling military manouevres, involving small numbers of fifes and drums (infantry) and trumpets (cavalry). The repertoire for these signals were strictly limited to specified sequences used as a code, and clarinets and other band instruments were not involved.
- Raising and sustaining the morale of troops on the march, and before battle; the repertoire for this activity consisted primarily of patriotic marches.
- Entertaining the regimental officers (who paid most of the costs of the band) in the mess and at formal events such as balls; the repertoire would then be primarily dance music or operatic works that followed a suitable tempo.

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114 David F. Chapman, 'The Sixteen-Foot Violone in Concerted Music of the Seventeenth and Eighteenth Centuries: Issues of Terminology and Function,' *Eighteenth-Century Music* 12 (2015) 33–67,. https://doi.org/10.1017/S1478570614000347

115 Marshall Stoneham, Jon A. Gillaspie, and David Lindsey Clark, Wind Ensemble Sourcebook and Biographical Guide. Westport, CT: Greenwood Press, 1997, 64; W.A. Mozart. Serenade in B¨ major (c.1784). Critical edition. Kassel: Bärenreiter-Verlag, 1979; Antonín Dvořák. Serenade for Wind Instruments Opus 44 (1878). Berlin, Simrock, 1879.

116 H-Bn, Fol. German. 1434. Quoted in Stoneham, Gillaspie, and Clark, 346.

117 Charles Mandel, *Mandel's System Of Music.* London: Boosey & Co. 1869, 25; quoted in Herbert and Barlow, *Music and the British Military in the Long Nineteenth Century*, 309.

118 Email from Colin Dean, Kneller Hall Archivist, July 26 2014.

119 Herbert and Barlow, *Music and the British Military in the Long Nineteenth Century*.

- Frequently, being loaned or hired out to similar private functions, with similar repertoire.
- Providing concerts for the public, usually outdoors and often in bandstands in parks. These were intended purely for entertainment and consequently would help to improve the public image of the military and aid recruitment. The repertoire for these concerts primarily comprised arrangements of classical orchestral or operatic works; popular songs and ballads were certainly included, but many of these were derived from operas in the 'English' tradition as discussed above.

There was indeed a view that the musical role of a military or civic band in this context was to diffuse the great classical works to the public, in (usually free) outdoor concerts to which they had access, and for which the instrumentation of a band was far more suitable than that of the orchestra. The art of arranging such music for band was the duty of the bandmaster and was rigorously taught at Kneller Hall, though published band music from France, Germany and Italy was occasionally used. There appears to have been no drive for composers to write original music specifically for the band until Gustav Holst's suites for military band in 1909 and 1911 (which did include bass clarinets).[120] This approach has parallels to the somewhat earlier use of the 'Harmoniemusik' ensemble[121] across Europe which was very widely used to transmit operatic and symphonic music to venues that did not have scope for a full orchestra.[122]

In a more international overview of military music written in 1892, by which time the bass clarinet was thoroughly established in most musical genres, Hermann Eichborn says:

> The further we pursue the development of military music, the richer the instrumental apparatus becomes. It is impossible for me to go into all the redesigns, new inventions and improvements, transverse flutes, bass horn, bass clarinet, bathyphon, small clarinets in D, Eb, F and A flat, fourth and fifth bassoons, serpentine, bass horn. … I just want to try to set up a tableau to give an overview of how the ensembles have been comprised over time.[123]

He then takes the periods: late eighteenth century, early nineteenth century, middle nineteenth century and lists the typical composition of bands from Germany, France and (for the last period) Austria and Belgium, giving numbers of each instrument and also distinguishing infantry from cavalry and hunter (Jäger) regiments. Although relative rarities such as clarinets in A♭ and F, alto clarinets and basset horns appear in the lists, bass clarinets do not. He does mention, however that, with the flourishing of military music after 1815,

> Not only was the number of musicians significantly increased … also a number of newly invented instruments, such as basset horn, bassclarinette, bathyphone, bass horn, not to mention the newly created brass instruments, found their way into the choirs. Through the latter, however, the whole music of this kind was given a different character … new combinations and tone-colourings appeared …[124]

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120 Herbert and Barlow, 9, 126; Gustav Holst, First Suite in E¨ for Military Band, Opus 28 No. 1 (1909), London: Boosey & Co., 1921; ———. Second Suite for Military Band, Opus 28 No. 2 (1911). London: Boosey & Co., 1922.

121 Pairs of oboes, clarinets, horns and bassoons, sometimes with a string or wind double bass

122 Stoneham, Gillaspie, and Clark, *Wind Ensemble Sourcebook and Biographical Guide*, 6.

123 Herm. Eichborn, 'Studien Zur Geschichte Der Militärmusik,' *Monatshefte für Musik-Geschichte* 24, (1892) 114–17.

124 Eichborn, 117.

France

It is impossible to discuss band music in France without considering the musical consequences of the French Revolution of 1789. Although these events impinged little on the direct development of the bassoon-form clarinet, which was largely a development occuring in the German States and the Austrian empire, they undoubtedly influenced the career and innovations of Adolphe Sax, who produced the main, and ultimately successful, competition to the bassoon-form instrument.

Although the idea that all forms of music were irreversibly changed in France by the Revolution has been somewhat discredited, it is undeniable that military music and musicians received a tremendous boost in organisation and status.[125] This began with the musicians assembled by Bernard Sarrette to support the storming of the Bastille on July 13 1789, continued with the same forty-five instrumentalists forming the core of the musical group of the French National Guard and later the National Institute of Music and finally the Paris Conservatoire in 1796 with Sarrette as its first head. Musicians were well motivated to seek military and government employment since they had lost their previous patronage from the court, the aristocracy and the church. In the first five years of the Revolution, the Institute provided more than four hundred musicians to the military and civil personnel of the Revolution, and eventually would provide all the musicians who served the *fourteen* armies of the French Republic. Thus, military bands were numerous, and undeniably important, to the government, the musicians and ultimately to the instrument makers.[126]

It appears that despite the inventions of Dumas' bassoon-form and Desfontenelles straight-form bass clarinets and their good reception by the Paris Conservatoire early in the century, the bass clarinet did not start to penetrate military bands until the invention of Adolphe Sax in 1838.[127] Thereafter, Sax embarked on a major effort over the next two decades to secure the adoption of this and also his new families of instruments, the saxhorns and saxophones and his improved versions of other instruments such as the trumpets, in the French military. He was fiercely opposed by many existing makers of the traditional instruments. The disputes were very public and are well documented.[128-130] There is no doubt that Sax contributed massively to the instrumentation and sound of the wind band in the nineteenth century, and his influence persists to the present day.[131] Despite this mid-century success, which included bass clarinets in the French infantry bands of the time, however, the bass clarinet did not appear to have become solidly established even in French military bands. No tutor specifically for bass clarinet appears in France until that of Sainte-Mairie in 1898, and this is a little later

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125 Carl Dahlhaus and Ludwig Finscher, *Die Musik des 18. Jahrhunderts*. Lauber: Laaber-Verlag, 1985; e'A French (R)Evolution in Music?,' *Age of Revolutions* (blog), https://ageofrevolutions.com/2016/09/05/a-french-revolution-in-music/. Accessed 22 October 2021.
126 Kastner, *Manuel Général de Musique Militaire A l'Usage des Armées Françaises*. 163ff.
127 Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 291 ff.
128 Kastner, *Manuel Général de Musique Militaire A l'Usage des Armées Françaises*, 262 ff.
129 Fétis, *Biographie Universelle Des Musiciens, Supplément et complément*, 1844, 54-57.
130 Oscar Comettant, *Histoire d'un Inventeur Au XIXe Siècle. Adolphe Sax, 1860*. 30 ff.
131 Crouch, 'The Contributions of Adolphe Sax to the Wind Band'; Rebekah E. Crouch, 'The Contributions of Adolphe Sax to the Wind Band, Part I,' *Journal of Band Research; Troy, Ala.* 5 (1969) 29–42; Rebekah E. Crouch, 'The Contributions of Adolphe Sax to the Wind Band, Part 2,' *Journal of Band Research* 6 (1969) 59–65.

than tutors for the clarinet with bass clarinet that appeared in Germany and England during the last decade of the nineteenth century.[132] In the lists of foreign military band instrumentations in Herbert and Barlow,[133] based on Kappey[134] and Kalkbrenner[135], the band compositions of documented bands in Prussia/Germany (5), Spain (4), France (2), Austria (2), Italy (1), Russia (1) and Japan (1) between about 1860 and 1884 are listed. Only in three of the Spanish bands, those of the three Naval divisions, are bass clarinets listed as a regular component. Use in a Russian band in the 1867 International World Band Competition has been noted above.[136] The situation seems similar throughout Europe, though in all countries it is possible that bass clarinets substituting for bassoons could be found, as discussed below.

In common with the situation discussed in detail for the UK, much of the music played for private and public entertainment was dance music or arrangements of popular operatic excerpts. Georges Kastner does cite some 'dramatic' composers who have worked in the genre of band music, naming Méhul, Katel, Gossec, Berton, Spontini and Chérubini as well as himself. He is trying to encourage recognition and development of the genre, contrasting the position to Germany

> Thus in Germany the most famous composers do not disdain to write pieces of music specially intended for the players of their country.[137]

He goes on to list a number of German kings, princes, princesses and dukes who have composed for their own bands.

Germany

In Germany there is also some direct evidence. An editorial on an 1844 arrangement of the first eight Beethoven symphonies for military band by J.H. Rau (which does not itself appear to have survived) shows evidence for the many ensembles, and ends by quoting Rau himself on the instrumentation of his arrangements:

> Herr J.H. Rau, the musical director of the 2nd Kurhessische Infantry Regiment in Fulda, has arranged all Beethoven's symphonies, with the exception of the 9th, for full military band, and by simultaneously including the score of the first four symphonies for inspection is requesting the Editor to bring his work to public notice. … Should not the original publishers make the decision to print the scores in this form too? There would be no great risk in doing so. The many hundreds of German music ensembles would be a guarantee of good sales.
>
> … [the editor then quotes Rau as saying] …
>
> '…Finally I [Rau] do not think I should pass up the opportunity to draw attention of my colleagues who are still unfamiliar with it, to the very useful instrument, the bass clarinet, which has been constructed by the instrument-maker Herr Streitwolf in Göttingen. This instrument

[132] Sainte-Marie, *Méthode Pour Las Clarinette-Basse à LUsage Des Artistes Clarinettistes, Avec l'indications Des Doigté Pratiqués;* Kappey, *Tutor for the Bass and Alto Clarinets*, 1888; Robert Stark, *Grosse Theoretische-Praktische Clarinett-Schule Nebst Anweisung Zur Erlernung Des Bassetthorns Und Der Baßclarinette.* (Heilbronn: C.F. Schmidt, 1892).

[133] Herbert and Barlow, 311.

[134] J. A. Kappey, *Military Music: A Short History of Wind-Instrumental Bands*. London: Bossey & Co, 1894, 90-93. Quoted in Herbert and Barlow, 311.

[135] August Kalkbrenner, *Die Organisation Der Militärmusikchöre Alle Länder: Mittheilungen Über Die Dienstlichen Und Socialen Verhältnisse Der Musiker Und Der Dirigenten Sämmtlicher Militärmusikkapellen Aus 16 Verschiedenen Ländern*. Hannover: L. Oertel, 1884. Quoted in Herbert and Barlow, 311.

[136] David Whitwell. *The History and Literature of the Wind Band and Wind Ensemble. Vol. 5*, 116.

[137] Kastner, *Manuel Général de Musique Militaire A l'Usage des Armées Françaises*, 341.

> has the considerable range from bottom A flat to top B flat [presumably this is sounding pitch], and all parts, even the most difficult, can be very comfortably played on it. Its tone is extremely powerful and particularly in its low registers remarkably resonant. This instrument together with the chromatic bass horn create a very effective bass in a relatively small infantry ensemble. They have been produced in exceptional quality by Herr Streitwolf as well as by the court instrument-maker Herr Mollenhauer in Fulda,'…[138]

One bass clarinet made by Mollenhauer is known, a bassoon-form instrument dating to 1870 From the image it appears to be an advanced bassoon-form design, much later than the remark by Rau in 1843, indicating that the firm had already had experience in making bassoon-form bass clarinets.[139] There is also clear evidence of Streitwolf's instrument being used in miltary bands. Fétis remarks that Streitwolf's bass clarinet has been adopted for the military music of Hesse-Cassel, but also that, five years after his detailed review of the instrument, it had not been adopted in France or Belgium.[140] In 1834 we also read

> This bass clarinet has been in use by the Royal Prussian 28th Infantry Regiments for half a year, and during this time it has met with the greatest approval from all music lovers; we can therefore recommend it to the infantry music corps with the firm conviction that no one will later regret it being deployed.[141]

However, the bass clarinet does not figure in the lists of German band ensembles assembled by Herbert and Barlow and at present we can only say that it was regularly used in just a few cases.[142]

So far as repertoire is concerned, the best evidence is that from Kastner, cited in the previous section, in which he claims that famous composers do take band composition seriously in the German states. The only examples he gives, however, are the royalty such as Frederick the Great, William III, Prince Albert of Prussia, the Prince Royal of Hanover, Princesse Wilhelmina, the Prince Royal of Sweden etc. Whilst these rulers and consorts were distinguished by their interest and skills in music, they were hardly the most celebrated composers of their countries.

USA

The American school of bassoon-form bass clarinet making by George Catlin and his various partners in the early 1800s in New England was discussed in Chapter 2 and has been studied by Robert Eliason.[143] Eight instruments have been preserved. No documentation on their usage in Art music has been found, but three lithographic sheet music covers exist that may show their use in bands playing popular song or dance music, published in Boston in 1837-

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138 Anon. 'Arrangement Der Beethoven'schen Symphonien für Militair Musik.', *Neue Zeitschrift für Musik* XVIII (1843) 32. Tr. by Robin Hildrew.

139 By Thomas Mollenhauer of J. Mollenhauer & Sohne, 1870. Private collection. Illustrated in Dullat, *Klarinetten*, 200.

140 Fétis, 'Exposition Des Produits de l'industrie,' 171–72.

141 Anon. 'Nachrichten: Cöln am Rhein, im Februar.' *Allgemeine musikalische Zeitung*, 1834, 193–94.

142 Herbert and Barlow, 311.

143 Robert E. Eliason, 'Oboe, Bassoons, and Bass Clarinets, Made by Hartford Connecticut, Makers before 1815,' *The Galpin Society Journal* 30 (1977) 43–51,. https://doi.org/10.2307/841365; Robert E. Eliason, 'George Catlin: Hartford Musical Instrument Maker Part I,' *JAMIS* 8 (1982) 16–37; Eliason, 'George Catlin: Hartford Musical Instrument Maker Part II.'

1840. According to Eliason, the band is the Boston Brigade Band and the pieces are clearly identified as *Berry Street Rangers* and Captain *E.G. Austin's Quick Step*. Rice adds a third, *Whig Gathering, Song and Chorus Respectfully Dedicated to the Whigs of the United States,* [144] Eliason argues plausibly that the images show bass clarinets of the Catlin design, and whilst this is certainly a possibility, the images are not clear enough in detail (such as the shape of the crook of the instruments) to put the identification beyond doubt.

Italy

Several bassoon-form instruments (usually called *glicibarifono* for instruments by or derived from Catterini, or *clarone* more generally in Italian texts) have been found that are from North Italy (then part of the Austrian Empire): Catterino Catterini[145], Paolo Maino[146], Giacinto Riva[147] and two unmarked instruments[148], all of which I have examined. The use of the glicibarifono in La Fenice, Venice and elsewhere is discussed above, and there is also excellent evidence from parts lists of its use in both orchestra and band in the town of Persiceto, Italy, near Bologna (the home of the wind and *glicibarifono* maker Giacinto Riva) in the early 1840s. Giacinto Riva made one of these instruments for the band after Catterini's pattern in 1844.[149] His brother Pasquale, who won a local award in 1844 as a student of glicibarifono, played in the band, presumably on this instrument. Vincenzo Lodini is listed along with Pasquale as a glicibarifono player in 1846.[150] There is a very good quality bassoon-form bass clarinet by Giacinto Riva in New York, in the Metropolitan Museum.[151]

The community archives of Persiceto contain one orchestral and nine band works in which the glicibarifono is listed in the ensemble, as shown in Table 3.1. The band had been established by the National Guard in 1806 but was freed from both military and papal control[152] in 1817 when it was refounded by the Comune as the 'Society of Young Amateurs of Music'; by the 1840s it had a purely community function and community financial support. These works are all excerpts from operas (as indeed are most of the other c.90 works collected as repertoire for the band). It seems probable from the listing of occasions when the band was demanded by the Comune that some or even most of these performances were outdoors.[153] The bass clarinet would therefore provide a stronger bass line than could the bassoon, but with the advantage of blending better with other woodwind instruments than would the brass basses. Solo passages for the glicibarifono are indicated on some of these parts.

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[144] "Whig Gathering, Song and Chorus Respectfully Dedicated to the Whigs of the United States (Boston: Henry Prentiss, 1840). Cited by Rice, *From the Clarinet d'amour to the Contra bass*, 268.
[145] GB.O.ub.496
[146] B.B.mim.0941
[147] US.NY.mma.89.4.3124
[148] US.NY.mma.89.1635 and US.NY.mma.89.1636
[149] Giacinto himself played bassoon in the band but resigned due to ill health in 1844.
[150] Anna Valentini, "L'Orchestra a San Giovanni in Persiceto e Le Istituzioni Musicali Dell '800," in *Accademia e Società Filharmonice in Italia: Studie e Recherché*, ed. A. Carlini (Trento: Società Filharmonica Trento, 1999), 273–304.
[151] US.NY.mma.89.4.3124
[152] Persiceto was within the territory of the Papal States after 1815.
[153] Valentini, "L'Orchestra a San Giovanni in Persiceto e Le Istituzioni Musicali Dell '800," 279.

Table 3.1. Compositions by band and orchestra with Glicibarifono named in score or parts[154]

Composer/Arranger B – band, O - orchestra	**Title**	**Date**
V.Bellini/G. André/B	Aria Finale nell'opera *Beatrice di Tenda*	1843
V.Bellini/G. André/B	Aria Finale *Beatrice di Tenda*	1843
G. Donizetti/G. André/B	Aria nell'opera *Lucia*	1844
L. Ricci/G. André/B	Coro nell'atto primo dell'opera *Chi dura vince*	1844
G.Donizzetti/G. André/B	Aria nell' *Imelda de' Lambertazzi* a Tromba	1845
G.Donizzetti/G. André/B	Aria dalla *Lucia di Lammermoor*	mid -1800s
G.Donizzetti/G. André/B	*Romanza* dalla *Lucrezia Borgia*	mid -1800s
G.Donizzetti/G. André/B	Aria: *io ti dirò negl'ultimi singhiozzi* nell'opera *Roberto Devereux*	mid -1800s
L. Pacini/Anon./O	Sinfonia Nell'Opera *il Falegname Livonia*	mid -1800s

The idea about the usage of the bass clarinet in Italy is somewhat reinforced by the pitch of the nominally C instrument of Catterini in Oxford[155]. From my own measurement in playing tests, it is pitched approximately a semitone above the C in a scale of A4 = 440 Hz, that is, it is an instrument in C but at a very high pitch (A4 = 465 Hz). This is much sharper than the pitch of the northern italian opera houses. We do not have the exact pitch of La Fenice, Venice, but tuning forks from Bologna, Turin, Milan and Naples varied only between 443.1 and 446.6 Hz as measured by the physicist Hermann von Helmholz.[156] It is likely that the Oxford instrument was not used in the opera but in a church or city band that was tuned, for example, to an older organ of higher pitch.

Persiceto is just one city in Italy, but one for which detailed archives have been preserved and examined for its musical history. It is likely that there are many similar cases. Allesandro Gandini, in reviewing the history of the music at the theatre in Modena in 1873 describes Catterini's success in the Modena demonstration on Feb 12 1838, and then adds:

> Now that instrument is adopted with good effect in the musical bands of central Italy.[157]

Whilst it appears that La Fenice, Venice was the only opera house in Italy where a bass clarinet or glicibarifono/clarone was established in the orchestra, it is clear that it was well known in many city bands. These probably played mainly outdoors but it is known that they also supplied players for operas in the local theatres. We cannot therefore assume that every time a performance of *Emma d'Antiochia* occurred, as it did in Milan (1835), Naples (1835), Trieste (1835), Genoa (1836) and Padua (1837),[158] or when other concerts using the glicibarifono were given in Parma (1837), Modena, Trieste (1847) and Bologna (1847),[159] that Catterini was the player or that one of his instruments was used. Beside the instrument built by Fornari and

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[154] Valentini, 302.
[155] GB.O.ub.496
[156] Helmholtz, Hermann von. 'On the sensations of tone' (*Tonempfindungen*). Tr. of 4th German edition of 1877 by Alexander J. Ellis. London: Longmans, 1885 and reprinted New York: Dover, 1954, 510.
[157] Gandini, Allessandro.. Modena: Tipografia sociale, 1873, 363
[158] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 342.
[159] Adriano Amore, *La Scuola Clarinettistica Italiana: Virtuosi e Didatti*. Frasso Telesino: author, 2006, 22; reported in Rice, 276.

used in Venice,[160] there is a bassoon-form bass clarinet made by Losschmidt in the Civico Museo Teatrale 'Carlo Schmidl' in Trieste, which could well have been used in that theatre.[161]

The uses of the military and civic bands in Italy seem to have been much the same as those in the UK and the rest of Europe, with, as would be expected, a very strong bias towards music from the classical Italian opera.

In summary, bass clarinets were used from their invention in civic and military bands, to play both martial and entertainment music. There is clear evidence for their adoption in military bands in most countries but it is surprisingly sparse and it is relatively rare to find them in lists of players as a regular part of the lineup. However there is also evidence that they were accepted and used as replacements for bassoons and as important supplements to bass instruments such as the ophicleide, so the available lists must significantly underestimate their usage. There are only rare cases of detailed documentation of civic bands such as that in Persiceto, but we know from incidental comments by the reviewer of Rau's arrangements that there were *hundreds* of bands in Germany that could employ a bass clarinet, and from Gandini that there were a significant number of bands in central Italy actually using the bass clarinet.[162] Documentation of these may well exist in local archives but remains to be discovered.

Concluding remarks

Scores and instrumentations of most operatic works from the nineteenth century are quite well known from multiple manuscript copies kept in theatres, and now in libraries. They have generally been preserved except in cases of loss in fire or wars. Operatic works that were published, and published orchestral scores from almost all composers have generally also been preserved because of their wide distribution. We can therefore be sure that at least the great majority of compositions for bass clarinets in operatic and orchestral music are captured in this chapter. The impressive use of the bass clarinet was demonstrated remarkably quickly, by the 1830s virtuoso obbligati by Mercadante and Meyerbeer, and facilitated by the excellent instruments of Catterini, Streitwolf and Sax. The technical facility required for these early works was equalled by Viviani in 1849 but not exceeded, even by Wagner or Liszt, until the works of Richard Strauss at the end of the century. The adoption of the bass clarinet in Art music has been a case of gradual, but inexorable penetration. It is fair to say that this came about from two factors. The realisation by composers of its tonal and expressive qualities led to the obbligati and other solos by (for example) Mercadante, Meyerbeer, Viviani, Wagner and later Strauss. But also the trend in the nineteenth century for larger and louder orchestras with extended tonal colouration, suited the bass clarinet perfectly. It is the strongest orchestral bass woodwind instrument and also the one with the greatest dynamic range. Its use was a natural consequence of the development of the whole orchestra; the works of Richard Strauss and Gustav Mahler, both of whom used the bass clarinet extensively and thoughtfully at the end of the century, spring to mind.

160 Della Seta, '`From The Glicibarifono To The Bass Clarinet'.
161 I.TS.mt.10492
162 Anon. 'Arrangement Der Beethoven'schen Symphonien f'ür Militair Musik.'.'

We do not have the same confidence in the preservation of chamber, recital and small ensemble works despite the impressive early work by Neukomm. Often we know that there were recitals by a bass clarinettist, and we know the name of the player but not what music was played. We know that sometimes these were the player's own compositions, e.g. the case of Catterini in his promotional tours[163] but I have not found a single case in which this has been preserved. Sometimes they would have been arrangements, such as the trios from *Les Huguenots* played by Maycock in Dublin[164] and again these would not normally have been published. The situation is even worse in the case of bands, both civic and military. Evidence has been presented that it was the norm for bands to perform arrangements and not original works except in the case of marches (a necessary but not dominant mode of their operation). And since there was *no* standard instrumentation for the military, let alone the civic band in the nineteenth century, and indeed it was rapidly developing with the invention of new instruments, it was not even possible for a significant market in arrangements to exist. This contrasts strongly with the earlier Harmoniemusik ensembles, which had standardised instrumentation over several decades and for which thousands of compositions and arrangements have survived.[165] And although a large number of pieces for the nineteenth-century wind band have been discovered by Whitwell, the majority of these are single copy manuscripts in libraries;[166] from an RISM search it seems that parts for the bass clarinet are extremely rare. We also know that it was one of the contractual duties of a bandmaster to arrange works for his own band; this was rigorously taught at Kneller Hall, for example. Therefore we can be certain that our knowledge of the use of the bass clarinet in military and especially in civic bands is seriously lacking and will remain so until many more local archives of the type found in Persiceto come to light.

What was the role of the bassoon-form instrument in this steady penetration of all musical genres? It was clearly required for the operatic works using the greater range at the bottom of the instrument, such as Mercadante, Viviani and (probably) Balfe and Verdi's *Ernani*, and indeed influenced these works. It appears to have been the norm for Art music in the first half of the nineteenth century except in France where Sax's new instrument dominated after 1838. However, no such works requiring the bassoon-form instrument are known after about 1850, and Wagner did not require notes below written E2 in any of his works. But bassoon-form instruments are found in museums across Europe in significant numbers, totalling over 80, with dates of manufacture throughout the century (see chapter 4). Although direct evidence is preferrred to circumstantial, I have to conclude that the bassoon-form instrument was indeed in widespread use in military, civic and church bands throughout the century. It is clear that the direct evidence of band use must be a considerable underestimate, and that the compact form and upward-facing bell of the bassoon-form instrument were perceived as very

163 Anon. 'Recital review: Catterino Catterini.'
164 Anon. 'Jullien in Dublin.'
165 Stoneham, Gillaspie, and Clark, *Wind Ensemble Sourcebook and Biographical Guide*. 5. Over 12,000 works by 2200 composers are listed.
166 Dr David Whitwell, *The History and Literature of the Wind Band and Wind Ensemble: Nineteenth-Century Wind Band and Wind Ensemble Repertoire: Volume 9*, ed. Craig Dabelstein, 2nd ed. edition (Austin, TX: Whitwell Books, 2012).

useful attributes for outdoor playing. It is also quite possible that its sound was perceived to be more suitable for band ensemble playing; this did not involve significant solo passages but was required to blend with the lower instruments. This may account for the choice of the bassoon-form instrument in band and outdoor music, despite its likely extra cost compared with a straight-form instrument.

Table 3.2: List of known or inferred repertoire for the bass clarinet in the period up to the early 1850s

Date	**Composer**	**Player** (if known) **location**	**Work**	**Genre**	**Evidence**	**Instrument (where known)**
1794	Johann Stranensky	Johann Stranensky **Stockholm**	*'Romance with a Rondo à la Polonaise'* for Clarinette Fagotte Quintet with two flutes, two horns, and Clarinette-Fagotte Terzette from Grétry's opera *Zémire et Azor* (1771) arranged for two horns and Clarinette Fagotte	Chamber Music	Concert programme	Bassoon-form bass clarinet by Heinrich Grenser
1809	unknown	Ahl the Younger **Mannheim**	Recital	Chamber Music	Contemporary AMZ report	No information
Early 1800s?	Beethoven arrangement	**Moscow**	Arrangement of Op 18 No. 1 quartet for 3 clarinets and bass clarinet	Chamber Music	Arranger's manuscript	Quartets for 2 violins, viola, and cello op. 18 NN 1 and 5. Arrangement for the quartet of wind instruments
1830	unknown	Hebestreit **Kassel**	Performance tour with clarinet and the new Streitwolf bass clarinet	Chamber Music	Article by Heinroth on the Streitwolf instrument	Bassoon-form bass clarinet by Streitwolf
1830 14 January	Deichert?	Deichert **Kassel**	Trio	Chamber Music	Contemporary AMZ report	
1836	Sigismund Ritter von Neukomm	Thomas Lindsay Willman **London**	*'Make haste, O God, to deliver me'* for alto voice, bass clarionet concertant and string quartet	Chamber Music	Manuscript score Concert Programme	Bassoon-form bass clarinet probably by George Wood
1836	Giacomo Meyerbeer	Dacosta **Paris**	*Les Huguenots*	Opera Obbligato	Manuscript and printed score	Straight-form bass clarinet by Louis-Auguste Buffet
1838	Hector Berlioz	**Paris**	*Benvenuto Cellini*	Opera	score	Straight-form clarinet by Sax

1838	Gaetano Donizetti	unknown **Venice**	*Maria de Rudenz*	Opera	Manuscript	
1840	Johann Friedrich Diethe	unknown	*Romanze* for solo bass clarinet plus 2 ob., 2 cl,. 2 bn., 2 hn.	Chamber Music	Manuscript c.1840 and print version 1903	Bassoon-form bass clarinet is likely (Streitwolf?)
1840	Saverio Mercadante	Catterini **Venice**	*La solitaria della Asturie*	Opera incl. stage solo	Manuscript	Bassoon-form bass clarinet ('glicibarifono') by Catterini ?
1842	Hector Berlioz	**Paris**	*Grand Symphonie Funèbre et Triomphale*	Orchestral	Printed score	Straight-form clarinet by Sax. Two bass clarinets.
1843	Gaetano Donizetti	**Paris**	*Dom Sébastien, Roi de Portugal*	Opera		Two bass clarinets
1843	Hector Berlioz	**Paris**	*Chant Sacré*	Arrangement for chorus and chamber ensemble		
1844	Giacomo Meyerbeer	**Berlin**	*Ein Feldlager in Schlesien*	Opera		
1844	Giuseppe Verdi	**Venice**	*Ernani*	Opera	Printed score and manuscript	Bass clarinet in C (with the note C2 written in one bar)
1844	Michael W. Balfe	**London Drury Lane** J. H. Maycock	*The daughter of St. Mark*	Opera, solo in overture and before one aria	Interview in *The Musical Herald* and score	Bassoon-form instrument, maker unknown, probably from Paris.
1846	Hector Berlioz	**Paris**	*La Damnation de Faust*	Orchestral	Printed score	Straight form by Sax
1849	Hector Berlioz	**Paris**	*Te Deum*	Choral and orchestral	Printed score	Straight form by Sax
1843-45	Richard Wagner	**Dresden**	*Tannhaüser*	Opera	Printed score	Probably straight form
1846-48	Richard Wagner	**Weimar**	*Lohengrin*	Opera, (including prominent solos)	Printed score	Straight form, possibly by Johann Adam Heckel incl. bass in A
1851-52	Ferenc Liszt	**Weimar**	*Mazeppa*	Tone Poem	Printed score	Bass clarinet in C

Before 1846	L. Pacini Pasquale Riva and/or Vincenzo Lodini	**Persiceto, Bologna**	*Sinfonia* from *il Falegname Livonia*	Sinfonia from opera	List of works including glicibarifono in Persiceto archives	Catterini-type glicibarifono made by Giacinto Riva of Persiceto
1849 (January)	Meyerbeer John Henry Maycock	**Dublin**	Themes from *Les Huguenots* arranged for trio of oboe (Barret), bass clarinet (Maycock) and ophicleide (Prospere)	Chamber music, arrangement from opera.	Review in *The Musical World*	Bassoon-form instrument, maker unknown, probably from Paris.
1849	Luigi Maria Viviani	**Florence**	*Il Fausto* Act V	Ballet	Manuscript score	Ophicleide form (bimbonclaro)

Chapter 4

Extant bassoon-form bass clarinets

Many large musical instrument museums will be found to contain examples of instruments in one of the bassoon-form clarinet types discussed in Chapter 2. The starting point of the research for this thesis was to discover as many of these as possible and to enter them in a database. Altogether, 88 clarinet-type instruments in bassoon-form were found. Most were bass clarinets, but there were twelve of other types including the usual soprano clarinets, alto clarinets, basset horns and contrabass clarinets. However, only bass clarinets were studied in detail. The database only includes instruments that survive, at least in fragmentary form, since a primary objective of the whole research is to emphasize the evidence of the extant instruments.

Sources of information, basis of classification and the database

Before this study, information was limited to secondary sources such as monographs and theses on the clarinet or wind instruments.[1-4] None of these contained as many as half of the bassoon-form instruments listed in this chapter. The online MIMO catalogue of instruments in European museums and the RCM collection of museum catalogues were major sources. [5-9]

Where possible these were then checked against museum catalogues and checklists or by correspondence, to verify that they were still in place, since about a dozen instruments have been lost through theft or war. Only those catalogues that contain bass clarinet entries are listed in the bibliography. A few were added from private collections and from visits to museums. [10]

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[1] Albert R. Rice, *From the Clarinet D'amour to the Contra Bass*. 249-324.

[2] Dullat, *Klarinetten*, 73-95 and 157-241.

[3] Erich Tremmel, *Blasinstrumentenbau Im 19. Jahrhundert in Südbayern.* Augsburg: Wißner, 1993. 465-467

[4] Charles Albert Roeckle, 'The Bass Clarinet – an Historical Survey' Master's thesis, University of Texas, Austin, 1966, 64-162.

[5] see list of museums visited, Chapter 1.

[6] I thank Albert Rice for our mutual agreement to share information and images on bassoon-form instruments.

[7] ICOM. 'The MIMO Project: Musical Instrument Museums Online'. https://icom.museum/en/ressource/themimo-project-musical-instrument-museums-online/ accessed 22 November 2020.

[8] Jean Jenkins, ed. *International Directory of Musical Instrument Collections.* Buren: ICOM, 1977.

[9] Herbert Heyde, *Musikinstrumentenbau in Preußen.* Tutzing: Schneider, 1994. 529-545.

[10] Bär, *Verzeichnis Der Europäischen Musikinstrumente in GNM Nürnberg.* Band 6. 214-263; University of Edinburgh, Musical Instrument Museums, collection search. https://collections.ed.ac.uk/mimed. Accessed 26 October 2021; Anon. *Catalogue of the Conservatoire National de Paris.* [n.p.], 1875; Anon. 'Catalogue of the Collection'. New York: Metropolitan Museum of Art, 1904; Anon. *Museo Degli Strumenti Musicale Catalogo Castello Sforzesco.* [n.p], [n.d]; Luisa Cervelli, *La Galleria Armonica: Catalogo Del Museo Degli Strumenti Musicali Di Roma*. Rome: Istituto Poligrafico, 1994; R. Meucci, E. Falletti and G. Rossi Rognoni, Florence, Eds. *'Per La Lettura Dalla Schede e Catalogo.'* In E. Falletti, R. Meucci, and Gabriele Rossi Rognoni, Eds. *La Musica e i Suoi Istrumenti. 1. La Collezione Granducale Del Conservatorio Cherubini.* Florence: Giunta (2001); Mario Fabbri, Vinicio Gai and Leonardo Pinzauti, *Antichi Strumenti: Collezioni Dei Medici e Del Lorena, Firenze,*

The data that were stored for each instrument are as follows:

1. Maker's name, in the form listed in the New Langwill.[11]
2. Maker's City, if known. The latitude and longitude of this location are also stored in the database to enable the mapping of geographical distributions.
3. Contemporary state of maker's city at the time of making.
4. Current location (city) of instrument.
5. CIMCIM museum or collection sigil.[12]
6. Museum or collection accession number.
7. Approximate date of manufacture, taken from museum records or publications.
8. Instrument type: Bass, basset horn, alto, soprano.
9. Tonality of instrument.
10. Lowest note on instrument.
11. Number of keys.
12. Material of bell.
13. Diameter of bore in major parallel region, mm.
14. Material of body, where known.
15. Military or other ownership stamp if present.
16. Source(s) of information.
17. Notes (museum and other descriptive notes).

In its full form, the database includes the available images of the instrument and check boxes to note whether the instrument has been examined and/or measured in detail.

Item 3, the contemporary states of the makers, needs some more explanation due to the complex political changes in the nineteenth century and since; indeed this account is necessarily highly simplified.

- The UK, USA, France, Austria, Belgium and Russia have all retained their historic names though boundaries have changed, sometimes drastically, and some kingdoms or empires have turned into republics.

Palazzo Vecchio Florence: Giunti-Barbera, 1981; Guido Bizzi, 'La Collezione Di Strumenti Musicali Del Museo Teatrale Alla Scala,' in *Milan: Silvana Editoriale*, 1991; Heinrich Seifers, *MusikInstrumente Katalog Der Bläsinstrumente.* München: Deutsches Museum, 1980; Anon. *Gli Strumenti Musicali Nel Museo Del Conservatoire Di Milano* (Milano: Ulrico Hoepli, 1908); Nicholas Bessaraboff, *Ancient European Musical Instruments in the Museum of Fine Arts, Boston.* Boston: Harvard University Press, 1941; Anon. *Museum Für Hamburg Geschichte.* Hamburg: Ulster-Verlag, 1930; Anon. *Ausstellung Bayerischen Nationalmuseum München.* [n.p.], 1951; Paul Rubardt, *Führer Durch Das Musikinstrumentem-Museum Der Karl-Marx Universität Leipzig* Leipzig: Breitkopf u. Härtel, 1955; Karl Nef, *Katalog Der Musikinstrumente Im Historischen Museum Zu Basel*. Universität Basel, Mittelalterliche Sammlung, afterwards Historisches Museum. In: Festschrift zum Zweiten Kongress der Internationalen Musikgesellschaft, 1906; Philip T. Young, *Die Holzblasinstrumenten Im Oberösterreichischen Landesmuseum.* Linz: Land Oberösterreich/OÖ. Landesmuseum, 1997; Günter Dullat, *400 Jahre Musikinstrumentenbau in Graslitz, Katalog zur Somderausstellung im Heimatmuseum Nauheim*. Nauheim: Heimat= und Museumsverein Nauheim e.V., 2014.

[11] Waterhouse, *The New Langwill Index*.

[12] 'Sigla for musical instruments collections', https://cimcim.mini.icom.museum/wp-content/uploads/sites/7/2020/05/Sigla-for-Musical-Instrument-Collections.pdf accessed 5 November 2021

- The Austrian Empire, 1804 – 1867, was created by proclamation in 1804. It was based on the Habsburg (or Hapsburg) monarchy and empire which evolved and grew from the thirteenth century. The Empire exercised dominion over the Czech lands of Bohemia and Moravia, the Kingdom of Lombardy-Venetia and the semi-independent Kingdom of Hungary and was allied with the Grand Duchy of Tuscany.
- In 1867, the Austrian Empire merged with the Kingdom of Hungary to become Austria-Hungary, but with the loss of the Italian duchies and kingdoms. Austria-Hungary was dissolved in 1918.
- The other states listed in the database are those existing after the defeat of Napoleon in 1815, and before the unifications of Italy and of Germany, which both culminated in 1871. In the unification of Italy, the Italian kingdoms and duchies and the Papal States merged (by agreement, annexation or rebellion), and ended the Austrian hegemony to form the Kingdom of Italy.
- In Germany, the powerful Kingdoms of Prussia, Saxony and Bavaria joined with the Duchy of Saxe-Weimar-Eisenach, the Rhenish Palatinate, the Electorate of Hanover, Hesse-Darmstadt, and a number of smaller states, largely by negotiation and agreement, to form the German Empire under the leadership of Prussia. However, note that throughout the nineteenth century, the German Confederation (including Austria) encouraged collaboration and cooperation throughout the German (speaking) lands.

Choice of the platform for the database was determined by practicality. Although the Microsoft 365 office system is provided by the RCM, the version for Apple Mac computers, which I personally use, does not include the popular Access database. No facilities were available for cloud-based use of Access. Accordingly, the Tap Forms database for the Mac systems was used. This contains all the features needed, including image fields, large text fields and a mapping facility allowing simple acquisition of latitude and longitude data and the display of geographic distribution maps.

An Excel spreadsheet exported from the full Tap Forms database (including the geographical data) is given in the digital files accompanying this thesis and also in the RCM repository. A condensed printout of the latest version is reproduced in Appendix E (for convenience placed at the end of the thesis) to give easy reference to all the instruments found. In order to fit on the pages, some fields have been omitted from this printout, as explained in Appendix E.

Geographical and territorial distributions

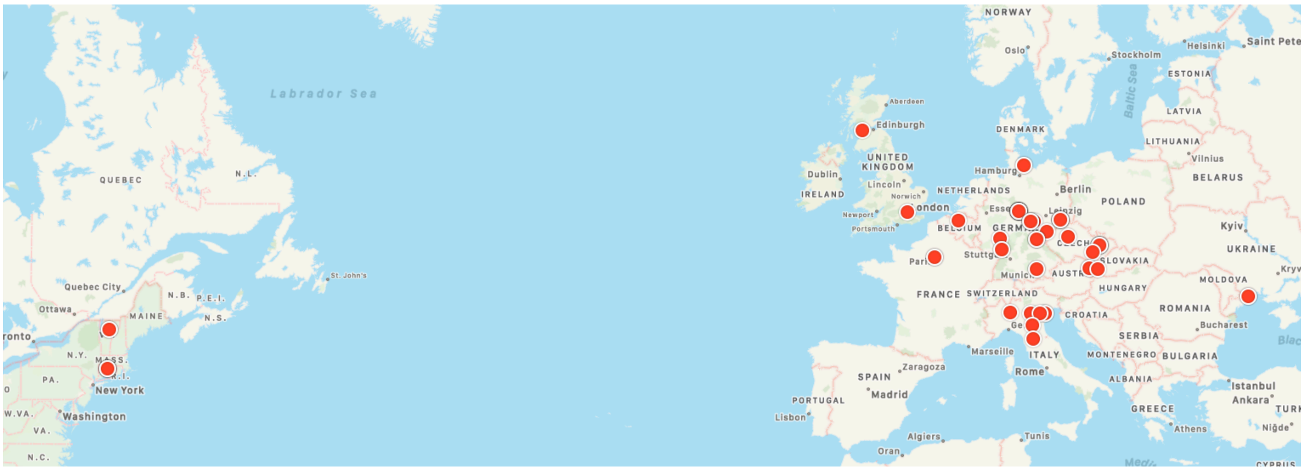

Figure 4.1. Global distribution of known makers of bassoon-form bass clarinets.

The global and European distribution of makers are shown in Figures 4.1 and 4.2. They stretch from the USA to the Ukraine. The American group in New England arose from one maker and his collaborators, George Catlin of Hartford, Connecticut,[13] who independently invented and made quality bassoon-form instruments before any European maker other than the Grensers. Sadly, no tradition was established and his instruments died out with the passing of this group of eight or nine makers. The Ukraine, then in the Russian Empire, is represented by a single maker, Josef Schediwa, who trained in Bohemia and emigrated to Odessa in 1881. However, no information was discovered about any instruments in museums or collections to the east of the Czech Republic and there may well be undiscovered instruments from makers in those countries, especially in the former Russian Empire.

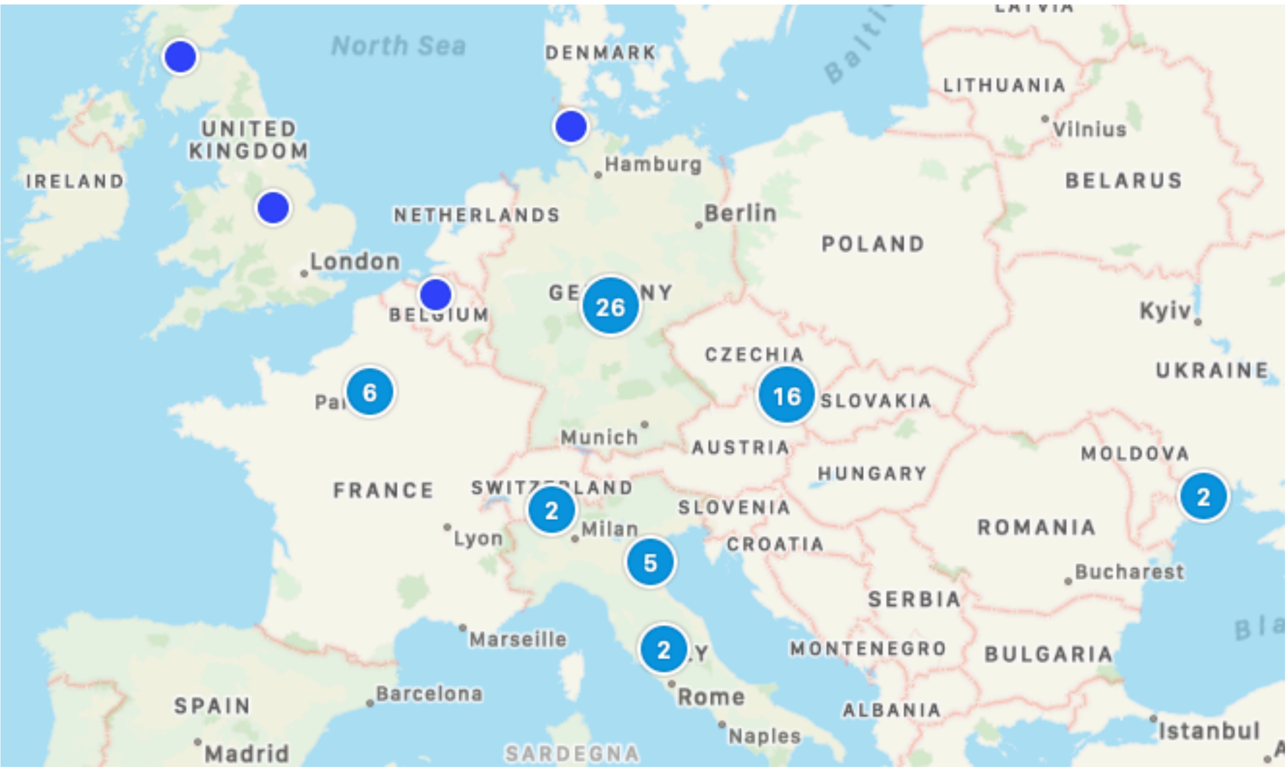

Figure 4.2. European distribution of surviving bassoon-form bass clarinets, showing the total number of instruments that survive from the maker or makers in that location. Markers without a number represent a single maker, and where the city is not known, the marker is placed centrally in the country (e.g. England).

The main centres of invention and manufacture of these instruments were those in Germanic regions as well as areas on the Italian peninsula.[14] Whilst these boundaries do not correspond to current political regions, they were fairly stable in the period between the end of the Napoleonic Wars in 1815 and the unifications of Germany and Italy in 1871. These are shown on the maps in Figure 4.3 and Figure 4.4, noting that there were changes even during this period.[15]

[13] Third cousin once removed of the famous American painter of the same name.

[14] See also the detailed maps of woodwind makers in Central Europe in the inside covers of Waterhouse, *New Langwill Index*.

[15] 'Political Map of Germany, 1815-1868' https://commons.wikimedia.org/wiki/File:Deutscher_Bund.svg accessed January 15, 2021; 'Political Map of Italy 1843' https://commons.wikimedia.org/wiki/File:Italy_1843_de.svg accessed January 15, 2021.

Figure 4.3. Political divisions in Germany during the period 1815 – 1868. Note especially: Kaiserreich Österreich, the Austrian Empire; Königreich Bayern, the Kingdom of Bavaria; Kgr. Sachsen, the Kingdom of Saxony; and Lombardo-Venezien, the Kingdom of Lombardy-Venetia (subject to Austria).

A comparison of the distributions of instruments in Figure 4.2 with the political divisions shown in Figure 4.3 shows immediately that the contiguous states of the Austrian Empire (including the Czech Lands and Lombardy-Venetia) and the Kingdoms of Saxony and Bavaria made by far the largest contribution to the invention and development of the bassoon-form clarinet-family instruments, judging by the instruments remaining in museums; 50 of the 88 found are from these states. The Italian Peninsula is shown in more detail in Figure 4.4.

Figure 4.4. Political divisions in Italy in 1843

The northern Kingdom of Lombardy-Venetia, subject to the Austrian Empire, is well represented with makers from Venice, Padua, Verona, Milan and two anonymous instruments probably from the same kingdom (see chapter 7). There is one other maker just over the border in the Papal States. Judging from reports of concerts discussed in the major musical magazines, some of which are discussed in Chapter 3 in connection with players and repertoire, these states not only had an active musical life especially in opera, but enjoyed good opportunities for musicians to travel. News of musical inventions would travel quickly across this region, a sort of Freedom of Travel zone of its time.

The database also allows us to understand more about the territorial distributions of instrument makers, through the recognition of the contemporary names of the states. Table 4.1 lists the makers under their contemporary states, which stretch from New England, USA to Odessa in the Ukraine. Note the concentration of makers in the central European states and the Austrian Empire.

United Kingdom of Great Britain and Ireland	*Key, Douglas*
United States of America	*Catlin, Miner, Marsh, Chase, Fischer, Bacon*
Kingdom of France	*Buffet, Martin Frères, Widemann*
Kingdom of Belgium	*Tuerlinckx*
Duchy of Saxe-Weimar-Eisenach	*Beck*
Rhenish Palatinate	*Berthold*
Kingdom of Saxony	*Grenser H. Grenser A, Golde, Liebmann*
Kingdom of Bavaria	*Stengel, Ottensteiner*
Kingdom of Prussia	*Skorra, Wiepricht, Kruspe*
Electorate of Hanover	*Streitwolf*
Hesse-Darmstadt	*Seidel*
Austrian Empire (Austria, Bohemia, Moravia plus North Italy)	*Pauer, Tomschik, Losschmidt, Ludwig & Martinka, Lempp F, Lempp M, Rott, Uhlmann, Nechwalsky*
Kingdom of Lombardy-Venetia (subject to the Austrian Empire)	*Maino, Catterini, De Azzi, Chiesara, Ghirlanda*
Grand Duchy of Tuscany (allied with the Austrian Empire)	*Bimboni*
Papal States	*Riva*
Russian Empire (Ukraine)	*Schediwa*
Swiss Confederacy	*Seelhoffer*

Table 4.1. The makers of bassoon-form bass clarinets, listed under the contemporary states of their workplaces.

Concluding remarks

The normal descriptions of instruments that appear in texts, such as pitch, range of notes, number of keys are included in the database, where known, and form a ready reference. Where possible, bore diameters have also been included since the acoustic work reported later showed that this parameter has greater importance than has normally been appreciated. The inclusion of geographical information has illuminated the growth and spread of the bassoon-form bass clarinet from its mid-European beginnings. The high culture of the large Austrian Empire was clearly important but not dominant; it did not inhibit the growth of makers and inventions in the neighbouring Kingdoms of Prussia, Saxony and Bavaria. Although France appears to be under-represented on the European map, it must be remembered that the influence of Adolphe Sax with his innovative design of the large-bore straight bass clarinet in 1838 rapidly became dominant in France and Belgium, and later the UK. Sax's straight-form designs took over throughout Europe as the only design of bass clarinet for Art music from about 1850; they were made with narrower and less flared bores in Germany, a tradition that continues to the present day. Bassoon-form instruments with stamps indicating military ownership appear on high quality instruments by Ottensteiner (1869) and Berthold (fl. 1850 – 1900)[16] and half-bassoon form instruments are found as late as 1914. This suggests that bassoon-form bass clarinets were used in military bands in Germany and elsewhere some 50 years longer than their use – in Germany and elsewhere – in Art music.

[16] The stamp 'J.R.' for 'Jägerregiment' indicates military ownership (Ezster Fontana, private communication).

Chapter 5

The acoustics of woodwind instruments

The most important method used in this project to discover the sound qualities of historic instruments was the careful geometric measurement of a number of historic instruments and the calculation of their input impedances (internal resonances) by means of computer modelling and simulation. The modelling of complex physical situations is a field that has shown enormous development in recent years in many scientific and technological fields, and computer languages are now even designed to facilitate this application. MatLab™, used in this project, is one such language. The principle upon which the main methodology of this thesis is based is therefore that *the acoustic properties of a wind instrument are dominated by the shape of its air column.*

This obviously needs justification. Woodwind and brasswind instruments are in general very much simpler to model than string instruments. Whilst it is easy to model the pitch of string instruments, the details of sound formation involve interaction with complex materials (wood, varnish, bow hair, fingers) in complex shapes, the fine details of which certainly influence the sound. Although some significant insights are possible, a useful mathematical and computational description of the full resonances of a complete instrument such as a violin has yet to be achieved, partly through the variability in properties of natural materials, partly through the difficulty of the modelling and partly through the uncertainty as to which properties are actually significant. The artisan is well ahead of the technologist at present.

There are, and probably always have been, endless arguments about the influence of materials on a wind instrument. A useful summary is provided by Bret Pimentel[1], who points out that makers, players and historians have generally felt, on purely subjective grounds, that materials are very significant in the tone of the instrument.[2,4] However, scientists conducting rigorous experiments have insisted that, in the case of essentially circular woodwind instruments, by far the most important factor is the detailed shape of the air column, with small effects arising from the roughness and porosity of the tube wall, from the compliance of the pads and from shading effects of the keys.[5,6] The reason is that for the stiff materials and the circular geometry used, the resonant frequencies of the air column and of the tube material are several orders of magnitude apart, meaning that the coupling between these vibrations is very small

[1] Bret Pimentel, 'Does Material Affect Tone Quality in Woodwind Instruments?: Why Scientists and Musicians Just Can't Seem to Agree,' Bret Pimentel, Woodwinds (blog). https://bretpimentel.com/does-material-affect-tone-quality-in-woodwind-instruments-why-scientists-and-musicians-just-cant-seem-to-agree/ accessed March 1, 2007.

[2] e.g. Theobald Boehm. *Die Flöte Und Das Flötenspiel (The Flute and Flute Playing in Acoustical, Technical and Artistic Aspects)*. Munich: J. Aibi, 1871, 53-56.

[3] e.g. F. Geoffrey Rendall, *The Clarinet: Some Notes on Its History and Construction*. 11-15.

[4] e.g. Anthony Baines, *Woodwind Instruments and Their History*, 117.

[5] A. H. Benade, *Fundamentals of Musical Acoustics*, 2nd. Edition. Oxford: OUP 1976. Corrected edition New York: Dover, 1990, 499-501.

[6] Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments.* 2nd Edition. New York: Springer, 2010. 717 ff.

indeed. It has been established conclusively that *at least* 99% of the energy emitted by an instrument arises from the air column vibration and that the body vibration of an instrument is inaudible at *c.*25 mm from the instrument.[7] Detailed measurements and comparisons on flutes have shown that neither the player nor the audience can distinguish between flute tubes made from silver, copper and grenadilla if played with the same headjoint in a double blind experiment.[8] It appears that many materials can be made into an excellent instrument, at least provided that they have a reasonably high density and have low and uniform ('diffuse') porosity.[9] This conclusion does not exclude that there may be a somewhat more significant effect on the sensations experienced by the player, felt largely through bone conduction via the teeth. One would expect this to be more noticeable in clarinets than in other woodwinds (especially flutes) because of the way in which the embouchure is connected to the instrument body. There are also more recent studies that conclude that there is a just-measurable difference between the acoustical behaviour of different materials in the vibration of the walls.[10]

Such differences between materials, if any there be, are unlikely to be recoverable from tests or measurements on historical instruments. Their materials will have changed very substantially in acoustical properties from long storage, loss of water content, and other irreversible changes on ageing.[11] This thesis will therefore only consider the >99% of the acoustic energy that arises from vibrations of the air column, but will show that the results correlate well with a detailed study on an actual historical bass clarinet (see Chapter 6).[12]

Likewise, all players know the importance of the mouthpiece and the reed in the playability of the instrument, but as long as the volume of the mouthpiece is chosen so as to preserve the intonation, the effect on the *sound* perceived by a listener is perceptible but secondary.[13] Indeed, a clarinet-type mouthpiece of suitably small volume works reasonably well on an oboe, and the instrument sounds like an oboe not like a clarinet.[14,15] An example is the 'alto fagotto' instrument in the RCM Museum,[16] a conical bore instrument with mostly clarinet keywork and a small clarinet-type mouthpiece. This appears to be an alto bassoon (or possibly cor anglais) designed for use by a clarinettist. On the other hand, we know that a cylindrical

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7 John Backus, 'Effect of Wall Material on the Steady-State Tone Quality of Woodwind Instruments,' *J. Acoust. Soc. Am.* 36 (1964) 1881–87,. https://doi.org/10.1121/1.1919286

8 John W. Coltman, 'Effect of Material on Flute Tone Quality,' *J. Acoust. Soc. Am.* 49 (1971) 520–23. https://doi.org/10.1121/1.1912381

9 From personal discussions with the instrument maker Daniel Bangham.

10 e.g. R.A. Smith and D.M.A. Mercer, 'Possible Causes of Woodwind Tone Colour,' *Journal of Sound and Vibration* 32 (1974) 347-358. https://doi.org/10.1016/S0022-460X(74)80090-8; Guillaume Nief, François Gautier, Jean-Pierre Dalmont, and Joël Gilbert, 'Influence of Wall Vibrations on the Behavior of a Simplified Wind Instrument,' *J. Acoust. Soc. Am.* 124 (2008) 1320–31. https://doi.org/10.1121/1.2945157

11 See the discussion in Chapter 1 in the section *Playing an original instrument*.

12 Bowen et al. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played.'

13 A. H. Benade, 'On Woodwind Instrument Bores,' *J. Acoust. Soc. Am.* 31 (1959) 137–46. https://doi.org/10.1121/1.1907682 . Corrected version in E.L. Kent (ed.), *Musical Acoustics: Piano and Wind Instruments*, vol. 9 of *Benchmark Papers in Acoustics*, pp 274-283. Dowden, Hutchinson and Ross, 1977.

14 Arthur H. Benade, *Horns, Strings and Harmony*. New York: Anchor, 1960, 200.

15 Sandra Carral, Christophe Vergez, and Cornelis Nederveen, 'Toward a Single Reed Mouthpiece for the Oboe,' *Archives of Acoustics* 36, (2011), 267-282,). https://doi.org/10.2478/v10168-011-0021-0

16 GB.L.cm.456

bore activated by a double reed overblows a twelfth like a clarinet: this is the structure of the crumhorn, which is not normally overblown, but if forced will overblow a twelfth.[17] The mouthpiece or reed does not define the instrument, but the air column, in combination with some sort of reed generator, does. If we can understand the influence of the detailed shape of the air column on the sound production, for all notes and all relevant frequencies, we shall know a great deal about the nature of the instrument. Furthermore, this knowledge is objective and not subject to the physiology or prejudices of any player.

This realisation was one of the key insights of Adolphe Sax in formulating his Law of Proportions, quoted by Berlioz in 1842:

> The timbre of an instrument is determined by the proportion of the column of air rather than by the substance from which the instrument is made[18]

It appears that Sax formulated this law sometime in the mid to late 1830s and certainly by 1839. He does not appear to have published it himself, but is quoted by Fétis in the first edition of his Biographie.[19] He discussed the topic with Sax himself and gives this interesting account:

> for a long time Sax had been preoccupied with the need to reduce the construction of wind instruments to a general and positive theory from which all improvements would follow … The difficulty was great, because until now physicists have left this part of science in an imperfect state. The revolution of September 1830, by shutting down his workshops for some time, left him the necessary leisure to meditate on this important subject. Finally, a sudden enlightenment made him find the infallible law with the help of which he divides the sound bodies, and measures the column of air contained in the tubes. From then on he was able to give the tubes proportions relative to the amount of air they must contain …[20]

Sax also communicated his theories to the eminent physicist Félix Savart, who reported on the French exhibition of 1839 at which Sax exhibited. Fétis quotes Savart's report as follows:

> Mr. Sax discovered the laws that no acoustics treatise could teach him; for it must be admitted, the learned works of Bernouilli, of d'Alembert, of Euler, and even of Lagrange were of little use to instrument making. Their theories of sound and their calculations could never guide him in the boring of extracylindrical tubes.[21]

This is very high praise, in view of the eminence of the authors cited by Savart. These were among the most distinguished scientists and mathematicians of the eighteenth and early nineteenth centuries and their works are still used and respected amongst scientists. They had also made specialised studies of musical acoustics; d'Alembert was the first to solve the wave equation fundamental to all musical acoustics.[22] Fétis further remarks that an acoustic demonstration was made by Sax's father, the instrument maker Charles-Joseph Sax. Reportedly, he made a flute by drilling large toneholes in a tube at the positions dictated by the Law of Proportions, simply using a compass for the division. Savart was impressed that these played well in tune without cross-fingerings or any fine tuning of the positions of the

[17] 'Crumhorn | Musica Antiqua.' https://www.music.iastate.edu/antiqua/instrument/crumhorn accessed November 20, 2020.
[18] Quoted by Berlioz, 'Instrumens de musique.' 1842.
[19] Fétis, *Biographie Universelle Des Musiciens*. Supplément et complément, 1844, 54-57.
[20] Fétis, 56.
[21] Ibid.
[22] Jean le Rond D'Alembert, 'Recherches Sur La Courbe Que Forme Une Corde Tenduë Mise En Vibration,' *Histoire de l'académie Royale Des Sciences et Belles Lettres de Berlin* 3 (1747) 214–19.

holes. This prefigures and predates by a few years the Theobald Boehm patent of 1847; but in his text book of 1871, Boehm himself states that he determined the positioning of the (large) holes empirically, not by theory.[23] In view of Berlioz's remarks in 1842 on the precision of intonation and correct acoustic positioning of holes in the Sax bass clarinet, announced in 1838, it seems likely that Sax formulated the rule before he developed his bass clarinet.

Note, however, that the principle of the *dominant* effect of the wind column applies only to reed instruments and, with some modifications, to flutes and recorders. Input impedances are also important in brasswinds, but they operate slightly differently, in that the 'reed' (the lips) open up as the player increases the pressure, in contrast to the reed instruments, which close down as the mouth pressure is increased above a certain level.[24] Whilst this seems to be a minor difference, it reduces radically the stable range of pressure in which oscillation may be maintained.[25] As a consequence, brass instruments are much more sensitive to mouthpiece design and construction, and to the skills of the players with their embouchure, than are the woodwinds. This is not to say that clarinet mouthpieces are unimportant, but that they are much less important than the rest of the instrument so far as the pitch, intonation, temperament and timbre are concerned.

The aim of the acoustical investigations in this thesis is therefore to model, by computer simulation, the most important parts of the acoustic behaviour of a bass clarinet in order to draw conclusions about its behaviour purely from its measurements. More importantly, this opens up most of the instruments in museums to organological study with little risk of damage. The methodology therefore involved the development of a computer tool incorporating accurate acoustical equations to perform this modelling.

Acoustics is a very large, diverse and complex subject spanning physics and engineering and requires considerable mathematical skill to develop. The subject dates back to the classical period, with Aristotle discussing aspects of harmony in *Metaphysics*, (350 BCE). Marin Mersenne was the first to measure and formulate the laws concerning the vibration of strings, and the first to determine the actual frequency of a musical tone and is often spoken of as 'the father of acoustics'.[26] Vibration in tubes and the nature of wind instruments were not considered in such detail until the nineteenth century, and as discussed above, Adolphe Sax's *Law of Proportions* must be considered a milestone equivalent to that of Mersenne. In the mathematical theory there were pioneering contributions, summarised in the books by Lord Rayleigh[27] and especially by Helmholtz. These authors were mostly concerned with the mathematical understanding of sound waves and how to formulate and solve the complicated equations that result from the mathematical description. Rayleigh considers vibrations in

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[23] Theobald Boehm, The Flute and Flute Playing in Acoustical, Technical and Artistic Aspects. 16.

[24] To clarify, the role of the mouth pressure is to select the operating point on the curve describing the mouthpiece pressure variation, seen in Figure 5.2. It is the sinusoidal variation of the pressure waves that actually causes the reed to close. Thus the mouth pressure is the controlling parameter; the lip pressure also plays a role in that the higher the lip pressure, the lower is the blowing pressure for closure to occur.

[25] Murray Campbell and Clive A. Greated, *The Musician's Guide to Acoustics*. Oxford: OUP, 1994. 259 ff. 304 ff. ; Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments (2nd Edition)*, 401 ff.

[26] Marin Mersenne, *Harmonie Universelle*. Paris: Sebastien Cramoisy, 1636.

[27] J. W. (Baron Rayleigh) Strutt, *The Theory of Sound.* London: Macmillan and Co, 1877; Helmholtz, 'On the sensations of tone'.

tubes but only discusses stringed instruments in detail. However, Helmholtz treated pipe vibrations and both woodwind and brasswind instruments in considerable detail. He correctly deduced the different behaviours of (heavy) metal, (light) cane and lip 'reeds'; he formulated the resonances of both cylindrical and conical pipes; and correctly calculated the wavelengths of harmonics generated by clarinets, oboes, bassoons, flutes, organ pipes and brasswinds.[28] The field has burgeoned since the early 20th century, commencing with the pioneering work of Bouasse.[29]

I have not developed any original acoustical equations or methods in this research. My method is to select the best models from existing theory to apply to acoustic modelling of bass clarinets. In this chapter I shall describe the state of knowledge of tone production in reed instruments and in particular in the clarinet family, and identify the key properties that need to be calculated for this approach to succeed. In the following chapter, I shall critically identify and review the most recent and reliable of the models and equations that have been developed for various aspects of the acoustic calculations and shall show how they have been incorporated in a new and efficient computer implementation in MatLab™. I shall also describe the extensive research carried out to test this program, employing an historical instrument that could be measured both dimensionally and acoustically, and which could be played. The computer program then became an organological tool for investigating the musical properties of instruments that one can only measure and not play. It is also a powerful tool for the design or modification of woodwind instruments in general. The acoustical work has been published in a conference and in the peer-reviewed scientific literature together with collaborators at the Open University, where the acoustic measurements were performed.[30]

Introduction to the concepts of woodwind acoustics

The primary texts used for this section are Benade, Backus, Campbell and Greated, Fletcher and Rossing, Chaigne and Kergomard and Nederveen,[31] supplemented by the papers or theses by Keefe and Worman on the issues and methods of modelling the reed-driven instrument.[32] Many other books and articles have also been consulted, as listed in the Bibliography and

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[28] Helmholtz, 'On the sensations of tone'. 99 and Appendix VII (388-397).

[29] H. Bouasse, *Instruments à Vent (Vols 1 and 2)*. Paris: Libraire Delagrove, 1929.

[30] D. Keith Bowen, Kurijn Buys, Mathew Dart and David Sharp. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played,' *Applied Acoustics* 143 (2019) 84–99. https://doi.org/10.1016/j.apacoust.2018.08.028

[31] Benade, *Horns, Strings and Harmony*; ______, *Fundamentals of Musical Acoustics*; John Backus, *The Acoustical Foundations of Music*, 2d ed (New York: Norton, 1977); Campbell and Greated, *The Musician's Guide to Acoustics;* Fletcher and Rossing, *The Physics of Musical Instruments (2nd Edition)*; Antoine Chaigne and Jean Kergomard, *Acoustics of Musical Instruments (1st English Edition)*. New York: Springer-Verlag, 2016; C.J. Nederveen, *Acoustical Aspects of Woodwind Instruments (Revised Edition)*. Dekalb, IL: Northern University Illinois Press, 1998.

[32] D. H Keefe, 'Theory of the Single Woodwind Tonehole,' *J. Acoust. Soc. Am.* 72 (1982) 676–87. https://doi.org/10.1121/1.388248; D. H. Keefe, 'Experiments on the Single Woodwind Tonehole,' *J. Acoust. Soc. Am.* 72 (1982) 688–99. 99. https://doi.org/10.1121/1.388249; D. H. Keefe, 'Acoustical Wave Propagation in Cylindrical Ducts: Transmission Line Approximations for Isothermal and Non-Isothermal Boundary Conditions,' *J. Acoust. Soc. Am* 75 (1984) 58–62. https://doi.org/10.1121/1.390300; D. H. Keefe, 'Woodwind Design Algorithms to Achieve Desired Tuning,' *J. Catgut Acoust. Soc.* 1, no. 3 (1989) 14–22; D. H. Keefe, 'Woodwind Air Column Models,' *J. Acoust. Soc. Am.* 88 (1990) 35–51. https://doi.org/10.1121/1.399911; Walter E. Worman, 'Self-Sustained Nonlinear Oscillations in Clarinet-Like Systems.' PhD thesis, Case Western Reserve University, Cleveland, Ohio, 1971.

referenced where appropriate. An acoustics glossary may be found to be useful, as may an online course in musical acoustics provided by the University of New South Wales.[33]

I shall approach an understanding by giving first a basic description of a musical instrument and then describing what happens in the generation of a tone in a woodwind instrument. The description applies equally to clarinets, oboes, bassoons, crumhorns and bagpipes and with some modification to flutes and recorders.

The production of sound in any musical instrument involves an *oscillator* and a *resonator*: reed and air column, string and soundbox, vocal chords and vocal tract, hammer/string and soundboard, lip/mouthpiece and air column. Except in electronic instruments, the resonator does not amplify the sound at all (this point is often misunderstood). However, it resonates at certain specific frequencies (pitches), emphasizes these in the characteristic timbre of the instrument and sums the energy over a certain time interval to increase the perceived volume.

What exactly happens in a resonator? If we pluck a violin, guitar or piano string in free space, the sound is weak and short-lived. Once it is attached to a suitable soundboard, however, it appears louder and has a distinctive character. The soundboard begins to vibrate, in forced vibrations arising from energy injected by the string, at frequencies corresponding to the vibrations of the string. The amplitudes of vibration of the soundboard are determined by its dimensions, density and elasticity; hence its influence on the musical timbre. While the vibration of the string is dying away it is still injecting energy into the soundboard. This process accumulates energy, over a short period of time, in the soundboard's vibrations, and hence the sound radiated is louder than that of a bare string. The effect is enhanced still further if a soundbox is attached to the sound board, since vibrations now accumulate in the air of the box as well. The effect is enhanced in a resonant room, in which sound energy accumulates, compared to the open air or, in the limit, an anechoic chamber. Eventually the sound dies away due to damping (loss of elastic energy to heat) in the materials of the string, soundboard and soundbox and the instrument itself, and in the air or the walls and furnishings of the room. In a wind instrument, the air column of the instrument is the resonant body and the resonant frequencies are determined by its length, its bore and by the disruptions of the tone holes.

There is no physical law that states that the modes of vibration from a resonator must be in a musical concord. They are determined through the shape of the soundboard for, say, a harp or violin, but in, a Turkish Clash they are decidedly not harmonious. More precisely, we may say that modes of vibration can be harmonic or anharmonic. Harmonically-related frequencies are in simple integer ratios, for example 220, 440, 880 … Hz.[34] We hear such a set

[33] 'Acoustic Glossary, Sound and Vibration Definitions, Terms, Units, Measurements - Home Page'. http://www.acoustic-glossary.co.uk/ accessed April 1, 2019; Joe Wolfe, 'Music Acoustics, Physics, Science, UNSW'. http://newt.phys.unsw.edu.au/music/ accessed April 2, 2019.

[34] The Herz, Hz, is the SI unit of frequency, measured in cycles of oscillation per second. The orchestra normally tunes to A4 = 440 Hz.

of frequencies as a musical note at a pitch corresponding to the lowest ("fundamental") frequency,[35] with a tone colour controlled largely by the specific mixture of harmonics.[36]

The situation changes fundamentally when the sound is continuously excited, as by the bow of a violin or by the air pressure supplied by wind players. Now the vibrations can accumulate over much longer periods, giving, for example, the large volume difference in a string instrument between *pizzicato* and *arco* playing. The vibrations reflect from the ends of the strings or the bell of a wind instrument, and indeed from any discontinuity, and accumulate as time passes. The volume is then limited not by the decay of the vibrations in the string but by the balance between the energy input (by the bow, reed etc) and the losses in the instrument due to 'damping', that is, absorption of the vibrations by the materials of the instrument and by the air. In a reed-driven wind instrument only about 1% of the energy expended by the player goes into sound vibrations heard by the listener.[37] The rest goes into heating up the instrument or the air.

There is another fundamental change when the sound is continuously excited. Although many frequencies may be excited by the oscillator, it is a mathematical requirement that if the tone is 'steady', i.e. periodic and not varying with time, all the frequencies must be harmonically related. If the lowest frequency, the *fundamental,* is at, say 100 Hz, it is possible for component frequencies to exist at 100, 200, 300 etc. Hz but not at intermediate frequencies. This is a conclusion of the Fourier theorem (see standard mathematical textbooks such as Jeffrey[38]). If this were not so, the sound cannot be steady but must vary with time as it does in all percussion instruments; this is very easily heard in the timbre of a cymbal or Turkish Clash and even in a piano if one listens to the changing timbre as the sound decays.

Restricting now the discussion to reed instruments, the oscillator is the vibration of a reed in isolation. In order to be an oscillator that can easily be started and maintained by the air flow it must be in some sort of structure; either a double reed which can be blown through, or a mouthpiece with a curved facing which provides a slot for the airflow and a means of controlling the length of the reed by pressing it with the lips along the curve (the 'lay'), as shown in Figure 5.1.

Figure 5.1. Cross section of a clarinet mouthpiece. The dashed line shows the 'lay' or curved facing that constrains the closing of the reed. Figure courtesy Huw Bowen.

[35] This is a somewhat simplistic view, since 'pitch' is a musical concept dependent on neurological perception, not simply a matter of frequency; a note played at constant frequency but increasing volume will be perceived as flattening slightly. However, the acoustic arguments in this thesis are unaffected.

[36] Henry J. Watt, *The Foundations of Music.* Cambridge: Cambridge University Press, 2014, 57.

[37] Benade, *Fundamentals of Musical Acoustics*, 264

[38] Alan Jeffrey, *Mathematics for Engineers and Scientists, Sixth Edition* London: Chapman and Hall/CRC, 2004, 773

When the player starts to blow into the mouthpiece, the pressure rises inside the mouthpiece and the airflow past the reed increases. At some critical point the airflow starts the oscillation of the reed. The pressure in the mouthpiece first rises, and then falls till it is zero when the reed has closed, as seen in Figure 5.2. This behaviour is generic for reed-driven instruments, though the details of the shapes will vary.

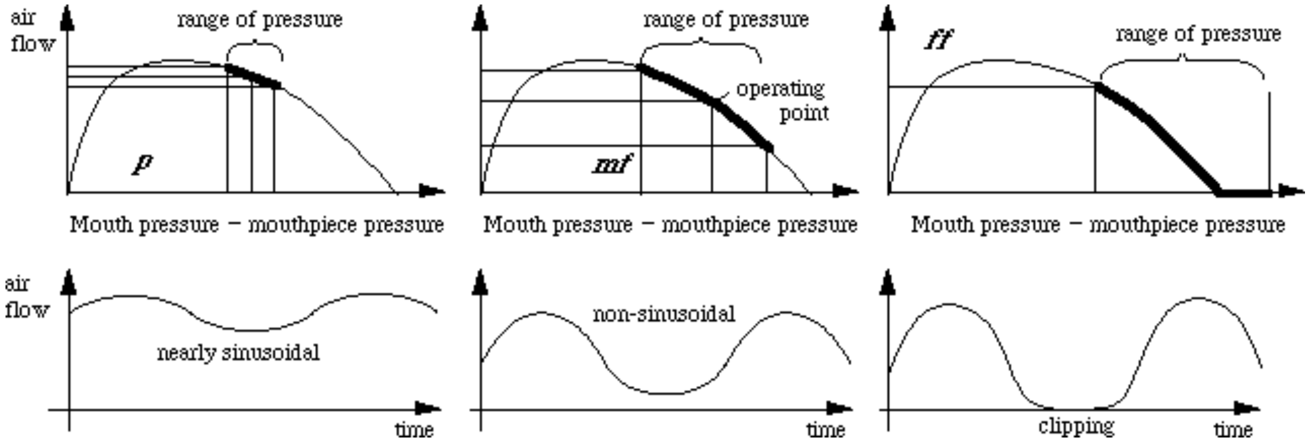

Figure 5.2. Schematic of the pressure variation in the mouthpiece of a clarinet, or the staple of an oboe or bassoon, just beyond the reed itself. The horizontal axis shows the blowing pressure and the vertical axis the consequent air flow. The flow rises as pressure is increased, then falls as the reed closes up against the mouthpiece rails. The heavy black lines indicate the operating conditions for soft, medium and high pressure. The non-linear (non-sinusoidal) behaviour increases with pressure. See also Fletcher and Rossing[39]. Figure courtesy J. Wolfe, reproduced with permission.[40]

The airflow fluctuates with the vibration of the reeds over the heavy black line in the figure. At lower airflows this is almost a straight line; the airflow is almost proportional to the pressure and the vibration is almost a pure sine wave. But even if the reed itself is perfectly linear (i.e. its deflection is simply proportional to the pressure), the heavy black line becomes curved, due to the non-linearity of the relationship between mouth pressure and air flow rate.[41] At still higher pressures, the reed starts to beat against the mouthpiece rails and the flow is even further from linear with the pressure. Further non-linearity will come from the reed itself. It is a basic property of non-linear oscillators that they generate harmonics (integer multiples of the lowest frequency) as well as the fundamental sinusoidal tones,[42] and these will be available as input to the resonator. This is the rest of the mouthpiece after the vibrating reed, plus the air column of the instrument's body.

When the resonator is attached there is a further consideration. Consider now the initiation of a note. Air is blown into the reed/mouthpiece, setting the reed in oscillation and a sound pressure wave starts to travel down the tube[43]. At this stage, the frequency (pitch) is only

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[39] Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments (2nd Edition). Edition)*, 418.
[40] Joe Wolfe, 'Clarinet Acoustics: An Introduction,' https://newt.phys.unsw.edu.au/jw/clarinetacoustics.html accessed 11 November 2021.
[41] Chaigne and Kergomard, *Acoustics of Musical Instruments (1st English Edition)*. 485-486.
[42] Harry F. Olson, *Music, Physics and Engineering*. New York: McGraw Hill (1967); Dover Reprint 1952, 595
[43] Mathematically, we can equally well describe the wave as one of pressure, or as one of velocity or displacement of the air particles. I shall consistently use pressure waves to describe the acoustical behaviour of air columns, since it is the pressure that acts directly on the reed and on the eardrum; also, conical instruments are easier to describe, both qualitatively and mathematically, in terms of pressure.

controlled by the player knowing exactly what embouchure and air pressure to use, hence the very beginning of a note is the hardest to learn and to control. But when the wave reaches the end of the instrument or the first open tone hole, which takes a few milliseconds[44] in the case of the bass clarinet with the lowest note fingered, a large fraction of it is reflected back up the tube. The remainder is radiated out and is heard by the listener. This is caused by the discontinuity at the end of the bell, and is the same phenomenon as light reflecting in a sheet of glass: it part reflects and part transmits. We now have two waves, travelling in opposite directions inside the tube. These add up to form 'standing waves'; these are crucial for the understanding of instrument acoustics and will be discussed further. Many dynamic illustrations are available on YouTube, for example Kiesel[45] and the UNSW web site.[46]

Standing waves in cylindrical tubes

In a standing wave, the travelling motion in one direction is effectively cancelled by the equal and opposite motion of the wave going in the other direction. However, the amplitudes add up. This means that the travelling aspect of the wave is removed but the amplitude and pressure oscillates at each point in the tube between zero and plus or minus some maximum value, as illustrated in Figure 5.3 and Figure 5.4. At some points (called *nodes*) the pressure is always zero, at others, (*antinodes*) the value oscillates between the extrema. At other points the value is intermediate.

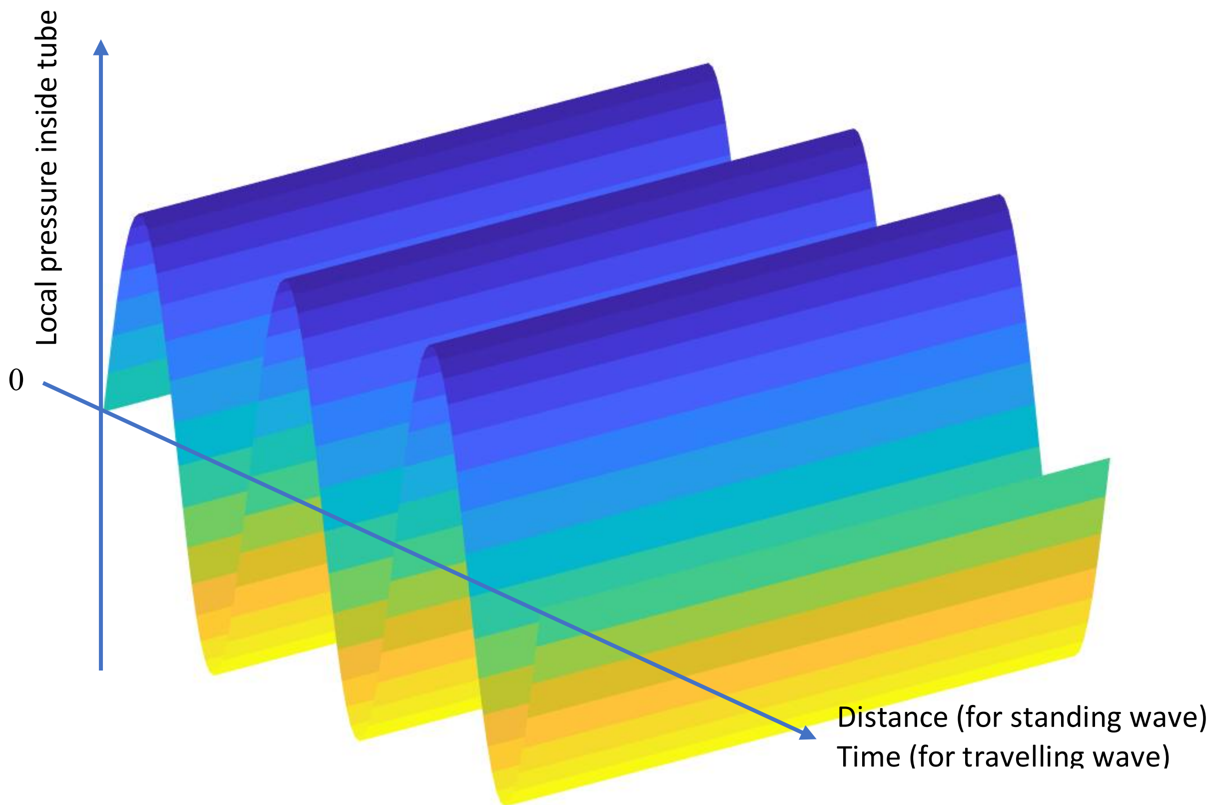


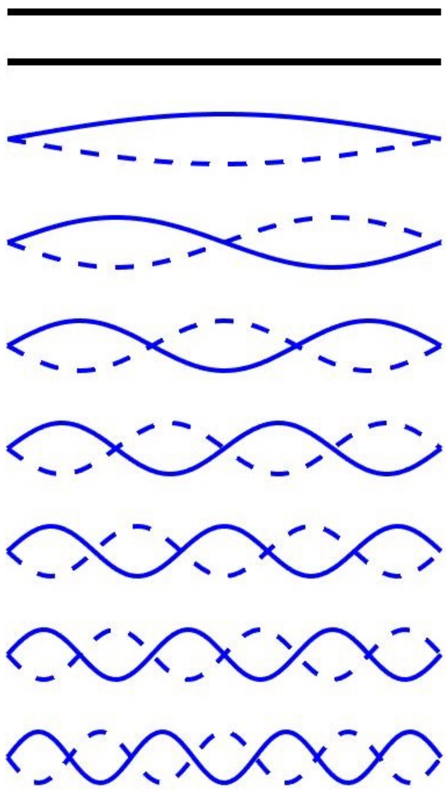
Figure 5.3. A schematic of a travelling or standing plane wave. A true plane wave would extend infinitely in all three axes, but the wave travelling down a tube of constant cross-section is a reasonable

[44] Abbreviated ms, 1/1000 of a second. At a metronome mark of 120, a semiquaver lasts 125 ms.
[45] Gregory Kiesel, 'Traveling versus Standing Waves'. https://www.youtube.com/watch?v=2KBJp5ysS74 accessed 23 July 2011.
[46] Wolfe, 'Music Acoustics, Physics, Science, UNSW.'

approximation. A travelling wave propagates in the direction of the arrow, but a standing wave remains fixed, and points oscillate up and down without moving their position. The positions of zero oscillation are called nodes, and position of maximum oscillation are antinodes.

Let us now show the positions of standing waves for real musical instruments, beginning with instruments based on cylindrical tubes (flute and clarinet). In these instruments the sound wave is approximately planar, travelling down the tube with no modification other than frictional losses. This is illustrated in Figure 5.3. Waves of many types exist, but in sound waves, the oscillation is longitudinal and consists of air being alternately compressed (the blue areas in Figure 5.3) or rarefied (the yellow areas).

Since it is better to map the pressure fluctuations, we shall now look simply at the cross-section of these along the air column. These are shown first for a number of harmonics of an open-ended tube (e.g. the flute) in Figure 5.4. The positions of the nodes and antinodes are determined by the geometric constraints.[47] The flute is open to the atmosphere at both the mouthpiece and at the end of the instrument, therefore these positions must be pressure nodes. Hence the pattern of standing waves inside the flute must be such as to fit an exact number of half-waves inside the length between pressure nodes. The longest 'fit' corresponds to a single half wave, called the fundamental or first harmonic, followed by the second harmonic at an octave higher, and so on.



n	λ	f
1	$2L/1$	$1c/2L$
2	$2L/2$	$2c/2L$
3	$2L/3$	$3c/2L$
4	$2L/4$	$4c/2L$
5	$2L/5$	$5c/2L$
6	$2L/6$	$6c/2L$
7	$2L/7$	$7c/2L$

Figure 5.4. The possible pressure standing waves in an open-ended cylindrical tube such as a flute. The curves show the pressure waves at the maximum and minimum values of their oscillation. n is the harmonic number, λ is the wavelength and f the frequency of the standing wave, where c is the speed of sound and L is the length of the tube. The first seven harmonics are shown.

[47] These are called 'boundary conditions' in mathematics.

In order for the instrument to play different notes, holes in the side of the tube are opened up to shorten the tube. The length from the mouthpiece to the first open hole now replaces the overall length L in this figure, hence many notes can be played.

The case of the clarinet is similar but with one important difference. Whilst 'open' at the bell, the clarinet, indeed all wind reed or lip instruments are considered to be 'closed' at the entry end. This at first sight seems illogical, since one blows into the mouthpiece or reed to maintain its oscillation. It is better understood by thinking of it as a pressure antinode rather than as a displacement node. It is logical that the point just beyond the reed is at least one of the points at which the pressure oscillates with its maximum amplitude.

Simple equations show the frequencies selected at the fundamental. If the length of the instrument is L, it is obvious from Figure 5.4 that the wavelength λ of a full cycle is $2L$ for the flute and $4L$ for the clarinet. The frequency $f = c/\lambda$, where c is the speed of sound, so the lowest note of the clarinet has half of the frequency of that of the flute, hence is an octave lower.[48]

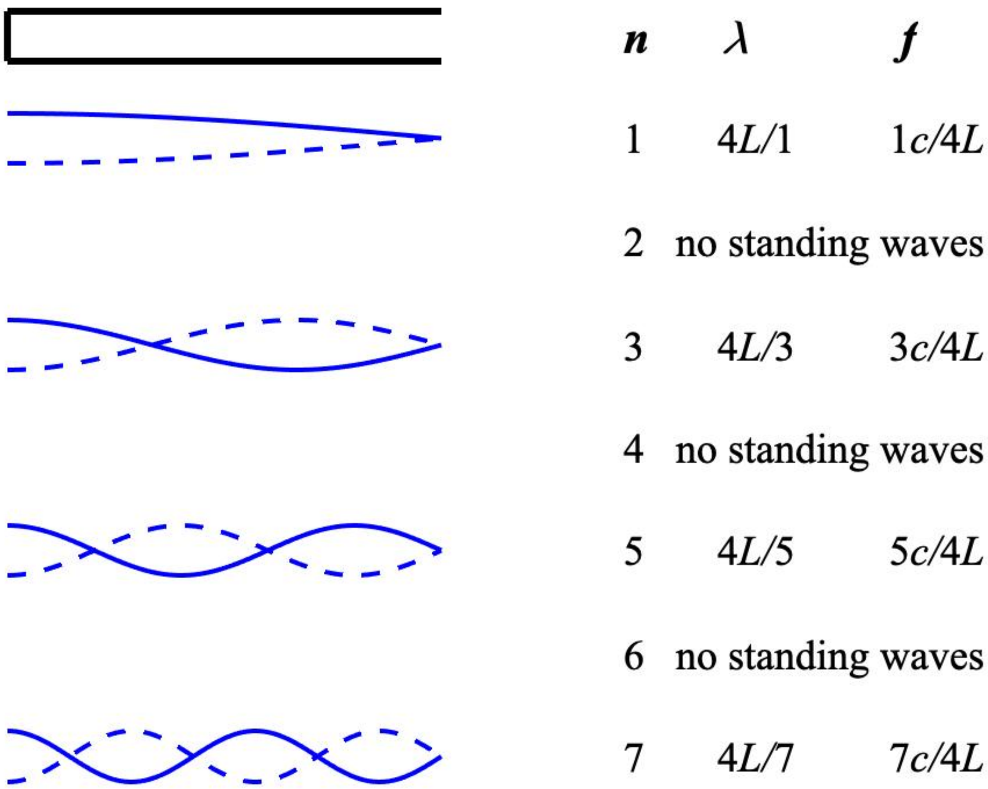


Figure 5.5. The possible pressure fluctuations and standing waves in a single-closed-end tube such as a clarinet. The first seven potential harmonics are again shown, but the even values of *n* do not satisfy the condition of a pressure node at the open end, and are not present. The length scales and symbols are the same as for Figure 5.4 and it is seen that the same wavelength (pitch) is achieved for a tube half the length of the flute; in the clarinet the reed end is effectively closed, forcing a pressure antinode.

[48] by the general properties of a wave. This simplified discussion ignores details such as the effects at the end of the bell and any variable bores of the tube, such as polycylindrical geometries adopted in the 20th Century, but all such details are taken into account in the computational model.

These standing waves are substantial phenomena and high pressures can be attained (recall that the pressures build up as a note is played). If a pressure antinode coincides with the position of a large pad which does not have a sufficiently strong spring then it can easily make the pad leak or vibrate. This puts a lower bound on the lightness of springing in an instrument with large holes, such as a bass or contrabass clarinet.[49]

The point just beyond the reed is seen to be a pressure antinode, where the pressure is oscillating at exactly the same frequency as the note that is being played (plus its harmonics if present). This pressure therefore acts on the reed to stabilise and maintain its oscillation. Reed-driven instruments are therefore *feedback* instruments, in which the reed vibrates at the frequency corresponding to the note that is fingered, and to its harmonics. The vibration is driven by the pressure of the player's lungs through the reed system and stabilised by the resonance of the instrument itself. When a player addresses the mouthpiece and begins to blow, the reed starts to close; it then returns under its own springiness and by the pressure feedback from the instrument air column and then admits more air. If the conditions are right for stable oscillation (see below) it will continue to vibrate and cause waves in the instrument that travel towards the bell. At any discontinuity in a bore, such as an open tone hole or the bell, part of the sound wave is reflected back towards the mouthpiece and part is transmitted further down the instrument, or into the open air. The part reflected combines with the waves still coming from the reed to form stable standing waves.

This pressure oscillation in the mouthpiece is what couples the air column to the reed, and maintains the reed in oscillation at the frequency of the note being played. There are some more conditions for oscillation. First, the reed should have a natural vibration frequency much higher than the note attempted. Second, the blowing pressure should exceed some threshold, usually about a third of that required to close the reed against the mouthpiece lay. Next, the embouchure must be appropriate to allow the reed to vibrate at this frequency. Finally and more subtly, the pressure oscillations inside the mouth and oral cavity must match those just inside the mouthpiece but in an opposite sense: when the mouth is pushing, the mouthpiece cavity must be pulling, i.e. the pressure oscillations are out of phase but act on the reed in the same direction.

The standing wave is not established and stabilised until the sound waves have travelled down the instrument and back. This is a barely-perceptible few milliseconds even on a bass clarinet, but the reed has to be vibrating at around the right frequency in the initial puff in order to stabilise quickly. Hence, the initial (transient) sound of the clarinet is strongly dependent on the player's embouchure, as is known by every teacher of beginning players. If the embouchure or oral cavity spaces are not set reasonably close to begin with, then the initial sound can be uncontrollable or non-existent. The transient situation is even more

[49] Christopher C. Lawrenson et al. 'Measurements of Macrosonic Standing Waves in Oscillating Closed Cavities,' *J. Acoust. Soc. Am.* 104 (1998) 623–36,. https://doi.org/10.1121/1.423306, At first sight a saxophone would appear to be very susceptible to this effect since some of its pads are very large. However, these are near the end of the expanding bore, where the standing wave pressure is lowest.

pronounced on brass instruments, where the lip resonance must be set very closely to the desired pitch before the note is started.

This discussion shows why the embouchure and oral cavity shape of the player (and hence the vocal tract resonances) have such an influence on the sound and even pitch; it influences the regular 'voicing' of all notes, and, at its extreme, enables the glissando in *Rhapsody in Blue*. This has been extensively studied by Wolfe and his collaborators at UNSW.[50]

Once the wave arrives back at the reed and the standing waves are established, the note is stabilised. The pressure wave antinode at the reed ensures that the reed vibrates at the frequency of the note. If the sound is to persist and not be quickly damped, the air in the tube of the clarinet must therefore resonate at the frequencies (fundamental and harmonics) of the reed. In more detail, provided that the sound wave is truly periodic, the reed will vibrate not only at the fundamental frequency but also simultaneously at its harmonics, which are integer multiples of frequency of the fundamental. It cannot simultaneously vibrate in a sustained tone at additional non-harmonic frequencies, by Fourier's theorem (see above). A simple explanation of this is that the reed is a connected elastic body. It can simultaneously vibrate at fundamental and harmonic frequencies because these all maintain the same phase relationship. Other frequencies will be (or rapidly will become) out of phase, and the reed could not then stay connected to itself. It is therefore essential, for a good instrument, that the harmonic frequencies are also aligned to resonance frequencies of the tube.

For completeness, I should note that in recent decades so-called 'extended' playing techniques have been developed on wind instruments, especially the clarinet and bass clarinet.[51] An important example of these is the production of multiphonics, in which two (or sometimes more) notes are heard simultaneously. Type I (periodic) multiphonics are based on the harmonic series and use embouchure and oral cavity changes to induce two prominent harmonic components to sound simultaneously as apparent fundamentals. These do not change the location of standing waves in the instrument but change their relative amplitudes. Type II (quasi-periodic) multiphonics are produced by special fingerings in which hole

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[50] Joe Wolfe, Maëva Garnier, and John Smith, 'Vocal Tract Resonances in Speech, Singing, and Playing Musical Instruments,' *HFSP Journal* 3 (2009) 6–23. https://doi.org/10.2976/1.2998482; Jer-Ming Chen, John Smith, and Joe Wolfe, 'Do Trumpet Players Tune Resonances of the Vocal Tract?,' *J. Acoust. Soc. Am.* 131 (2012) 722–27. https://doi.org/10.1121/1.3651241; Jer-Ming Chen, John Smith, and Joe Wolfe, 'Saxophonists Tune Vocal Tract Resonances in Advanced Performance Techniques,' *J. Acoust. Soc. Am.* 129 (2011) 415–26. https://doi.org/10.1121/1.3514423; Jer Ming Chen, John Smith, and Joe Wolfe, 'Experienced Saxophonists Learn to Tune Their Vocal Tracts,' *Science (New York, N.Y.)* 319 (2008) 776. https://doi.org/10.1126/science.1151411; Claudia Fritz and Joe Wolfe, 'How Do Clarinet Players Adjust the Resonances of Their Vocal Tracts for Different Playing Effects?,' *J. Acoust. Soc. Am.* 118 (2005) 3306–15,. https://doi.org/10.1121/1.2041287; Noel Hanna, John Smith, and Joe Wolfe, 'How the Acoustic Resonances of the Subglottal Tract Affect the Impedance Spectrum Measured through the Lips,' *J. Acoust. Soc. Am.* 143 (2018) 2639-2650. https://doi.org/10.1121/1.5033330; Alex Tarnopolsky et al. 'The Vocal Tract and the Sound of a Didgeridoo,' *Nature* 436 (2005) 39–39,. https://doi.org/10.1038/43639a; Alex Z. Tarnopolsky et al. 'Vocal Tract Resonances and the Sound of the Australian Didjeridu (Yidaki) I. Experiment,' *J. Acoust. Soc. Am.* 119 (2006) 1194-1204. https://doi.org/10.1121/1.2146089.

[51] e.g. Bruno Bartolozzi, New Sounds for Woodwind, ed. and trans. Reginald Smith Brindle (London: Oxford University Press, 1967), 35; Phillip Rehfeldt, New Directions for the Clarinet, rev. ed. (Lanham, MD: Scarecrow Press, 2003), 41; Sarah Watts. *Spectral Immersions: A Comprehensive Guide to the Theory and Practice of Bass Clarinet Multiphonics*. London: Metropolis, 2016.

patterns and embouchure and oral cavity modifications encourage the presence of two sounding lengths and hence two sets of standing waves inside the tube. The requirement for mechanical continuity of the reed is then satisfied by an interaction between the two resulting fundamental frequencies in which each modifies the other. Such sounds are very dependent upon the specific design of the instrument, and upon control of the embouchure and vocal tract.[52]

Not all frequencies contribute to the feedback when a note is fingered. Above the so-called 'cut-off frequency' the waves do not reflect at the first open tone hole but travel down and out of the tube. The reason for this is that the tone holes themselves contain an amount of air, which has a certain inertia, forming what is known as an acoustic *inertance*. An inertance behaves as a short circuit to the outside air at low frequencies, thus forcing a pressure antinode and defining the pitch of the note. But at high frequencies it behaves as a high resistance and is effectively ignored as a discontinuity. Instruments have, according to Benade[53], evolved through experiment to have a roughly constant cut-off frequency whatever the fingering. It is around 1500 Hz for clarinets (around G6, the G an octave above the treble stave) and an octave lower for bass clarinets. Notes or harmonics above this are still possible up to the resonance frequency of the reed, which is around 1800 – 3000 Hz for the lowest vibrational mode in a soprano clarinet.[54] Acoustic analysis in this project has shed additional light on the cut-off phenomenon, as discussed in Chapters 6 and 8.

A most important parameter in the understanding of wind instrument acoustics is that of the input impedance of an air column. Mathematically, the acoustic impedance[55] Z at any location in the tube and at a defined frequency is defined as the ratio between the acoustic pressure p at that frequency and the volume flow velocity v, thus

$$Z = p/v$$

The interesting location is at the input, just beyond the reed. Here we require the pressure oscillation to be at a maximum amplitude in order to synchronise (or 'couple') the reed vibrations with that of the air column. From this equation we see that the pressure p is maximal if, and only if, the input impedance Z is also maximal. This deduces a most important principle: *the possible resonant frequencies in a reed-driven air column are those for which the input impedance of the column is a maximum.*[56] For completion, it should be noted that

[52] John Backus. 'Multiphonic Tones in the Woodwind Instruments'. *J. Acoust. Soc. Am*. 63, no. 2 (1978): 10; Douglas H. Keefe and Bernice Laden. 'Correlation Dimension of Woodwind Multiphonic Tones'. J. Acoust. Soc. Am. 90 (1991): 1754–65. https://doi.org/10.1121/1.401656; Jack Yi Jing Liang. 'Clarinet Multiphonics: A Catalog and Analysis of Their Production Strategies'. DMA thesis, Arizona State University, 2018; Doc, J.-B., C. Vergez, S. Missoum. 'A Minimal Model of a Single-Reed Instrument Producing QuasiPeriodic Sounds'. Acta Acustica united with Acustica, 100 (2014), 543-554. https://doi.org/10.3813/AAA.918734

[53] Benade, *Fundamentals of Musical Acoustics*, 485-488;

[54] Stephen C. Thompson, 'The Effect of the Reed Resonance on Woodwind Tone Production,' J. Acoust. Soc. Am. 66 (1979) 1299–1307. . https://doi.org/10.1121/1.383448

[55] Acoustic properties of a tube are also sometimes discussed in terms of the 'admittance' or 'acoustic conductivity', *Y*, which is simply the inverse of *Z*. *Z* and *Y* are complex numbers, with real and imaginary parts; the imaginary part is related to the phase of the quantity.

[56] As mentioned above, the sound generators of the flute and recorder are different. Because they are open to

inclusion of the oral cavities in the modelling of the resonances lowers the frequency of a resonance to just below its maximal value when measured in a laboratory.

This principle was established by Benade,[57] and it contradicted the long-held theory of respected acousticians, summarised by Lamb,[58] that the mouthpiece/reed system generates a broad sound spectrum (a squawk) from which the air column resonances filter out the tone that is heard. Benade showed in some cleverly-designed experiments that this was not how a reed instrument worked, but that the operative mechanism was feedback from a set of harmonics that stabilise the oscillation at the desired fundamental frequency.[59] Worman treated this concept in mathematical detail.[60]

Any air column will have resonant peaks, but unless the column is a simple cylinder or cone with no side holes, the peaks will not necessarily lie in simple harmonic relationships. Indeed, Benade and his associates once designed and built a clarinet-like instrument, nicknamed a 'tacet horn', which was virtually unplayable at any pitch since none of the peaks in the impedance spectrum were harmonically related to any others.[61] This proves an important principle in woodwind design, that the reed-column coupling needs a number of harmonically-related peaks in the spectrum in order to create the standing waves that make a musical tone. As discussed above, the harmonics are automatically generated in the non-linear reed/mouthpiece system.

The vibration is stabilised if the harmonics also lie at resonance (impedance) peaks, since the energy input to the system by the player is automatically distributed amongst (and only amongst) the harmonic peaks. At low amplitudes most of the energy goes into the fundamental; as the blowing pressure increases, the energy distributed to the harmonics increases, according to the height of each impedance peak and its harmonic order. The general conclusion from the calculations and experiments on instruments lead to the conclusion that *it is important for stability, intonation and quality of sound that three or more harmonics contribute to stabilising the sound*.[62] This phenomenon is an example of 'mode locking' and it is a consequence of the non-linear generation of sound at the mouthpiece.

But note that the mode locking also contributes to the quality and richness of the musical sound. A pure sine wave has indeed a recognisable pitch but is a somewhat boring sound. All musical instruments have a characteristic mix of harmonics (also called 'partials') which gives them their characteristic sound.[63] The acoustical theory and the experience of the maker here

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the atmosphere at the mouthpiece end. they do not work on pressure but on the velocity of the air jet created by the player. Thus from $Z = p/v$ they require a minimum input impedance not a maximum. The same concepts of input impedance resonances apply, but in the flute case we are looking for impedance minima (or, equivalently 'admittance' maxima) to find the notes that can be played..

[57] Benade, A.H. 'Relation of Air-Column Resonances to Sound Spectra Produced by Wind Instruments'. *J. Acoust. Soc. Am.* 40 (1966): 247–49. https://doi.org/10.1121/1.1910050

[58] Lamb, Horace. *The Dynamical Theory of Sound*. London: Edward Arnold 1910, 276-283.

[59] A. H. Benade and D. J. Gans, 'Sound Production in Wind Instruments', *Annals of the New York Academy of Science* 155 (1968): 247–63. https://doi.org/10.1111/j.1749-6632.1968.tb56770.x

[60] Walter E. Worman, 'Self-Sustained Nonlinear Oscillations in Clarinet-Like Systems'.

[61] Benade and Gans, 'Sound Production in Wind Instruments'.

[62] Ibid.

[63] Ibid.

converge. An excellent illustration is the empirically-based remark of the well-known recorder maker, Hermann Moeck:

> Above all, one should remember that there is a definite correlation between the tone of a recorder and its intonation.[64]

Standing waves in conical tubes

Saxophones, oboes, bassoons and bagpipe chanters (and many early instruments and folk instruments) have approximately conical rather than cylindrical bores, with either single or double reeds. Again we shall consider a generic conical tube to understand the general principles and rely on computer modelling to take care of the details. We cannot understand the standing waves in conical tubes by the simple arguments we used for cylindrical tubes, in which the waves propagate largely as plane waves[65]. Instead they appear as shown in Figure 5.6. The waves in a cone behave as if they emanated from the tip of the cone where the reed is located, and they have a curved wavefront. They are known as spherical waves, and are key to the behaviour of conical instruments and to conical segments of clarinets, such as the bell. Indeed there are many mistakes or omissions in textbooks on acoustics, as pointed out by Ayers et al. in 1985.[66] Several authors treat the problem incorrectly. Others ignore it but simply quote the well-known result, which is that the lowest pitch of an oboe is the same as that of a flute of the same length, not, as one might expect, the same as a clarinet, despite the fact that both have ends closed by a reed and have open bells. The following discussion uses the paper of Ayers et al. along with the UNSW musical acoustics website and the pedagogical treatment of Ruiz. [67]

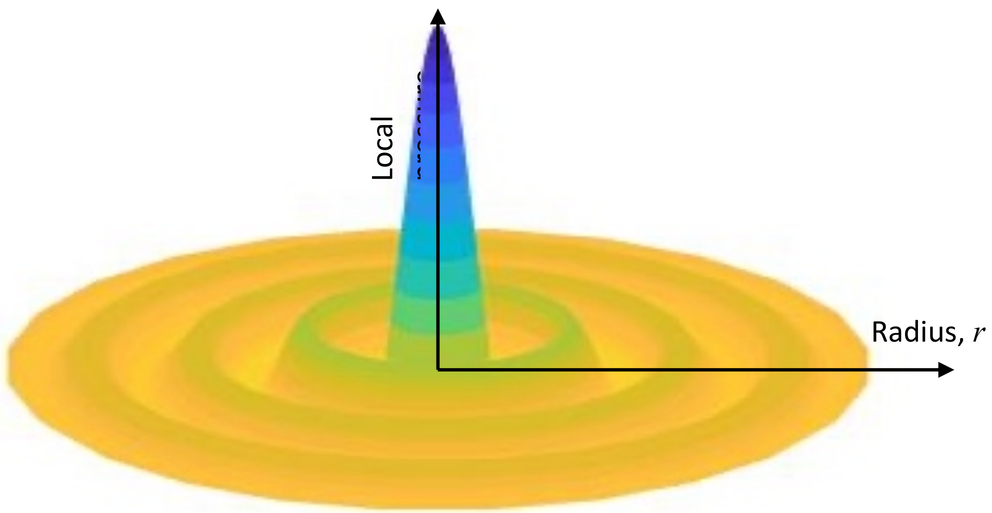

Figure 5.6. Schematic 3D plot of the amplitude of a spherical standing wave. The colour map is the same as that used for the plane wave in Figure 5.3. There is a strong pressure antinode at the centre, with the amplitude damped by the inverse of the radius away from the centre.

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[64] Hermann Moeck, 'Recorders: Hand-Made and Machine-Made,' *Early Music* 10, issue 1 (1982) 10–13. https://doi.org/10.1093/earlyj/10.1.10

[65] We do in fact model tapered sections of the clarinet such as the flare and bell, by spherical-wave theory.

[66] R. Dean Ayers, Lowell J. Eliason, and Daniel Mahgerefteh, 'The Conical Bore in Musical Acoustics,' American Journal of Physics 53 (1985) 528–37. https://doi.org/10.1119/1.14233

[67] Wolfe, 'Music Acoustics, Physics, Science, UNSW.'; Michael J. Ruiz, 'Hearing the Transformation of Conical to Closed-Pipe Resonances,' *Physics Education* 52 (2017) 035012. https://doi.org/10.1088/1361-6552/aa64f1

The difference is caused by the spherical wavefronts.[68] The key point is that the amplitude of a plane wave remains constant during its propagation, unless it is subject to losses such as absorption. However, spherical wavefronts spread out as they propagate, and their amplitude decreases by $1/r$ (and their intensity by $1/r^2$) after travelling for a distance r from the origin at the centre of the sphere. Instead of the standing waves being represented by $\sin x$ or $\cos x$, as are the plane waves in a flute or clarinet, they are represented by $(\sin r)/r$. This function, also called the *sinc* function has nodes (zero values) in the same places as the familiar sine function at any point past the origin (since it must be zero wherever $\sin r$ is zero). But at the origin itself we find that the sinc function is $0/0$. In mathematics, this can be anything at all, depending on the functions that give rise to the zeroes. The problem is solved by considering the approach to zero.[69] When r becomes extremely small, the value of $\sin r$ becomes closer and closer to r, so the limit as $r = 0$ is simply 1. The sinc function thus does not have a node (in pressure) at the origin, but an antinode. This is just what is needed to sustain the oscillations of the reed. Moreover it is twice as wide near the origin as the sine or cosine functions. This is shown in Figure 5.7; this shows the sinc function (the red line), now representing standing waves in the oboe, bassoon or saxophone in comparison with the cosine function (blue line) representing standing waves in the clarinet. In contrast, Figure 5.8 shows the sinc function in comparison with the sine function, representing standing waves in the flute (blue line). We see that the nodes of the oboe, bassoon or saxophone match exactly with those of the flute. Thus the oboe overblows an octave like the flute, and its spectrum consists of all harmonics of the fundamental. At the fundamental of the lowest note of the flute or oboe, the wavelength of the sound wave is twice the length of the instrument; as we saw earlier, the corresponding wavelength of the lowest note of the clarinet is four times the length of the instrument and hence an octave lower.

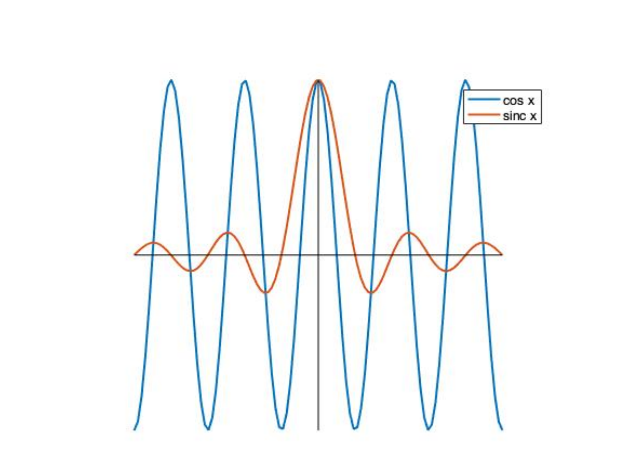


Figure 5.7. The sinc function (red line) in comparison with the cosine function (blue line). Note the greater width of the red line peak near the origin.

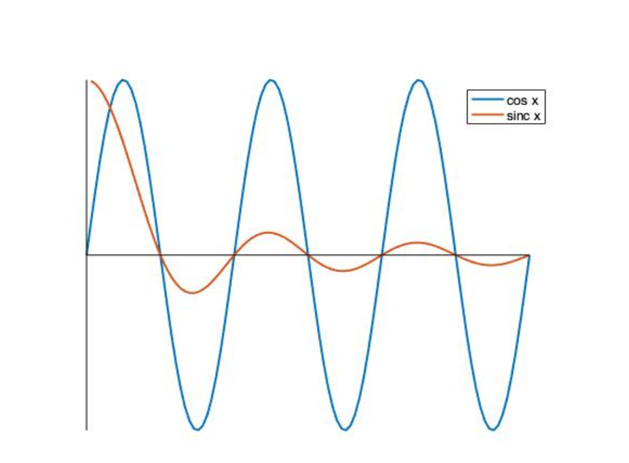
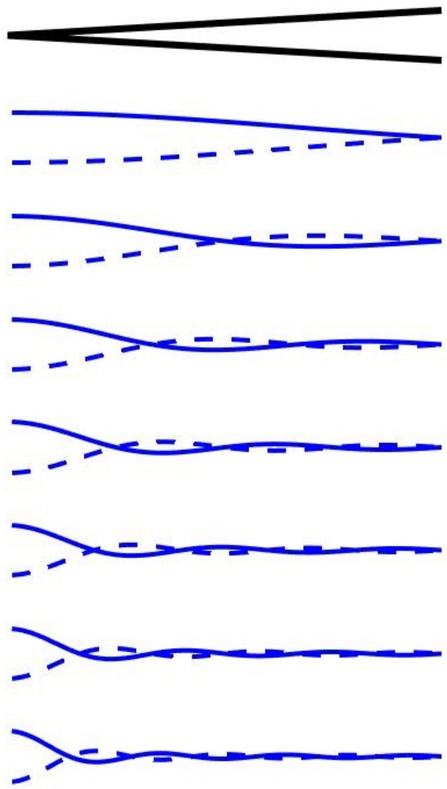


Figure 5.8. The sinc and sine functions for the first few oscillations near the origin on the positive side. Note that the zero crossing points are identical after the origin of the curves.

[68] This discussion is slightly simplified by ignoring 'end effects', which make a tube behave as if it were a little longer. However, these are taken into account correctly in the acoustic modelling described in the next chapter.

[69] Or purely mathematically by invoking L'Hôpital's rule in calculus.

Finally we may show the standing waves in conical instruments with a tip 'closed' by the reed, in Figure 5.9, to compare with Figures 5.4 and 5.5.



n	λ	f
1	$2L/1$	$1c/2L$
2	$2L/2$	$2c/2L$
3	$2L/3$	$3c/2L$
4	$2L/4$	$4c/2L$
5	$2L/5$	$5c/2L$
6	$2L/6$	$6c/2L$
7	$2L/7$	$7c/2L$

Figure 5.9. The possible pressure standing waves in an conical tube closed at the apex, such as an oboe (which is an approximate cone, closed by a reed at the apex). The curves show the pressure waves at the maximum and minimum values of their oscillation. n is the harmonic number, λ is the wavelength and f the frequency of the standing wave, where c is the speed of sound. The nodes are the same as for the flute except for the left hand end, where there is an antinode rather than a node. The first seven harmonics are shown. The amplitude of the antinode decreases with increasing length along the tube. Here, L is the slant length of the tube.

The input impedance

A useful way of considering the input impedance, has been given by Ayers et al. Think of a cylindrical tube (almost) closed at the input end, and open at the far end, stimulated by a vibrating transducer at the input end. We want to determine the peaks in the impedance spectra. At the lowest frequencies (wavelengths below 4L) no standing waves can be formed and only travelling waves exist, passing through the tube and out into open air. Some sound could be audible at very low volume. Then,

> As the frequency is increased from zero, the wavelength decreases but the standing wave must always have a pressure node at the open, output end of the bore. In the process of shrinking the wavelength, whenever a new pressure antinode passes through the input end, the input impedance hits a maximum. Similarly a new pressure node passing through the input end gives rise to an impedance minimum.[70]

[70] Ayers, Eliason, and Mahgerefteh, 'The Conical Bore in Musical Acoustics.'

For the straight pipe, the regular spacing of nodes and antinodes in the planar standing waves gives rise to a regular sequence of impedance extrema. Maxima fall half way between the minima. This is exactly what is observed in a well-designed instrument, as shown in the plot in Figure 5.10, taken from the work on the Heckel bass clarinet[71]. In a clarinet in its lowest register, the lowest-frequency peak is normally the strongest, and the higher frequency peaks steadily reduce in intensity, as shown here.[72] Good alignment can be achieved between harmonics of the fundamental and several resonance peaks. If the register key be opened (Figure 5.11; all other fingering is the same as for Figure 5.10) most peaks are unaffected, but the first peak drops in intensity and shifts significantly in frequency. It is no longer aligned to other resonances and becomes virtually impossible to play. Small leaks near the top of the tube have a similar effect. Instead, the next peak serves as the basis for cooperative modes of oscillation and the note C4 is produced.

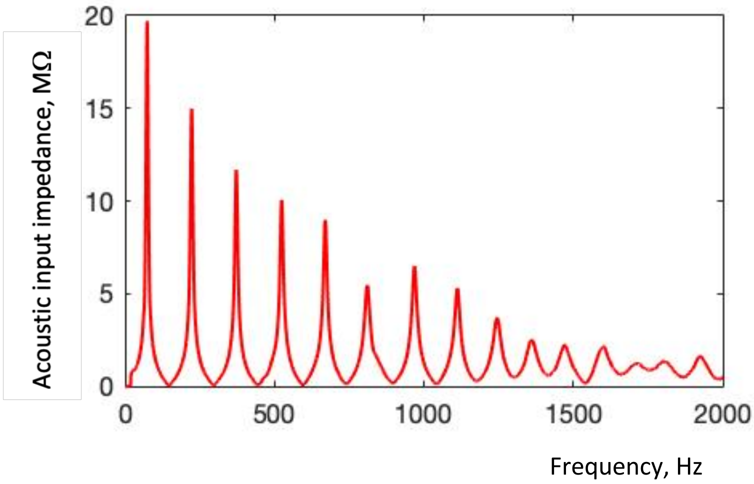


Figure 5.10. Measured acoustic impedance spectrum of the note F2 on the Heckel.

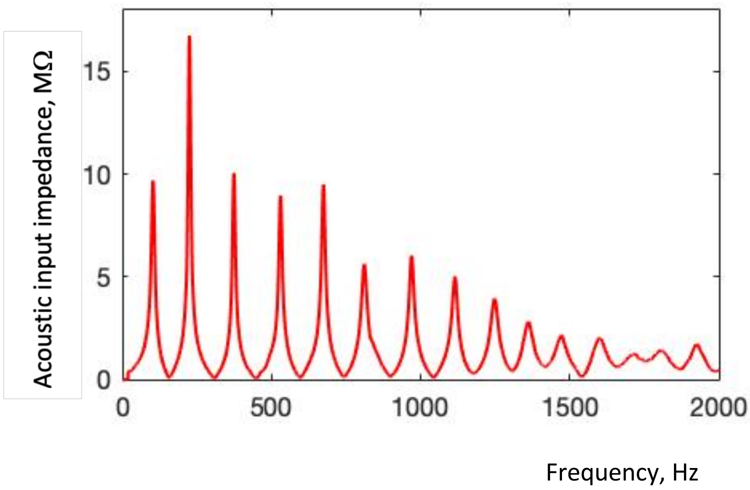


Figure 5.11. Measured acoustic impedance spectrum of the note C4 on the Heckel, a twelfth higher than F2 (identical fingering with the addition of the register key). Note that the first resonance peak has dropped in magnitude but, more significantly, shifted to a higher frequency. It is no longer in a harmonic relationship to the following resonances.

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[71] Bowen et al. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played.'

[72] This is not the case in the bassoon, in which the second and third resonances are usually stronger than the fundamental. This gives rise to its characteristic timbre, very different from a bass clarinet.

For a given fingering, the lowest resonance that is aligned with higher harmonics will be the main determinant of the pitch and temperament of the instrument. The degree of alignment of the resonances will determine both the strength of feedback that stabilises the note and also the admixture of harmonics that contribute to its timbre.

The alignment of the harmonics with resonance frequencies is automatic for the cylindrical tube (but only if one ignores end effects), but is not automatic for a real clarinet with side holes, discontinuities at the joints and a flaring bore. It is up to the maker to compensate for these effects by compensating perturbations such as hole size, hole undercutting or bore variation. Problems and failures of this approach are known in historical soprano clarinets and are known to have contributed to composers' choices and styles as discussed in Chapter 6. We may be able to detect similar problems in historic bass clarinets, especially the earliest ones. It will be of particular interest to compare bassoon-form and straight form instruments from a single maker.

Measurement of the input impedance of bass clarinets

The detailed modelling will be described in Chapter 6 and the geometric measurements in Chapter 7. Here, I discuss the bass clarinet used for the verification of the model, the methods for measuring the acoustic impedance experimentally, and the method of measuring the playing pitches.

The instrument used for the tests was a Heckel bass clarinet in A from 1910, owned by myself and shown in Figure 5.12. It is a 21-key system with 5 plateau keys (holes I and IV are open fingerholes), and is a Müller-pattern system with left- and right-hand brilles and a patent C#.[73] In total, 22 of the 24 holes are covered by keys or plateaux.

Figure 5.12. The Heckel bass clarinet in A used for the trials. (picture courtesy Huw Bowen)

Dated at 1910 from Heckel records[74] and formerly owned by the Kyiv Symphony Orchestra, the instrument has been kept in playing condition all its life, but only lightly played, no doubt as a consequence of there being comparatively few orchestral parts for the bass clarinet in A.[75] It has been recently repadded with leather pads similar to the originals and is in very good playing condition. It has a straight bell, so there is no need to consider complications due to a curved bell. The effect of the curve of the crook may be estimated from data given by Félix, Dalmont and Nederveen (2012).[76] The minimum axis of curvature parameter (tube internal

[73] Voorhees, *The Development of Woodwind Fingering Systems*, 2003, 163
[74] Edith Reiter, *Wilhelm Heckel.* Wiesbaden: Marixverlag, 2014. 277.
[75] Bowen, D. Keith. 'The Rise and Fall of the Bass Clarinet in A', (2011).
[76] Simon Félix, Jean-Pierre Dalmont, and C.J. Nederveen, 'Effects of Bending Portions of the Air Column on the Acoustical Resonances of a Wind Instrument,' *J. Acoust. Soc. Am.* 131 (2012) 4164–72. https://doi.org/10.1121/1.3699267

radius divided by bend radius) in this particular crook is $\kappa = 0.38$, and from their Figure 4, the length correction will be at maximum approximately 0.8 mm. We have neglected this quantity in the calculations at present, though it is automatically taken into account in the empirical embouchure correction discussed in chapter 6.

Experimental impedance measurement systems[77]

A complete set of input impedance measurements was made over 3 octaves from E2, including a number of alternative fingerings. Two systems were used to measure impedances in the laboratory at the Open University: an in-house single-microphone capillary system that has been extensively calibrated,[78] and the commercial BIAS system.[79] A single measurement (on note G3) was made with the in-house system, which verified that the agreement between the methods was good. For all subsequent measurements the BIAS system was used. Both the BIAS and single-microphone measurement systems are capillary-based. That is, a capillary channel connects a controlled sound source to the entrance of the wind instrument to be measured. The capillary is designed to have an impedance that is frequency independent, and has a much larger magnitude than that of the air column being measured.

The general principle draws from determining two characteristic signals at each end of the capillary, which allows one to obtain a good estimation of both the pressure and volume flow rate at the entrance of the measured instrument. One of these may be made constant using some active control. Provided the wavelength is sufficiently above the inner diameter of the instrument's bore, the ratio of pressure over flow rate gives the plane wave component of the impedance. Both systems are calibrated with a similar two-calibration method. The only difference between them is that the single-microphone calibration relies on the assumption that the cavity pressure remains the same regardless of the object being measured.

In contrast to a number of alternative, more accurate, impedance measurement systems, one advantage of capillary-based impedance measurement systems is that the apparatus can be made very compact. This is particularly useful in the context of the measurement of historical instruments, which may require the equipment to be transported to a museum. Furthermore, the measurement does not require post-processing and directly provides a sufficiently accurate impedance measurement over the frequency range of interest, which in our case is 20 – 2000 Hz. As shown in Chapter 6, the cutoff frequency beyond which standing waves are not formed in the instrument is approximately 1000 Hz in the Heckel instrument.

In the BIAS system a chirp signal is sent to a loudspeaker while a microphone monitors the acoustic pressure in the cavity between the loudspeaker and the capillary. The envelope of the chirp signal is designed to compensate for the cavity resonances, such that the variation in

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[77] This section on experimental impedance measuring systems is taken from the section written by collaborators at the Open University, Prof. D. Sharp and Dr. K. Buys for our joint publication. I participated fully in the measurements and undertook their interpretation.

[78] Sharp, D. Mamou-Mani, A. and Van Walstijn, M. 'A Single Microphone Capillary-Based System for Measuring the Complex Input Impedance of Musical Wind Instruments', *Acta Acustica United with Acustica*, 97 (2011) 819-829. https://doi.org/10.3813/AAA.918462

[79] Widholm, G. Pichler, H. and Ossmann, T. 'BIAS: A computer-aided test system for brass wind instruments', Audio Engineering Society (1989) Paper No. 2834,

the acoustic flow emerging from the capillary is minimised. By measuring the pressure amplitude recorded by a second microphone at the entrance to the air column under test, the input impedance magnitude can be determined. Impedance phase information can also be obtained from the system through the use of a phase meter connected to the two microphones.[80] The BIAS (Brass Instrument Analysis System) was originally developed for brasswind, and later modified for woodwind[81] and it has been applied in the quality control of brasswind instruments since 1989.[82] The knowledge and application of impedance and other scientific measurements to instrument manufacturing has been assisted in recent years by the Pafi collaboration (Plateforme modulaire d'aide à la facture Instrumentale) [83] in France, which seeks to make scientific measurements, including input impedance, available to small manufacturers together with software tools to predict the effects of changes.

In the Open University in-house single-microphone capillary system, there is no cavity microphone. Though the cavity pressure is not monitored during a measurement, the apparatus is still able to provide accurate values of input impedance magnitude via prior calibration. Moreover, this set-up is also able to provide accurate measurements of input impedance phase.[78] However, unlike the BIAS system, the single-microphone system is an in-house design, whose set-up and operation is more cumbersome. This decreased ease of use can represent a considerable constraint for measurement of historical instruments at specific locations, which is why the BIAS system was preferred.

An adaptor was made from nylon to fit the BIAS system at one end and the crook socket of the bass clarinet at the other. The volume of the adaptor was made to be the same as that of the instrument mouthpiece at 28 cm^3, and the end fitted closely to the BIAS system. The instrument was therefore measured in the fully ‘pushed in’ condition, which refers to its sharpest possible tuning.

For any single measurement the appropriate note was fingered, while the BIAS system performed the frequency scan. It was evident during the experiments that the slightest inaccuracy in fingering or insufficient pressure on the pad, resulting in a tiny leak at the finger or pad, changed the amplitude of the impedances, especially that of the first resonance peak, quite drastically. Each measurement was therefore repeated after relaxing the fingering, to check that the two scans were essentially identical. This emphasizes the point made earlier,

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[80] Widholm, G. Winkler, W. ‘Evaluation of musical instrument quality by computer systems. Examples of realisation’, Proceedings of the SMAC93, Royal Swedish Academy of Music, ISBN: 91845289876, (1994) 560–565; Widholm, G. ‘Brass wind instrument quality measured and evaluated by a new computer system’, in *Proceedings of the 15th International Congress on Acoustics*, Trondheim, Norway (June 26–30, 1995), Vol. III, (1995), 517–520; W. Kausel, ‘Bore Reconstruction of Tubular Ducts from Its Acoustic Input Impedance Curve,’ *IEEE Transactions on Instrumentation and Measurement* 53 (2004) 1097–1105. https://doi.org/10.1109/TIM.2004.831440

[81] Kausel, Wilfried, and Helmut Kuehnelt. ‘A Practical Way to Measure Intonation Quality of Woodwind Instruments Using Standard Equipment without Custom Made Adapters’. *J. Acoust. Soc. Am*. 123 (2008) 3015. https://doi.org/10.1121/1.2932620

[82] Widholm G. Pichler H. Ossmann T. ‘BIAS: a computer-aided test system for brass wind instruments’. *Audio Engineering Society* Preprint; (1989) 2834.

[83] ‘Modular Platform for Assisted Instrument Construction’, https://www.ircam.fr/project/detail/pafi/ consulted 22 November 2017

that the instrument must be in good, leak-free condition for meaningful impedance measurements.

There are other ways in which input impedance can be measured experimentally. Another method is acoustic pulse reflectometry. In this method, an acoustic pulse is sent into the instrument under test and the reflected signal is measured. Analysis of the reflected signal enables the input impulse response of the instrument to be determined, from which both its bore profile and input impedance can be calculated. Details of this method have been published by Sharp and co-workers.[84]

Dalmont[85] provides a comprehensive review of input impedance measurement techniques developed during the 20th century.

Audio frequency measurements

In order to compare the measured and calculated impedances with the pitches actually produced, the instrument was played (after warming up), and the sounds recorded over the chromatic scale. Each note was played for several seconds, without looking at a tuner and while attempting to play in the natural 'centre' of each note. Two sets of recordings were made, one with the mouthpiece pushed in (corresponding to the acoustic measurement conditions) and the other with the mouthpiece pulled out 10.8 mm, the maximum practical on this instrument, to attempt correction of the perceived sharpness when referred to A4 = 440 Hz. Recording was made in a 'dry' acoustic room (though not an anechoic chamber) with a Rode NT1A microphone (20 Hz – 20 kHz) , using an Akai EIE Pro interface and Logic Pro X software, at 24 bit 44.1 kHz.[86] The resulting WAV files were segmented into sections for each note, each at least 4 seconds long after truncating the transients at the beginnings and ends of the note to leave a steady tone portion. The frequency was determined in MatLab™ using the YIN algorithm.[87] The accuracy of this cross-correlation method is estimated by its authors to be approximately ±1 cent, which is much better than can be obtained by digital Fourier transform methods on a short sample.

Concluding remarks

The major contribution put forward in this thesis is the acoustic analysis, which may be performed on any complete instrument that is not too fragile to handle. This gives much valuable musical information that has not previously been available. This chapter describes background acoustical principles underlying sound formation in a wind instrument in general

[84] Sharp D. B. *Acoustic pulse reflectometry for the measurement of musical wind instruments.* PhD thesis, The University of Edinburgh. (1996); Sharp, D. B. 'Increasing the length of tubular object that can be measured using acoustic pulse reflectometry'. *Measurement Science and Technology* 9 (1998) 1469-1479. https://doi.org/10.1088/0957-0233/9/9/016 ; Li A. Sharp D. B. and Forbes B. J. 'Increasing the axial resolution of bore profile measurements made using acoustic pulse reflectometry'. *Measurement Science and Technology*, 16 (2005) 2011-2019. https://doi.org/10.1088/0957-0233/16/10/017

[85] J.-p. Dalmont. 'Acoustic impedance measurement, Part I: Review'. *Journal of Sound and Vibration*, 243 (2001) 427–439; https://doi.org/10.1006/jsvi.2000.3428; J.-p. Dalmont. 'Acoustic impedance measurement, Part II: Review'. *Journal of Sound and Vibration*, 243 (2001) 441–459. https://doi.org/10.1006/jsvi.2000.3429

[86] I am grateful to Huw Bowen for providing and operating the recording equipment.

[87] de Cheveigné, Alain and Hideki Kawahara, 'YIN, a fundamental frequency estimator for speech and music', J. Acoust. Soc. Am. 111 (2002) 1917 – 1930. https://doi.org/10.1121/1.1458024

and the specific phenomena appertaining to the clarinet, including the most important parameter known as the *input impedance* of the instrument. The methodology of the experimental methods used for measuring the input impedance has been described, as have the methods of obtaining audio data and analysis of the playing pitches of a suitable historical instrument.

Chapter 6

Acoustic modelling of woodwind instruments

This chapter discusses the acoustic modelling method for the calculation of input impedances of woodwind instruments. After reviews of the historical developments in the theory of musical wind instruments since 1860 and of the understanding of the significance of the input impedance spectrum, the method of computation is outlined and the choices of the equations used for the various components of the calculations are specified and justified. The method is then applied to a single bass clarinet from 1910 that is characteristic of a late nineteenth century design of straight-form instruments with German bore and a development of Müller system keywork. In addition to the calculations, detailed acoustic impedance measurements have been made and playing tests performed to measure the correspondence between theory and experiment. Finally, a graphical presentation method, called impedance mapping, has been developed in order to present the output of either measurement or calculations, their musical significance and the comparison between instruments in a readily-comprehensible way. This chapter follows closely the peer-reviewed paper by Bowen, Buys, Dart and Sharp (2018), but experimental aspects of the impedance and audio measurements have already been discussed in Chapter 5.[1]

The development of the modelling of woodwind instruments

The progressive development of mathematical and computational methods of modelling woodwind instruments has taken place over more than a century and a half, beginning with the analytical ideas of Helmholtz and the textbook by J.W. Strutt (Lord Rayleigh).[2] Major contributions were made by H. Bouasse, John Backus, and by Arthur Benade and his collaborators, expounded and summarised in their books.[3] The understanding of woodwind acoustics progressed through analytical expressions for lossless and then lossy systems,[4] linear

[1] D. Keith Bowen, Kurijn Buys, Mathew Dart and David Sharp, 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played,' *Applied Acoustics* 143 (2019) 84–99. https://doi.org/10.1016/j.apacoust.2018.08.028. I was the lead author for this paper, performing almost all of the calculations and writing most of the manuscript. The impedance measurements were made in the Musical Acoustics laboratory of the Open University by kind permission and cooperation of Prof. David Sharp and Dr. Kurijn Buys. My co-authors set up and assisted in the experimental measurements of impedance, wrote the description of these measurements, and reviewed the manuscript.

[2] Helmholtz, Hermann von. *On the sensations of tone*; Strutt, *The Theory of Sound*.

[3] Bouasse, *Instruments à Vent (Vols 1 and 2)*; Backus, *The Acoustical Foundations of Music*; Benade, *Fundamentals of Musical Acoustics*.

[4] Lamb H. Dynamical theory of sound. London: E. Arnold (1910); Caussé, R. Kergomard, J. and Lurton, X. 'Input impedances of brass musical instruments—Comparison between Experiment and Numerical Models". *J. Acoust. Soc. Am.* 75 (1984) 241-254. https://doi.org/10.1121/1.390402

system calculations,[5] analysis of the reed/mouthpiece system,[6] impedance of the bell,[7] non-linear treatment of the reed generator[8] and other factors. An excellent recent treatment appears in Chaigne and Kergomard.[9] In 1979, Plitnik and Strong first applied the computer modelling method to the whole instrument.[10] They split the bore (of an oboe in this case) into short cylindrical segments, thus approximating the conical shape of the bore by the staircase approximation. They started from the calculated impedance of the bell radiating into open air and summed each complex impedance, in series for the segments and in parallel for the tone holes. A reed cavity impedance was added in parallel at the end of the sum. The result was the spectrum of impedance peaks as a function of frequency over the audible band. Note that this and most other approaches are based on linear theory and strictly only apply to small amplitudes. The non-linear effects of large amplitudes are critical in the understanding of the peaks selected, as discussed below, but there is agreement amongst all authors cited that linear acoustics suffices for the calculation of the tube resonances.

This general approach is still used today. Developments since Plitnik and Strong include improvements to the expressions for tone hole impedances, for wall losses, for the radiation impedance of the bell, for the influence of the reed generator and in the matrix formulation (analogous to electrical transmission line theory) which significantly speeds up the calculation.[11] Nederveen has added valuable insight into the elements of the modelling equations and a number of experimental measurements.[12] Research on simulating clarinet and saxophone sounds dynamically using digital formulations of the air column and reed/mouthpiece system in the time domain is also reaching an interesting stage, but has not been attempted in this research.[13]

[5] Backus, J. 'Small vibration theory of the clarinet'. *J. Acoustic.Soc. Am*. 35 (1963) 305-313. https://doi.org/10.1121/1.1918458

[6] C.S. McGinnis, and C.Gallagher. 'The mode of vibration of a clarinet reed'. *J. Acoust. Soc. Am.* 12, (1941) 529-531. https://doi.org/10.1121/1.1916135; Taillard, Pierre-André and Jean Kergomard. 'An Analytical Prediction of the Bifurcation Scheme of a Clarinet-Like Instrument: Effects of Resonator Losses'. *Acta Acustica united with Acustica* 101, 279-291 (2015). https://doi.org/10.3813/AAA.918826

[7] Levine, Harold and Julian Schwinger. 'On the radiation of sound from an unflanged circular pipe'. *Phys. Rev.* 73, 383-406 (1948). https://doi.org/10.1103/PhysRev.73.383; Dalmont, J.-P. C.J. Nederveen and N. Joly. 'Radiation impedance of tubes with different flanges: numerical and experimental investigations'. *Journal of Sound and Vibration* 244(3), 505-534 (2001). https://doi.org/10.1006/jsvi.2000.3487

[8] Worman, Walter E. 'Self-Sustained Nonlinear Oscillations in Clarinet-Like Systems'.

[9] Chaigne, Antoine and Jean Kergomard. *Acoustics of musical instruments (1st English edition)*. New York: Springer-Verlag (2016). 469-552.

[10] Plitnik G.R. and W.J. Strong, `Numerical method for calculating input impedances of the oboe'. *J. Acoust. Soc. Am.* 65 (1979) 816-825. https://doi.org/10.1121/1.382503

[11] Keefe, D.H. 'Woodwind air column models'. *J. Acoust. Soc. Am.* 88 (1990) 35-51. https://doi.org/10.1121/1.399911 ; Gary Paul Scavone, 'An Acoustic Analysis of Single-Reed Woodwind Instruments, with an Emphasis on Design and Performance Issues and Digital Waveguide Modeling Techniques'. PhD thesis, Montreal, Canada, McGill University, 1997; Shi Yong, 'Comparing Theory and Measurements of Woodwind-Like Instrument Acoustic Radiation' (MA thesis, Montreal, Canada, McGill University, 2009).

[12] Nederveen, C.J. *Acoustical aspects of woodwind instruments* (revised edition). Dekalb, IL: Northern University Illinois Press (1998). 109-133.

[13] Pierre-André Taillard and Jean Kergomard, 'An Analytical Prediction of the Bifurcation Scheme of a Clarinet-Like Instrument: Effects of Resonator Losses,' *Acta Acustica United with Acustica* 101 (2015) 279–91; Guillemain, P. J. Kergomard, and T. Voinier, 'Real-time synthesis of clarinet-like instruments using digital impedance

Two computer implementations of linear acoustic modelling have been made more widely available and are cited in the literature. The program IMPEDPS was written by Robert Cronin in the 1990s, based on the developments and equations given by Keefe[14] and by discussions with Keefe and Benade.[15] RESONANS was developed around the same time by IRCAM and the acoustics department of the Université du Maine in Le Mans; a brief note on application to recorders is given by Bolton.[16] Valuable summaries of the necessary equations for each component of the transmission line matrix formulation have been given by Scavone[17] and more recently Yong.[18]

The methodology descended from Plitnik and Strong is quite general for woodwind instruments that have reed generator excitation. It may also be used for flutes and recorders by using admittance peaks rather than impedance peaks, since the open entry ends of air-driven oscillators require a pressure node, rather than an antinode, at the entry end. I have therefore used this methodology together with experimental measurements and playing tests to validate the basic assertion, that acoustic impedance spectra can be calculated from geometric measurements on instruments to sufficient accuracy to give musically useful information.

Applications of impedance spectra to the understanding of woodwind instruments

The understanding of the influence of impedance spectra came first through experimental measurements and approximate analytical solutions of the acoustic equations, with particularly notable contributions made by Benade,[19] Backus[20,21] and their co-workers. Indeed, the increased understanding of instrument acoustics provided by measurements and calculations of input impedance led Benade directly to a new design of clarinet bore and keyhole placement, in which inaccuracies in intonation were corrected by enlargement or contraction of the bore around pressure nodes. Clarinets to the 'Benade NX design' are manufactured by Stephen Fox Clarinets (Toronto). [22]

Many of the experimental studies have been made primarily to test the modelling theory, rather than to investigate modern or historical instruments themselves. Campbell has written

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models,' *J. Acoust. Soc. Am.* 118 (2005) 483–494. https://doi.org/10.1121/1.1937507; Scavone, Gary P. and Smith, Julius O. 'A stable acoustic impedance model of the clarinet using digital waveguides'. *Proc. of the 9th International Conference on Digital Audio Effects (DAFx-06)*, Montreal, Canada, Sep. 18-20 2006.

14 Keefe, 'Woodwind Air Column Models.'

15 Robert Cronin and Douglas Keefe, private communications (2018).

16 Bolton, Philippe. 'Resonans: a software program for developing new wind instruments'. *Bulletin of the Fellowship of Makers and Researchers of Historical Instruments (Bull. FoMRHI)*, 79 (1995) 69-72 Communication No. 1356.

17 Scavone, Gary Paul. An acoustic analysis of single reed woodwind instruments.

18 Yong, Shi. Comparing Theory and Measurements of Woodwind-Like Instrument Acoustic Radiation. MA thesis, McGill University, Montreal, 2009.

19 Benade, *Fundamentals of Musical Acoustics*.

20 John Backus, 'Input Impedance Curves for the Reed Woodwind Instruments,' *J. Acoust. Soc. Am.* 56 (1974) 1266–79,. https://doi.org/10.1121/1.1903418

21 John Backus, 'Small-Vibration Theory of the Clarinet,' https://doi.org/10.1121/1.1918458

22 Stephen Fox. 'Benade NX clarinets in B♭ and A'. http://www.sfoxclarinets.com/Benade.html accessed 8 March 2018.

a review of the acoustic evaluation of wind instruments but the entry on woodwind instruments is very short.[23] The only acoustical investigation of historic clarinets appears to be the work of Jeltsch and co-workers. Jeltsch, Gibiat and Forest were able to perform acoustic impedance measurements on a set of four six-key clarinets made by Joseph Baumann (fl. Paris, c.1790 – c.1830).[24] The set was in very good condition and playing was permitted, so they could compare impedance measurements with playing frequencies, and also make comparisons with a modern (Noblet) clarinet; they did not attempt to model the impedances computationally. The set of historical clarinets was particularly interesting, since Baumann supplied the distinguished clarinettist and pedagogue Jean-Xavier Lefèvre. Lefèvre refers to these clarinets in his famous tutor[25] and gives particular fingerings to exploit or overcome their characteristics. In their data analysis, Jeltsch *et. al*. concentrated on the harmonicity relations produced by the fingerings of the clarinets. They showed, for example, that the first register was not well tuned, and also presented the concept of 'impedance maps', which clearly show the tuning and harmonicity relationships in the Baumann instruments. Lefèvre remarked on the tuning in his tutor and also deliberately composed his sonatas mainly in the better-tuned second register of the instrument. The modern clarinet showed much closer alignment of the harmonics. The impedance map concept is used and developed much further later in this chapter. Jeltsch *et al.* also observed that higher notes of the instruments were supported by apparently random combinations of resonances; I have shown that the combinations are not random but introduced logically and predictably through the cut-off phenomenon.[26] Jeltsch and Shackleton have performed a similar study on early nineteenth century clarinets by Alexis Bernard and Jacques François Simiot.[27]

The main concern in the pioneering modelling work of Plitnik and Strong was to demonstrate the close agreement between calculated and measured impedances for the (modern) oboe studied.[28] This indeed was found. Peaks were accurately located and peak shapes were also in good agreement, though the peak-to-valley ratios in the experimental measurement were typically a factor of about two lower than in the simulation. They ascribed this to unaccounted-for losses, in particular pad and finger resilience, socket junctions and sharp corners of tone holes, and similar discrepancies should be expected in the case of clarinets. They investigated a single oboe and were able to demonstrate why certain notes were 'bad' and why certain alternative fingerings worked. No application to historical instruments was made. Soon after, Schumacher[29] developed the theory of the clarinet to include the

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[23] Campbell, Murray 'Acoustical Evaluation of Historic Wind Instruments'. Forum Acusticum 2005 Budapest; *Acta acustica united with Acustica,* 91 Supplement (2005).

[24] Jean Jeltsch, Vincent Gibiat, and L Forest, 'Acoustical Study of a Set of Six Key Baumann's Clarinets,' in *Proc.International Symposium on Musical Instruments,* Dourdan (1995), 134–40.

[25] Jean-Xavier Lefèvre, *Méthode de Clarinette. Adopté Par Le Conservatoire Pur Servir À l'étude Dans Cet Établissement*. Paris: Impr. du Conservatoire de Musique, 1802.

[26] Bowen et al. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played.'

[27] Jean Jeltsch and Nicholas Shackleton, 'Caractérisation Acoustique de Trois Clarinettes de Facteurs Lyonnais,' in *Colloque Acoustique et Instruments Anciens: Factures, Musiques et Science*. Paris: Cité de la Musique, (1999) 103–124.

[28] Plitnik G.R. and W.J. Strong, `Numerical method for calculating input impedances of the oboe'.

[29] Schumacher, R.T. '*Ab Initio* calculations of the oscillations of a clarinet', *Acustica* 48 (1981) 71- 85; *J. Acoust. Soc. Am.* 65 (1979) S73–S73. https://doi.org/10.1121/1.2017413.

reed/mouthpiece generator and used a similar computational approach to Plitnik and Strong. He tested the theory on the experimental measurements of Backus on a single clarinet[30] and obtained similarly good agreement.

In the 1990s the IMPEDPS program was written by Cronin and applied to the understanding of the behaviour of fingerings and auxiliary fingerings on modern and replica baroque bassoons.[31] He was able to demonstrate the reasons for 'surprising' fingerings shown in contemporary fingering charts for the baroque bassoon, hence was able to obtain useful information on historical instruments by impedance calculations.

Mathew Dart, himself a maker of reproduction baroque bassoons, applied computational impedance modelling to the study of historical instruments in museums in 2011 using IMPEDPS.[32] He examined approximately 80% of surviving baroque bassoons, making detailed internal measurements of thirty-six instruments and computing impedance spectra. This enabled him to compare stylistic traits, to establish a new typology of baroque bassoons and to study eighteenth-century woodwind construction processes and tooling. He was also able to discover connections between an instrument's internal design and its probable playing characteristics. In two cases of incomplete historical instruments, he reconstructed the design and then built replicas of each. He found them to have different playing characteristics which could be understood in terms of their calculated acoustic impedance spectra.

In an investigation reported in 2012, Hichwa and Rachor used similar acoustic models to Keefe in a new program designed to investigate the effects of geometry in more detail, and to apply mathematical analysis to the results.[33] From measurements of 44 original bassoons and 14 reproductions from the baroque and early classical period, they were able to deduce the temperaments used by the original makers, which clustered in identifiable classes around mean-tone temperament. They showed by analysis how best the wing joint can be made to aid intonation. They were also able to identify acoustic inadequacies in some of the original designs, normally in the wing-joint, thus aiding the period-instrument maker in the selection of instruments to reproduce.

Dalmont, Gazengel, Gilbert and Kergomard have assessed modern clarinets, alto saxophones and oboes[34], using both impedance measurements and the RESONANS software, and reached valuable conclusions about the quantitative influence of the reed impedance, the placement of the register hole, and the measurement and effect of inharmonicity in the resonances.

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[30] Backus, J. 'Input impedance for reed woodwind instruments'. *J. Acoust. Soc. Am.* 56 (1974) 1266-1279.

[31] Cronin, Robert H. 'Understanding the operation of auxiliary fingerings on the modern bassoon'. *Journal of the International Double Reed Society*, 24 (1996) 13-30; Cronin, Robert and Douglas Keefe (1996). `Understanding the operation of auxiliary fingerings on conical doublereed instruments'. *Abstract for a Talk Presented at The* 131st meeting of the Acoustical Society of America, 13 -17 May 1996: 13–17. https://doi.org/10.1121/1.415473

[32] Dart, Mathew. *The Baroque Bassoon*: *form, construction, acoustics, and playing qualities.* PhD thesis. London: London Metropolitan University (2011).

[33] Hichwa, Bryant and David Rachor. 'In-depth acoustic modeling and temperament studies of 18th and early 19th century baroque bassoons comparing originals and reproductions by maker, time period, and region'. *Acoustics 2012*, Apr 2012, Nantes, France. Nantes: Société Française d'Acoustique, 2012.

[34] Dalmont, J.P. Gazengel, B. Gilbert, J. Kergomard, J.: 'Some aspects of tuning and clean intonation in reed instruments'. Appl. Acoust. 46 (1995) 19–60. https://doi.org/10.1016/0003-682X(95)93950-M

Sharp and co-workers have applied impedance measurement by both the capillary system and acoustic pulse reflectometry to the question of consistency of large-scale manufacture of woodwind instruments: trumpets[35], oboes[36] and clarinets[37]. In the case of oboes, for example, significant playing differences between instruments were found to be caused by relatively minor variations, such as in the venting height of one key, indicating that instrument variability can be at least partly due to the final regulation of the instrument. However, there were also larger quality-control differences such as variations in the bore profile.

Computational methodology

The approach in this thesis has been based largely on the equations developed by Keefe,[38] and uses his expressions for the impedance of conical segments including thermal and viscous losses, and for tone holes (closed, open and open with a key pad at a certain distance above the hole). Keefe's paper includes most of the advances made in theoretical modelling since Plitnik and Strong and was verified by experiments made by himself and Cronin. It is a linear, small signal, plane- and spherical-wave approach. The key parameters and equations are: the input constants, the radiation impedance of a bell, the impedance of a conic section (with thermal and viscous losses at a smooth wall), the tone hole impedances (open, closed and with a pad above) and the reed impedance. Some features such as the radiation impedance of a tone hole do not have a good theoretical model, and empirical factors have been used.

Input parameters

The input parameters are shown in Table 6.1.

Parameter	Value	Units
Speed of sound	347	m s-1
Density of air	1.19	kg m-3
Viscosity of air	1.85×10-05	Pa s
Specific heat ratio Cp/Cv	1.4	-
Thermal conductivity of air	2.6×10-02	W m-1 K-1
Specific heat at constant pressure Cp	1.006	J kg-1 K-1

Table 6.1. Parameters set in the software program IMPEDV2.

The parameters were chosen for appropriate playing conditions; that is, a somewhat elevated temperature (27° C) and humidity and a substantially elevated CO_2 content of the exhaled air. [39] The laboratory measurements were made under normal laboratory conditions, approximately 20°C and normal atmospheric composition. Coincidentally but conveniently, the product of air density and speed of sound (which determines resonant frequencies) for

35 Mamou-Mani, A. and D.B. Sharp. 'Evaluating the suitability of acoustical measurement techniques and psychophysical testing for studying the consistency of musical wind instrument manufacturing'. *Applied Acoustics*, 71 (2010) 668-674. https://doi.org/10.1016/j.apacoust.2010.01.013

36 Mamou-Mani, A. D.B. Sharp, T. Meurisse and W. Ring. 'Investigating the consistency of woodwind instrument manufacturing by comparing five nominally identical oboes.' *J. Acoust. Soc. Am.* 131 (2012) 728-736. https://doi.org/10.1121/1.3651088

37 Kowal, Paulina; Sharp, David and Taherzadeh, Shahram (2013). 'Analysing differences between the input impedances of five clarinets of different makes'. In: *Institute of Acoustics Annual Spring Conference 2013: Acoustics 2013*, 13 May 2013, Nottingham, UK.

38 Keefe, 'Woodwind Air Column Models.'

39 Nederveen, *Acoustical Aspects of Woodwind Instruments (Revised Edition)*. 17.

these two conditions agree to better than 1 part in 8000. This is approximately 0.2 cents, below the limits of audible perception, so no corrections are required for temperature and air composition when comparing theoretical and experimental data.

Radiation impedance of a bell

The precise calculation of the radiation impedance for a duct termination of various shape and flare is the subject of many papers. As noted by Chaigne and Kergomard,[40] there are no straightforward formulas for the radiation impedance of a cone or flared bell. However, in a detailed spherical-wave treatment, Hélie and Rodet have given an analytic, but computationally intensive, expression for the radiation impedance of a segment of a pulsating sphere, which should model a bell quite accurately.[41] Dalmont, Nederveen and Joly have experimentally investigated short, rapidly-flaring catenoidal bells and their approach may be applicable to at least some clarinets (though not the Heckel under consideration in this chapter).[42] Importantly, their results show that the overall input impedance of a clarinet-like tube is only weakly influenced by the radiation impedance of the bell. This might be expected, since one purpose of the design of the bell is to reduce its radiation impedance; moreover, the values of the radiation impedance of the bell are some three orders of magnitude lower than those of the overall instrument impedances, and in any case have little influence after the bottom notes in each register. The impedance spectra of the 'bell note' cases (E♭2, E2 and D2) have been calculated for the Heckel using (a) the semi-empirical formula due to Levine and Schwinger,[43] (b) the expression due to Hélie and Rodet (their equation 23),[44] and (c) the empirical formula due to Benade and Murday.[45] The only difference was a less than 5% change in the amplitude of some of the impedance peaks, with no detectable change in their frequency, in the 20 – 2000 Hz range of our calculations. I therefore selected the empirical formula of Benade and Murday, which has the benefits of experimental derivation and very efficient computation. Both tone holes in cylindrical bodies and radiating tubes with finite flanges are treated, and they give empirical formulas for the end correction. This is converted into impedance by the standard formula for a lossless cylinder (e.g.[46]), since there are no walls to cause losses.

The impedance of a conical segment

Equation 21 of Keefe's 1990 paper[47] on the modelling of woodwind air columns was used. This is a spherical wave solution, and includes viscous and thermal losses at a smooth wall. The

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[40] Chaigne and Kergomard, *Acoustics of Musical Instruments (1st English Edition)*. 684.

[41] Hélie, Thomas and Xavier Rodet, 'Radiation of a Pulsating Portion of a Sphere: Application to Horn Radiation,' *Acta Acustica United with Acustica* 89 (2003) 565–77.

[42] J.-p. Dalmont, C.J. Nederveen, and N. Joly, 'Radiation Impedance of Tubes with Different Flanges: Numerical and Experimental Investigations,' *Journal of Sound and Vibration* 24 (2001) 505–34. https://doi.org/10.1006/jsvi.2000.3487

[43] Harold Levine and Julian Schwinger, 'On the Radiation of Sound from an Unflanged Circular Pipe,' *Phys. Rev* 73 (1948) 383–406. https://doi.org/10.1103/PhysRev.73.383

[44] The Matlab coding for this equation was performed by Kurijn Buys.

[45] Benade, A.H. and J. S. Murday, 'Measured End Corrections for Woodwind Tone Holes,' *J. Acoust. Soc. Am* 41 (1967) 1609. https://doi.org/10.1121/1.2143715

[46] Fletcher, Neville H. and Thomas D. Rossing. *The physics of musical instruments*. 231.

[47] Keefe, 'Woodwind Air Column Models.'

wall losses are averaged by putting them equal to the loss at the centre of the conical segment, but since the losses vary with radius it is then essential to keep the segments short (a 'short staircase' model). A difference of less than 10% between the end diameters of the segments was used where possible. Kulik has proposed an analytic solution to the 'long cone with losses' problem[48] that offers much faster computation. However, this has been criticised on physical arguments by Grothe,[49] who also finds that it does not converge to the staircase or multi-conic models (which physically it certainly should). Kulik's theory has therefore not been employed.

Tone hole impedances

Equation 3 of Keefe's 1990 paper[50] on the modelling of woodwind air columns was used, with effective length corrections as given in his equations 5.9. These depend on both theory and on experiments by Benade and Murday and by Cronin and Keefe.[51] They give the series and shunt impedances of open and closed toneholes and include viscous and thermal losses and the presence of a pad above the hole. Following Cronin we divide the series impedance of the tone hole equally between the tone hole itself and the bore segment. The 'flange' of the open hole is taken as the cylindrical body of the tube, or the largest radius in the case of an elliptical body such as a butt joint, and a correction is included for the corner radius of the outside (but not the inside) edge of the hole. No undercutting model is included.

Several authors have published theories and experiments on tone-hole impedance since 1990: Nederveen, Dubos and Dalmont and their co-workers.[52] However, all these authors state that the accuracy of the experimental measurements is at present insufficient to distinguish between the theoretical models. Dalmont *et al*. and also Yong[53] provide figures for the length corrections on the different theories showing that the differences are not large. Moreover, the above papers mainly treat open or closed tone holes. The only information for tone holes covered with a key or plateau that appears to have been published since Keefe's paper of 1990 is that of Dalmont, Nederveen and Joly.[54] Unfortunately, they do not include the case of a pad-covered tone hole in the side of a cylinder; such holes comprise 22 out of the 24 holes on this bass clarinet. I have therefore retained Keefe's expressions and the experimental data of Benade and Murday,[45] used originally in the IMPEDPS program. It is possible that better expressions will become available in the future.

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[48] Kulik, Yakov (2007). 'Transfer matrix of conical waveguides with any geometric parameters for increased precision in computer modeling'. *J. Acoust. Soc.Am*, 122(5) EL179. https://doi.org/10.1121/1.2794865

[49] Grothe, Thimo. 'Experimental Investigation of Bassoon Acoustics'. Dr,-Ing thesis, Technical University of Dresden (2014).

[50] Keefe, 'Woodwind Air Column Models.'

[51] Benade and Murday, 'Measured End Corrections for Woodwind Tone Holes'; Robert Cronin. Unpublished; private communication, 2018.

[52] Nederveen, C.J. J. K. M. Jansen, and R. R. van Hassel, 'Corrections for Woodwind Tone-Hole Calculations,' *Acta Acustica United with Acustica* 84 (1998) 957–66; Dubos, V. Kergomard, J. Khettabi, A. Dalmont, J.-P. Keefe, D.H. and Nederveen, C.J. 'Theory of Sound Propagation in a Duct with a Branched Tube Using Modal Decomposition,' *Acta Acustica (Stuttgart)* 85 (1999) 153–69; Dalmont, J.-P. Nederveen, C.J. Dubos, V. Ollivier, S. Vincent Meserette, V. and te Sligte, E. (July/August 2002). Experimental determination of the equivalent circuit of an open side hole: Linear and non linear behaviour. *Acta Acustica united with Acustica*, 88 (2002) 567–575.

[53] Yong, 'Comparing Theory and Measurements of Woodwind-Like Instrument Acoustic Radiation.'

[54] Dalmont, Nederveen, and Joly, 'Radiation Impedance of Tubes with Different Flanges'.

External interactions between tone holes in this model are not included, in common with Plitnik and Strong, and Cronin. This is in principle a source of error, but interaction equations do not appear to be available for key-covered open holes. We expect the effect to be relatively small for bass clarinets, with widely-separated and covered holes. The work of Lefebvre *et al.* suggests that the error will be to flatten the computed resonant frequencies by perhaps a few cents, which, as will be seen, would slightly improve the comparison with experiment in the cases studied.[55]

Reed impedance

The reed volume (including an estimate of the average vibrating part of the volume) should in principle be accounted for as a complex impedance in parallel with that of the column, since the oscillation forces the reed away from the mouthpiece lay. A number of authors have studied the aeroacoustics in detail,[56] but for the current research we only need to know the effect on the instrument resonances. More accurately, we should need the impedance as seen from inside the mouthpiece looking back at the reed, whose imaginary part should be equal and opposite to that of the resonance peak, to ensure that there is no phase shift around the feedback loop to the reed. This therefore includes a contribution from the mouth and oral cavities, which is why one can adjust pitch and timbre slightly by voicing in the oral cavity. Hence, the frequencies selected by the instrument will be slightly below the impedance peaks of the tube alone, even when including a segment of equivalent volume to the mouthpiece.[57]

Benade and Gans[58] showed that the shift from the exact resonance peak is calculated by balancing the phase shift between pressure and flow in the mouthpiece with that arising from the inertia and stiffness of the reed and that of the oral cavity. This has been considered by Nederveen and by Dalmont and co-workers.[59,60] The latter have reported theoretical and experimental work on soprano clarinets, oboes and alto saxophones using an artificial mouth with a blowing machine. They show that reed impedance effects on the tuning can be satisfactorily incorporated in an impedance model by adding a frequency-independent equivalent length correction to the end of the tube (including the mouthpiece volume). For soprano clarinets, this end correction was found experimentally to be 7±2 mm, somewhat smaller than Nederveen's estimate of 10 mm for the length correction itself, plus a further 5

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[55] George R. Plitnik and William J. Strong, 'Numerical Method for Calculating Input Impedances of the Oboe'; Robert H. Cronin, 'Understanding the Operation of Auxiliary Fingerings on the Modern Bassoon'; Lefebvre, Antoine, Gary P. Scavone, and Jean Kergomard, 'External Tonehole Interactions in Woodwind Instruments,' *Acta Acustica United with Acustica* 99 (2013) 975–85. https://doi.org/10.3813/AAA.918676

[56] Nederveen, Acoustical Aspects of Woodwind Instruments (Revised Edition); Thompson, Stephen C. 'The effect of the reed resonance on woodwind tone production', *J. Acoust. Soc. Am. 66* (1979) 1299-1307. https://doi.org/10.1121/1.383448; M. E. McIntyre, R. T. Schumacher, and J. Woodhouse, 'On the Oscillations of Musical Instruments,' *J. Acoust. Soc. Am.* 74 (1983) 1325–45,. https://doi.org/10.1121/1.390157; Andrey Ricardo da Silva, 'Numerical Studies of Aeroacoustic Aspects of Wind Instruments' (PhD thesis, Montreal, Canada, McGill University, 2008); A. Hirschberg et al. 'Musical Aero-Acoustics of the Clarinet,' *Le Journal de Physique IV* (1994) C5-559-C5-568,. https://doi.org/10.1051/jp4:19945120

[57] Note that the same would apply to the oboe, bassoon, saxophone and reed instruments in general. The opposite shift holds for brass instruments.

[58] Benade and Gans, 'Sound Production in Wind Instruments'.

[59] Nederveen, *Acoustical Aspects of Woodwind Instruments (Revised Edition)*.133.

[60] J.P. Dalmont et al. 'Some Aspects of Tuning and Clean Intonation in Reed Instruments,' *Applied Acoustics* 46, no. 1 (1995) 19–60,. https://doi.org/10.1016/0003-682X(95)93950-M

mm for a correction due to reed damping. No estimates have been reported on bass clarinets to my knowledge, but an expression is given by Chaigne and Kergomard[61] from which we may estimate the scaling factor. They give the 'embouchure equivalent length', Δl as

$$\Delta l = \frac{\rho c^2}{p_M} \frac{S_r}{S} . H (1)$$

where ρ is the density of air, c the speed of sound, p_M the mouth (closure) pressure, S_r the reed area, S the bore area and H the slit opening of the reed when not under pressure. In comparison to a soprano clarinet, a bass clarinet of the same pitch class scales linearly in its length and linearly in its bore area (not diameter). Its mouthpiece thus has typically twice the reed area, twice the bore area, twice the slit opening and a similar mouthpiece pressure (resulting in a greater air flow through the larger aperture). The value of Δl can then be roughly estimated as around double the correction in soprano clarinets, namely 14 ±4 mm, which should be increased by about 6% (0.84 mm) in the present case since it is an instrument in A. This estimate is not accurate enough to incorporate immediately in the computations (in fact, Dalmont *et al*. suggest using this length as a fitting parameter) but will be discussed after presentation of the results. In the final implementation I use an equivalent length correction ('embouchure correction') as suggested by Dalmont *et al*.

Verification and performance of the program

The computational model used in this thesis was implemented under the MatLab™ programming platform and named IMPEDV2. The best way to verify a large computer program is by comparison with an existing program. The IMPEDPS program and its source code was kindly made available by Robert Cronin. IMPEDV2 could be configured to have identical implementations of the parameters and equations, and thereby it was verified that the outputs of the two programs were indistinguishable within computational precision. This gives the ability to calculate a complete instrument (up to 50 notes including alternatives) and to analyse its resonances in about two minutes,[62] and also gives the facility to introduce different acoustic models. For example, it was straightforward to introduce and calibrate an embouchure equivalent length, following Dalmont et al.[63] and this was eventually adopted; in fact it was the main difference between the IMPEDV2 and IMPEDPS implementations.

Output data structures

For each fingering, the program calculates the real and imaginary parts and the absolute magnitude of the impedance (resonance). The absolute magnitude is the value that is relevant to the acoustic properties, since this represents the pressure in the antinodes, but the other values are useful. The imaginary part, related to the phase of the wave[64] crosses zero positive-going at impedance maxima and negative-going for impedance minima. It can be used mathematically to define the maxima and minima very accurately. Moreover, inconsistencies in the plots of phase can indicate problems with the computation, so it is worth keeping all these numbers. There is one value for each frequency interval, normally 0.5 Hz from 20 to

[61] Chaigne and Kergomard, *Acoustics of Musical Instruments (1st English Edition)*. Equation 9.17.
[62] on a MacBook Pro (2014) with 3 GHz Intel Core i7. This is about 50 times faster than the original IMPEDPS program written in FORTRAN running in DOS.
[63] Dalmont et al. 'Some Aspects of Tuning and Clean Intonation in Reed Instruments.'
[64] The phase angle = tan $\left(\frac{imaginary\ part}{real\ part}\right)$.

2000 Hz, so a single instrument will be represented by about a quarter of a million numbers. Each fingering is output as a separate file, with filenames labelled sequentially by SPI-notated pitch, to aid automatic analysis.

Selection of harmonics by the instrument

As discussed in Chapter 5, the harmonic spectrum and its stability has a complicated dependence on blowing pressure as well as on the basic clarinet resonances at a particular fingering.[65] For the purposes of this research, we simply look for a good match between the first and at least one other resonance with harmonics of the pitch of the note being played, in the first register; on the clarinet these will be the third and if possible the fifth harmonics. In the second register, it is the second resonance peak that aligns with the fundamental of the sounded frequency, since the register key shifts the first peak out of 'alignment' with the harmonics so that it can no longer participate in a regime of oscillation. In the third register, the third resonance peak takes over this function. The cutoff phenomenon in instruments with tone holes and a bell whereby frequencies above cutoff do not reflect at the finger holes or the bell but pass through into open air, means that higher frequencies are unimportant in maintaining oscillation. The impedance curves show that there are small resonant peaks at frequencies after cutoff, so they can weakly affect the tonal colouration. They are only accidentally at harmonic frequencies of the note being played, because they reflect from the bell at different positions, depending on their frequency and on the shape of the bell.

We note that the cutoff effect is roughly twice as significant in clarinets as it is in bassoons, oboes or saxophones because of the absence of even harmonics, especially at low pitches. As a guide, notes above written G in the second register (i.e. notes above sounding pitch E4, approximately 330 Hz, in this case) have all their harmonics above the nominal cutoff frequency. The cutoff phenomenon will be examined in more detail in Chapter 8.

Results

Comparison of calculations and acoustic measurements

All measurements and comparisons have been made for the Heckel bass clarinet in A described in Chapter 5. The tone-hole cutoff frequency for this instrument is about 1000 Hz, calculated from Benade's formula[66] for an open tone-hole lattice

$$f_c = 0.11c\left(\frac{b}{a}\right)\left(\frac{1}{sl}\right)^{1/2} \quad (2)$$

where f_c is the cutoff frequency, c the speed of sound, a the pipe radius, b the hole radius, s the hole spacing and l the acoustic length of the holes. Clearly this is an approximation, since the hole spacings and diameters do vary, but it is approximately confirmed by visual inspection of the impedance spectra. It is worth noting this value, since for bass clarinets, and

[65] Benade and Gans, 'Sound Production in Wind Instruments'.

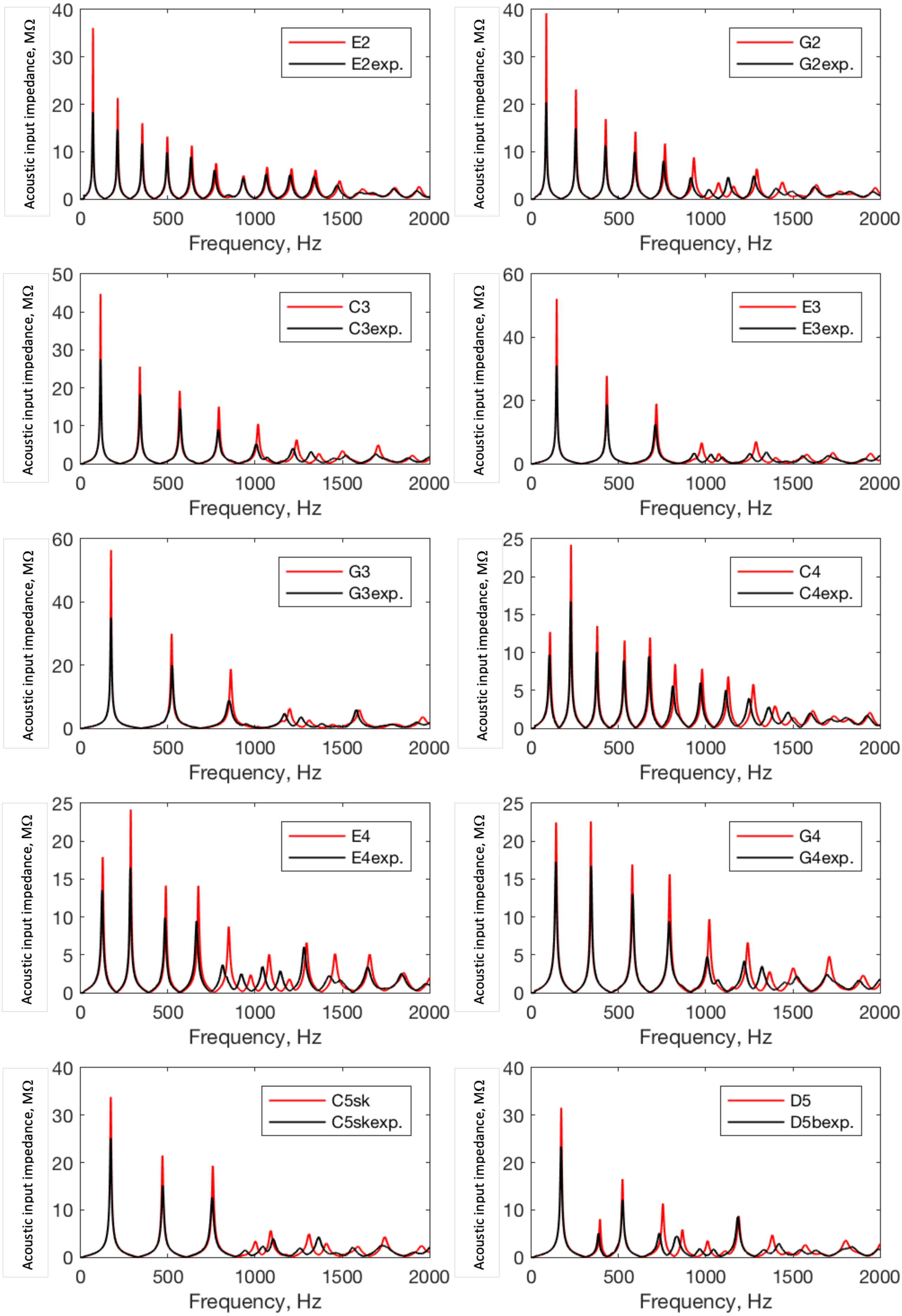
[66] Benade, *Fundamentals of Musical Acoustics*, 449; Joe Wolfe and John Smith, 'Cutoff Frequencies and Cross Fingerings in Baroque, Classical, and Modern Flutes,' *J. Acoust. Soc. Am.* 114 (2003) 2263–72. https://doi.org/10.1121/1.1612487

also by scaling from soprano clarinets, one would normally expect a cutoff around 750 Hz.[67] This is a significant parameter to evaluate in the study of historical instruments, since it definitely affects the musical sound and playing qualities. Benade suggests that woodwind instruments have 'evolved' over the centuries so that their cutoff frequencies became approximately constant over the whole range of the instrument. The range on the instrument for analysis was chosen to be from written E2 to D5 (69.3 to 494 Hz fundamental frequencies), corresponding to C#2 to B4 concert pitches. Whilst information could be obtained from higher note fingerings, it is less significant; only one resonance frequency contributes to defining the pitch produced for notes above about G4, and this pitch can be varied widely by embouchure control in the altissimo regime. In this regime the pitch of the sound produced is more reliant on the skill of the player than on the instrument.

To give an overall impression, first a sequence of notes is shown from (written) C major arpeggios from E2 up to C5, with experimental and calculated impedances superimposed (Figure 6.1). No embouchure correction was made for these data. The experimental absolute values of the impedance peaks agree well in frequency with the calculated values but are up to a factor of two lower in amplitude. This is consistent with the results of Plitnik and Strong,[68] and probably indicate that some losses in the tube, such as fingers, pads, turbulence at edges, or wall porosity are not taken into account in the model. However there may also be experimental reasons for the discrepancy, such as the smoothing algorithm used by BIAS, or the short measurement interval possibly being insufficient to excite high-Q resonances completely.[69] This discrepancy has not been investigated further in this thesis work, since the primary interest is in the frequencies of the peaks.

Figure 6.1 (next page). Ten comparisons of experimental and computed results, in a (written) C major arpeggio from low written E2 up to C5 plus D5. Measured data are shown in black lines, calculated impedances in red lines (with 'exp' added to the SPN). The abbreviation 'sk' deotes a side key (rather than a forked) fingering and 'b' indicates one of the alternate fingerings that was investigated. The measured and calculated lines largely overlap for each note, but the measured amplitudes are significantly lower and the frequencies very slightly lower. Note that for C4 to C5 the second impedance peak becomes the basis of the sound, through use of the speaker key, which depresses and shifts the first resonance out of a harmonic relationship with subsequent resonances. For D5, the sound becomes based upon the third resonance peak. The cutoff frequency is ~1000 Hz in this instrument; frequencies above this value are not expected to participate in the standing wave formation and in the feedback to the reed, ecept by accidental coincidence.

67 Chotteau, Michel. 'The Inspectrum Clarinet System', Master's thesis, Case Western Reserve University, Cleveland, OH, 1971. Quoted in Benade, *Fundamentals of Musical Acoustics*, 486.
68 Plitnik and Strong, 'Numerical Method for Calculating Input Impedances of the Oboe'.
69 I thank one of the anonymous reviewers of the Bowen et al. paper for *Applied Acoustics* for this suggestion.


Acoustic input impedance, MΩ
Frequency, Hz
E2
E2exp.
G2
G2exp.
C3
C3exp.
E3
E3exp.
G3
G3exp.
C4
C4exp.
E4
E4exp.
G4
G4exp.
C5sk
C5skexp.
D5
D5bexp.

The agreement between experiment and calculation can be tested in detail. Figure 6.2 shows the departures from equal temperament for the calculated and measured impedance values and for the frequencies determined from the playing tests. To magnify and quantify the intonation variations we express them in cents, the familiar musician's unit, where mathematically the difference in cents between two frequencies f_1 and f_2 is $1200.\log_2(f_2/f_1)$. This gives a deviation from a target pitch by an amount that is comparable over the whole range. As expected from the arguments above, the playing frequencies are slightly below the impedance peak values. It is also apparent that the instrument is playing somewhat sharp overall (relative to equal temperament at A4=440 Hz) and becomes sharper at higher notes. The calculations and playing tests were repeated for the instrument pulled out 10.8 mm at the mouthpiece (see Figure 6.3.b). As expected, this gives a useful correction to the intonation, and playing experience indicates that this is just acceptable for playing at A4=440 Hz, given the variation that is available by embouchure control especially in the upper notes.

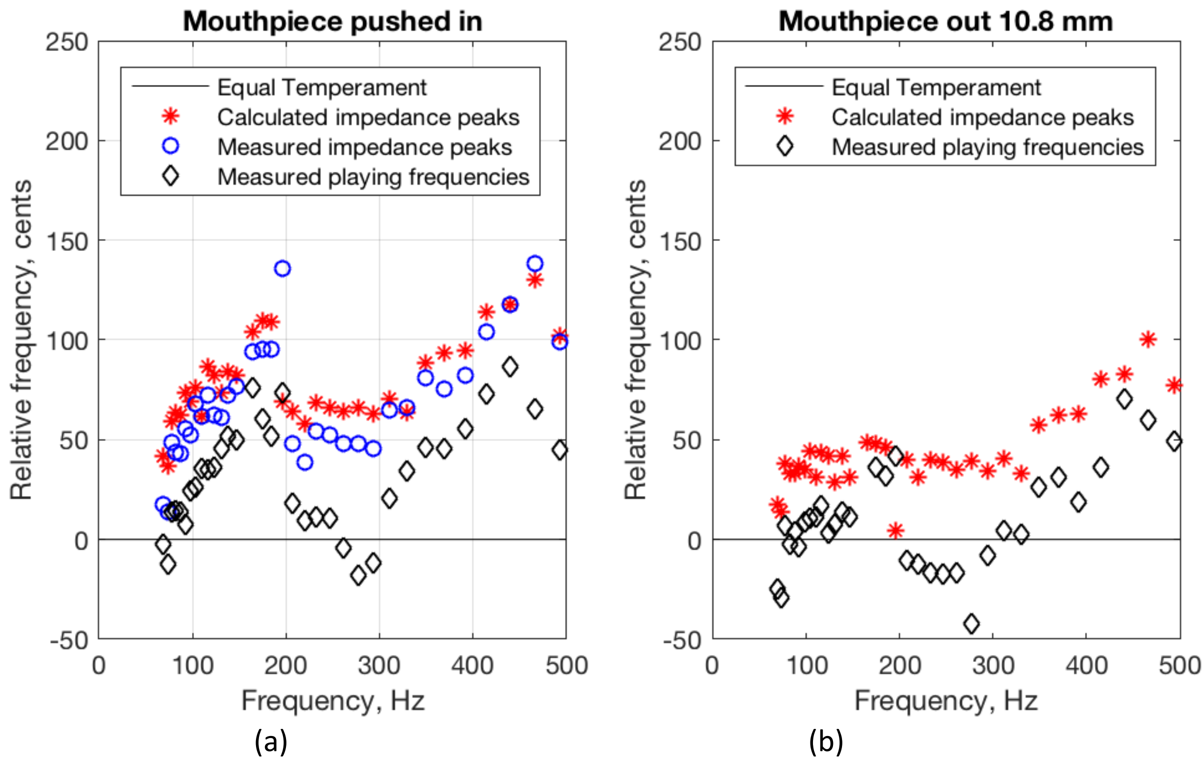


Figure 6.2. Deviation in cents for each note, (a): mouthpiece pushed in, (b): mouthpiece pulled out 10.8mm. The horizontal line at y=0 represents equal temperament at A4=440 Hz. Measurements of the 'pulled-out' impedances were not taken. The 'break' in the instrument ranges between written Bb3 and B3 occurs at about 200 Hz and that between C5 and C#5 at about 450 Hz. Up to the first break the first resonance frequency is plotted, between the first and second break the second resonance and above the third break, the third resonance peak. Each data point corresponds to a single note. The equal temperament frequencies are calculated at A4 = 440 Hz.

There is scatter in Figure 6.2a, but we see that the calculated peaks are close to the measured peaks but systematically a little higher in frequency. We also see that the playing frequencies are lower still (as expected from acoustic theory) but appear to follow the measured or calculated deviations. Again, these can be further quantified. Figure 6.3a shows the differences between calculated and measured impedance peaks, with the calculated peaks being a little higher in frequency. The difference averages at 10 ± 8 cents (±3× the standard deviation of the mean), which can be corrected quite well with a 3 mm calibration correction segment added to the mouthpiece (see below). It is possible that at least some of this difference can be ascribed to interactions between tone holes, which are expected to lower the resonance frequencies by a few cents.[70] Meanwhile, Figure 6.3b shows the difference between the measured impedance peaks and the playing frequencies. These average at 37 ± 8 cents and correspond to the effects of the reed impedance.

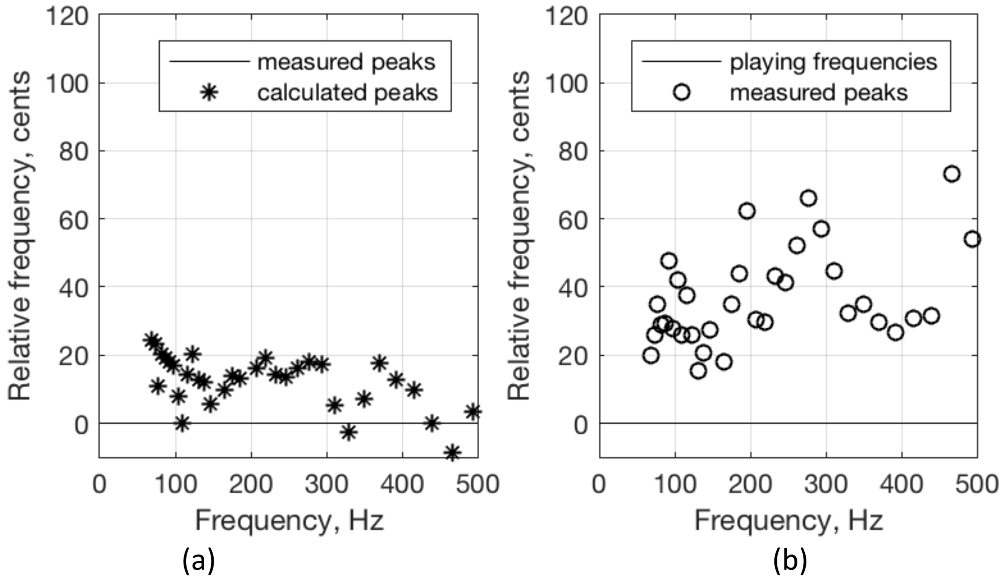


Figure 6.3. (a): differences between calculated and measured impedance peaks. (b): differences between measured impedance peaks and measured playing frequencies. In both cases the mouthpiece was fully pushed in, and in case (b) was played at *mf* levels. No embouchure or calibration correction was applied to the calculated results in (a). The *y* = 0 line corresponds to zero difference.

Since the impedance peak differences between calculation and experiment are small and reasonably consistent, they appear to be systematic and might be reduced by further development of the computation, for example to take account of losses other than the viscous and heat losses inherent from a smooth-walled tube, or of tone-hole interactions. Viscothermal losses due to porosity are the obvious candidates and indeed the Heckel instrument has a dry appearance and may need oiling. Note that much information on sound absorption of porous materials is available from the extensive literature on acoustic damping in architecture. However, I consider that an agreement within about 10 cents, which may be corrected empirically by an equivalent length of 3 mm on the mouthpiece segment, is sufficiently accurate for the research into historical instruments.

The difference of approximately 37 cents between the measured (or corrected calculated) peaks and the playing frequencies is ascribed to the embouchure correction discussed above. The results appear similar to those of Dalmont *et al.*[71] though there is more scatter in the present results, possibly because the former used a blowing machine not a player. From the scaling expected, an embouchure equivalent length of about 15 ±4 mm should be added to the

[70] Lefebvre, Scavone, and Kergomard, 'External Tonehole Interactions in Woodwind Instruments.'
[71] Dalmont et al. 'Some Aspects of Tuning and Clean Intonation in Reed Instruments.'

top of the mouthpiece impedance. I therefore recalculated the impedances with a number of embouchure equivalent lengths added to the top of the column, just before the terminating impedance. There was substantial scatter but the best estimate is that the equivalent length added onto the mouthpiece segment (at its same diameter) should be 17 ±4 mm, plus 3 mm to correct the ~10 cent difference between our computed and measured impedance curves. The graph for 20 mm total added length is shown in Figure 6.4 for both 'mouthpiece pushed in' and 'mouthpiece pulled out 10.8 mm'. This shows that the empirical, but theoretically supported, embouchure and calibration correction works equally well for these two conditions. The assumption of frequency independence seems reasonable within the experimental accuracy; there is some downwards trend in each register (which changes at about 200 and 450 Hz) but there is little overall frequency dependence. The value of +17 mm for the embouchure correction is consistent with the soprano clarinet values of Dalmont *et al.*, using the approximate scaling argument. They would vary somewhat with a different player and mouthpiece/reed, but the usefulness of this number is that, where the mouthpiece of an historical instrument is missing, we can make estimates of its effect based on the mouthpiece used in this investigation.

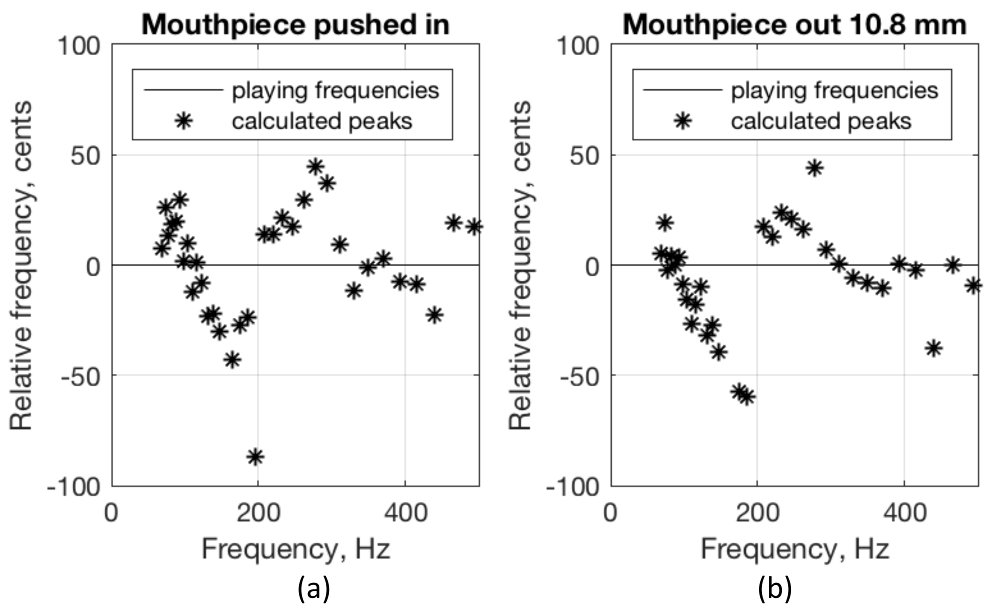


Figure 6.4. Comparison between calculated impedance peaks and measured playing frequencies when the overall embouchure end correction was 20 mm. (a) with mouthpiece pushed in, (b) with mouthpiece pulled out.

Note that a maker would not necessarily build the instrument so that the average deviation from playing pitch was zero, since notes that are flat are much harder for the player to correct than those that are sharp. Recall also that these are small-signal calculations and measurements and that on a clarinet the pitch drops at higher blowing pressure. Also, the player needs to be able to play in tune when the instrument is cold, especially for a doubling instrument such as a bass clarinet in A. A more suitable choice is an instrument that is slightly sharp on average with no notes that are too flat to be easily corrected. The graphs above show that this is indeed the case for the Heckel instrument. Moreover, the consistent tendency for the intonation errors to rise fairly smoothly from the bottom to the top of each register makes it easier for the player to manage the adjustment that is needed on each note.

Investigation of alternative fingerings

An important application of modelling in the understanding of historical instruments is comparative. For example, it is often of interest to study the intonation and stability of alternative fingerings (e.g. Cronin's work on bassoons[72]). This was tested by calculating and playing several notes that may have alternative fingerings in Müller-based systems: written B♭2, E♭3, F3, C#4 and C5. These are referred to as 'normal' or 'fork' and are shown in Table 6.2.

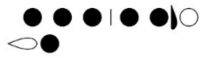
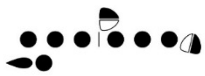
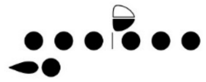
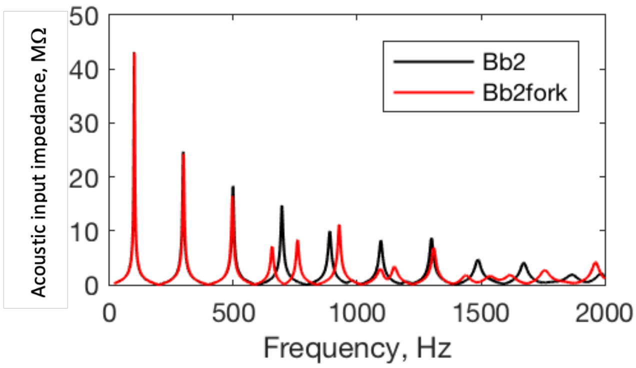
Note	Normal	Fork
B♭2		
E♭3		
F3		
C#4		
C5		

Table 6.2. Alternative fingerings investigated. The fingering diagrams were constructed using the Bret Pimentel Fingering Builder.[73]

Only the calculated results are shown, again using a 17 mm embouchure correction and a 3 mm calibration correction, in Figure 6.5 to Figure 6.9. In each case the 'normal' fingering is shown in black and the alternative in red. In all except Figure 6.9 the first resonance and at least one other resonance aligns well between the two fingerings, and these also align with the fundamental and third harmonic of the intended played note (the harmonic positions are not shown on the figures). For some notes, the resonances align well with the 5th and 7th harmonics also. The observation on playing was that a two-resonance match was sufficient to produce a good match in intonation for the two fingerings, but that the more resonances that were aligned, the more was the match in timbre between the alternative fingerings.



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[72] Cronin, 'Understanding the Operation of Auxiliary Fingerings on the Modern Bassoon'.

[73] Pimentel, Brett, *Fingering Diagram Builder*. https://fingering.bretpimentel.com/#!/clarinet-german/albert/ . Accessed 11 March 2018.

Figure 6.5 (previous page). Calculated impedance spectra for two fingerings for the note B♭2. The first three resonances overlap almost exactly for the two fingerings. To hear these fingerings as played, click the sound icon or play the external file Heckel Bb2 crosskey then fork and repeat.mp3.

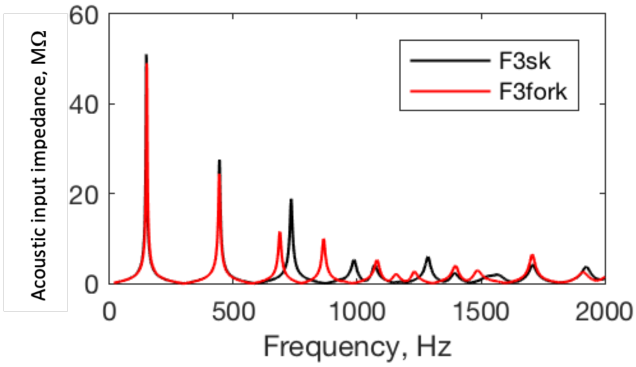

Figure 6.6. Calculated impedance spectra for two fingerings for the note F3. The first two resonances overlap almost exactly. To hear these two fingerings, click the sound icon or play the external file Heckel F3 side key then LT010 and repeat.mp3.

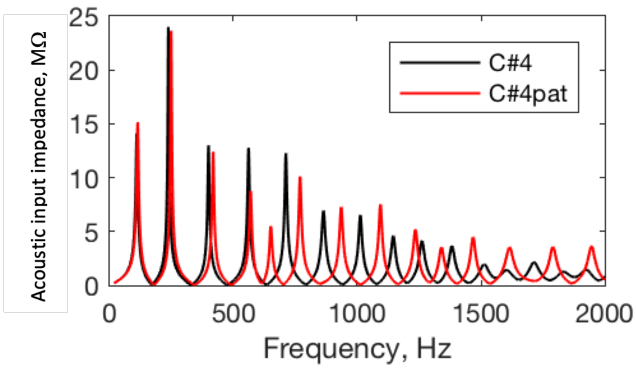

Figure 6.7. Calculated impedance spectra for two fingerings for the note C#4. The 'patent C#' fingering will be slightly sharp.

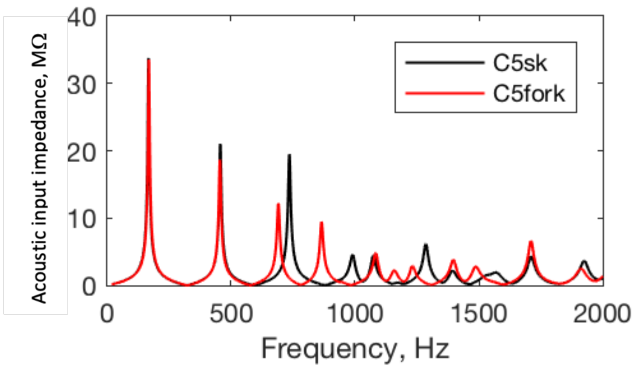

Figure 6.8. Calculated impedance spectra for two fingerings for the note C5. The first two resonances overlap almost exactly.

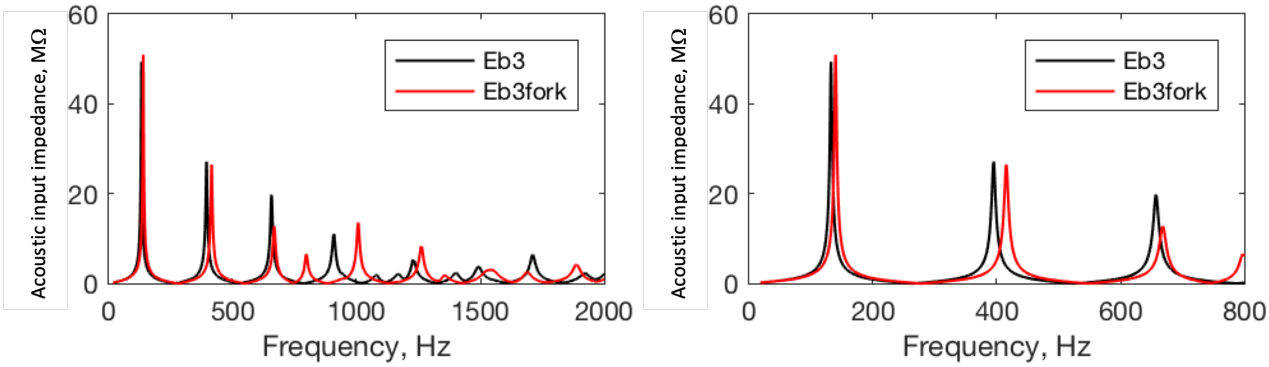

Figure 6.9. Calculated impedance spectra for two fingerings for the note E♭3, at two frequency scales. The resonances indicate that the 'alternative' fingering will be almost a semitone sharp. To hear these two fingerings, click the sound icon or play the external file Heckel Eb3 side key then LT101 and repeat.mp3.

However, the forked D#/E♭3 shown in Figure 6.9 showed a poor match between the two fingerings, and as predicted from the impedance curves, the fork fingering played almost a semitone sharp. Whilst the fork fingering is often acceptable for this note on earlier Müller system clarinets (sometimes it is the only fingering for this note) it is clearly not the case here; and is generally not the case for Albert system clarinets. This demonstrates both the accuracy and the usefulness of the impedance spectra.

Impedance maps and the cutoff frequency

A full set of calculations for all the notes on a clarinet results in some quarter of a million numbers or about 50 spectra. It is then very difficult to pick out differences between instruments. Jeltsch *et al.*(1995)[74] introduced the concept of impedance maps that show the resonances of all of the fingerings of the clarinet on one diagram and went on to apply it to experimental impedance measurements. They do not give the method of calculation, but I have developed a similar procedure and applied it to both experimental and calculated impedances. The latter is shown in Figure 6.10 for 3 mm embouchure correction, which should enable direct comparison with experimental impedances.

The maps highlight the accuracy with which the resonances of an instrument align with the harmonics of the fundamental. The method of plotting is as follows. After calculating the impedance spectra for all fingerings of the instrument, the impedance spectra are analysed computationally to determine all the peaks (resonances) in the spectra. It was sufficient to find only the first seven peaks in each impedance spectrum. For each note fingering and its corresponding set of resonances, the resonant frequencies are plotted with coordinates determined as follows:

- Ordinates: the nominal equal temperament frequency of the note, using (in this case) A4=440 Hz; this frequency is selected to best match the pitch of the instrument.
- Abscissae: the ratio of the actual frequency of the resonance to the nominal equal temperament frequency.

[74] Jeltsch, Gibiat, and Forest, 'Acoustical Study of a Set of Six Key Baumann's Clarinets.'

- The scales are logarithmic on both axes.
- Markers are placed at odd multiples of 1 on the horizontal axis.
- The calculated cutoff frequency, 1000 Hz in this case, is also plotted in the same way (thus at an ordinate of 500 Hz its abscissa will be 2, while at an ordinate of 250 Hz its abscissa will be 4). It will be a straight line in this plot.
- In our case, peaks up to 2000 Hz are included in the plot, and it is seen that this is sufficient for seven resonances (thirteen harmonics).

The meaning of this map is that, for an equal-temperament clarinet, perfectly tuned at A4=440 Hz, we should see the points representing all the cooperating resonances for a given fingering lying along a set of vertical lines near the odd integers on the horizontal scale, up to the cutoff frequency. They should be displaced slightly to the right because of the necessary embouchure correction due to reed impedance, discussed earlier, but they should compare closely with the experimental measured impedances. The latter are shown in Figure 6.11. The experimental map is constructed similarly, except that because of a small amount of noise in the experimental data, giving spurious peaks, each impedance spectrum is first processed to order the peaks by their 'prominence'[75] and then the first seven most prominent peaks are selected. This largely eliminates the spurious peaks. The register shifts on this instrument occur at approximately 200 and 450 Hz, and the change of resonance peak on which the note pitch is based is clearly seen.

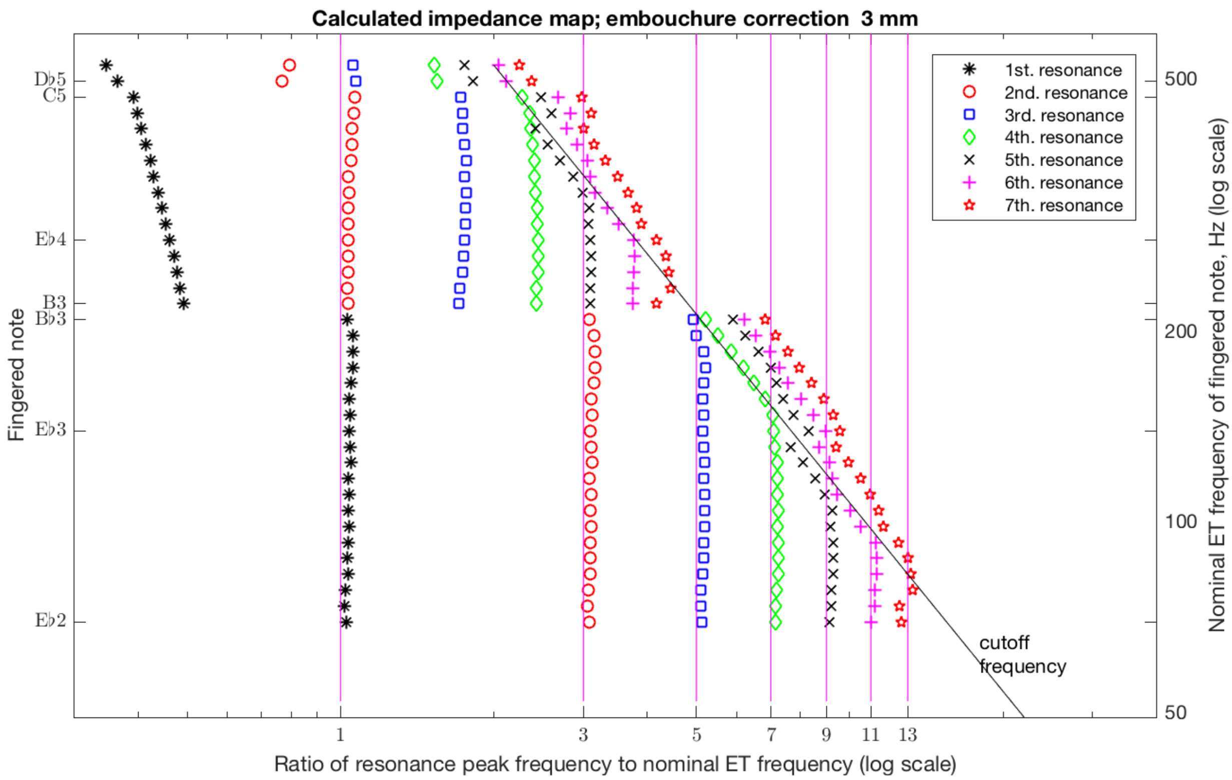

Figure 6.10. Impedance map of calculated impedances, using an embouchure correction of 3 mm, which should enable good comparison with measured impedances. See main text for explanation of method of plotting.

[75] The amount that the peak stands out due to its intrinsic height and its location relative to other peaks as defined in the MatLab™ function **findpeaks**(array).

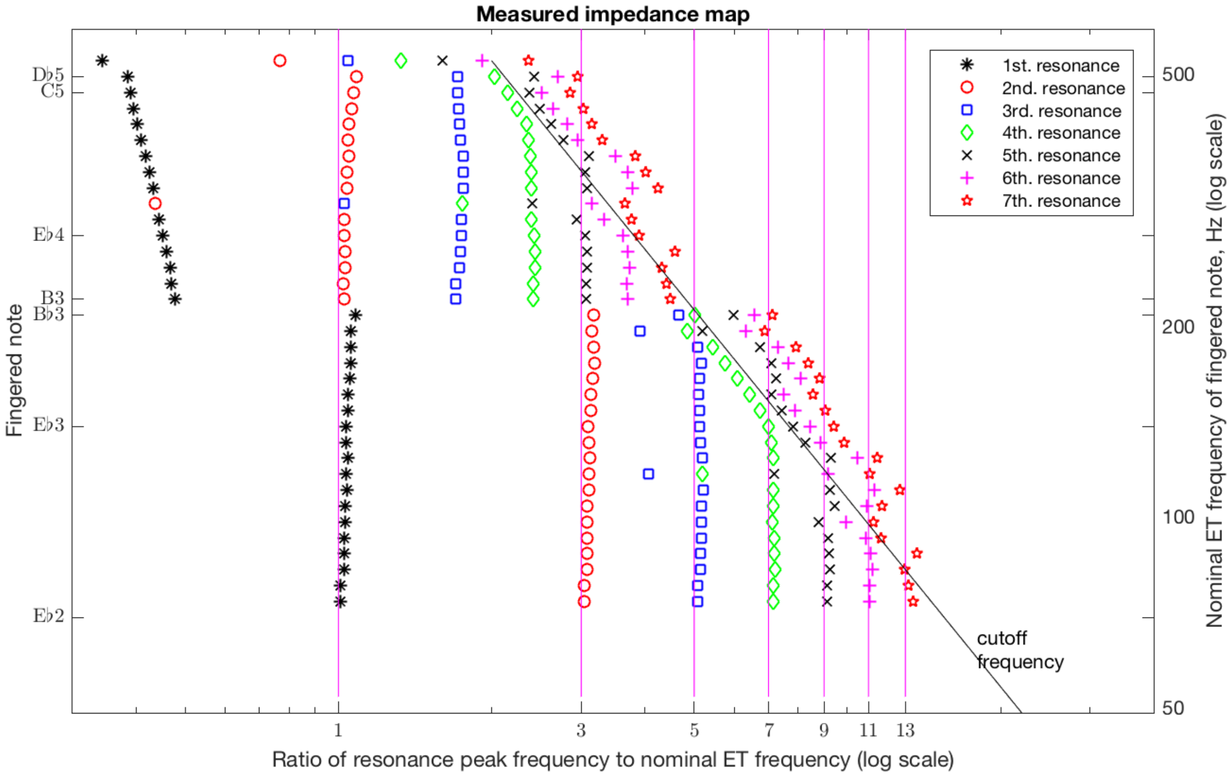

Figure 6.11. Impedance map of experimental impedances, to compare with Figure 6.10

To predict the actual playing pitches, the additional embouchure correction of 17 mm to allow for the reed impedance must be applied, as discussed above. The result is shown in Figure 6.12. The resonances are now seen to be mostly very well aligned with the harmonic numbers. Thus, when the non-linear reed generator is combined with these impedance characteristics, a cooperative regime of oscillation will be set up[76], with each harmonically-related resonance frequency contributing to the stabilisation of the oscillation, up to the cutoff frequency. It can be seen that the first seven resonance frequencies are involved at the bottom of the instrument's range, but only one resonance frequency (the second or third) contributes near the top of the range. A slight sharpness is indicated as was actually found in the playing tests.

[76] Benade and Gans, 'Sound Production in Wind Instruments'.

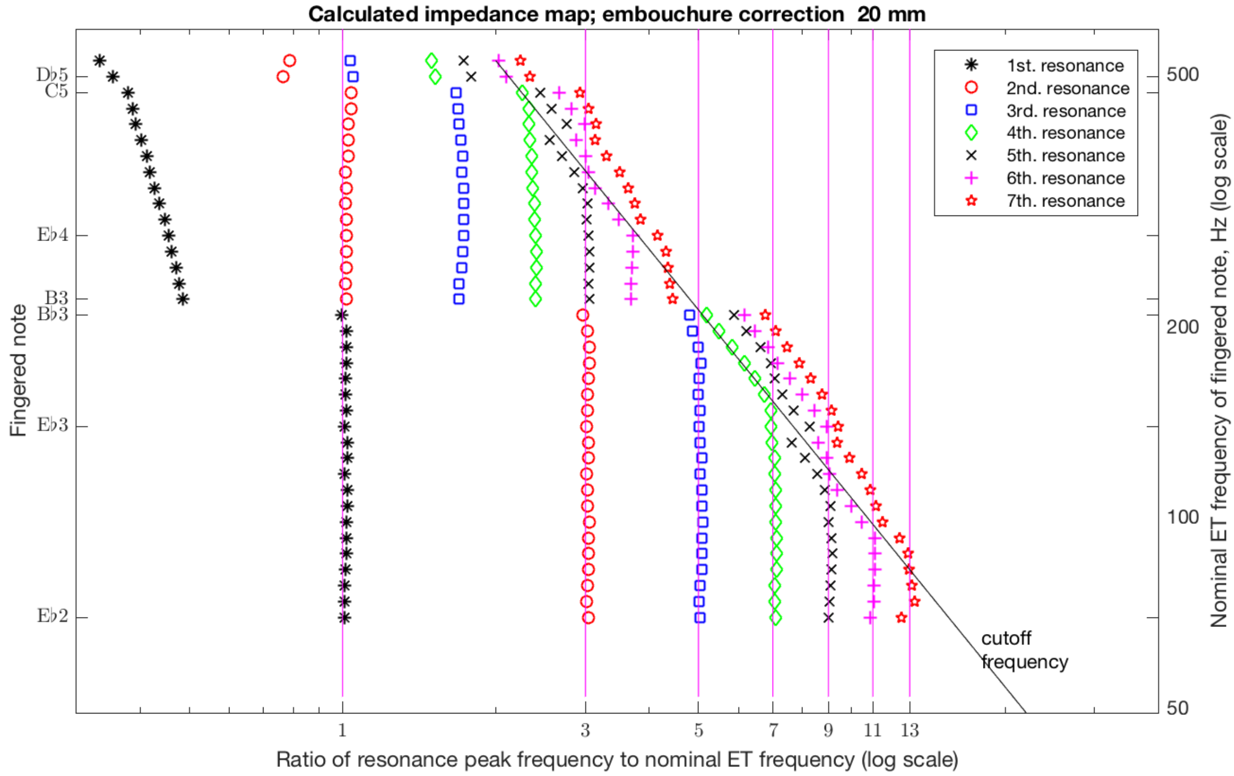

Figure 6.12. Impedance map of calculated impedances, using an embouchure correction of 20 mm. This should indicate the actual audio frequencies on playing.

If we follow any particular resonance vertically, we see discontinuities occurring at 200 and 450 Hz, the register change points. At each discontinuity, a higher resonance takes over the role of determining the playing pitch; for example the first resonance is replaced by the second at abscissa 1 at ordinate 200 (written B3). It can also be seen that, as one moves up through the registers of the instrument, for each note fingering there are still resonances which fall in the 1:3:5 etc. harmonic ratio, and thereby support harmonics of the played note.

Impedance maps also give a new insight into the nature of the cutoff frequency itself. If we look, for example, at the fourth resonance peak (denoted by green diamonds), we see that it runs vertically up to the point at which it intersects the line drawn at 1000 Hz, the approximate cutoff frequency from Benade's formula (equation (2)). Then the line turns sharply left to run parallel to the line tracing the cutoff frequency. Hence, although the resonance still exists, it ceases to be in a harmonic relationship with the first resonance peak for subsequent notes, and indeed becomes constant. At 200 Hz, the register key is applied and we see the discontinuity where the fourth peak moves to a lower frequency. This is now below cutoff, and the peak moves again along a vertical line. This does not correspond to any harmonic of the played note. However, if we instead follow the fifth resonance peak (denoted by black crosses), it can be seen that it initially supports the ninth harmonic of the played note. It then hits the cutoff and for the next few note pitches does not participate in the regime of oscillation. However, it then starts to support the third harmonic at 200 Hz (B3). This view of the cutoff behaviour explains in a systematic way why higher notes may combine apparently random mixtures of resonance peaks in their regimes of oscillation. If we look at the line representing the third harmonic in the impedance maps, we see that as one moves through the notes towards the top of the instrument's range, the fifth, sixth and seventh resonances all successively play a role in supporting the third harmonic.

The locus of the resonance peaks, as they start to deviate from a harmonic relationship with the lower resonances, follows closely the slope of the cutoff frequency line. We can therefore identify, if not a precise cutoff frequency, then certainly a cutoff band. The impedance map (corrected for embouchure impedance) is thus seen to contain a great deal of information about the instrument: its tuning, its harmonicity, its likely mixture of partials and the degree with which they are aligned with the resonances of the instrument. We can in essence regard the impedance map as a 'fingerprint' that characterises the acoustics of the instrument, and shall use it extensively in the study of different bass clarinets.

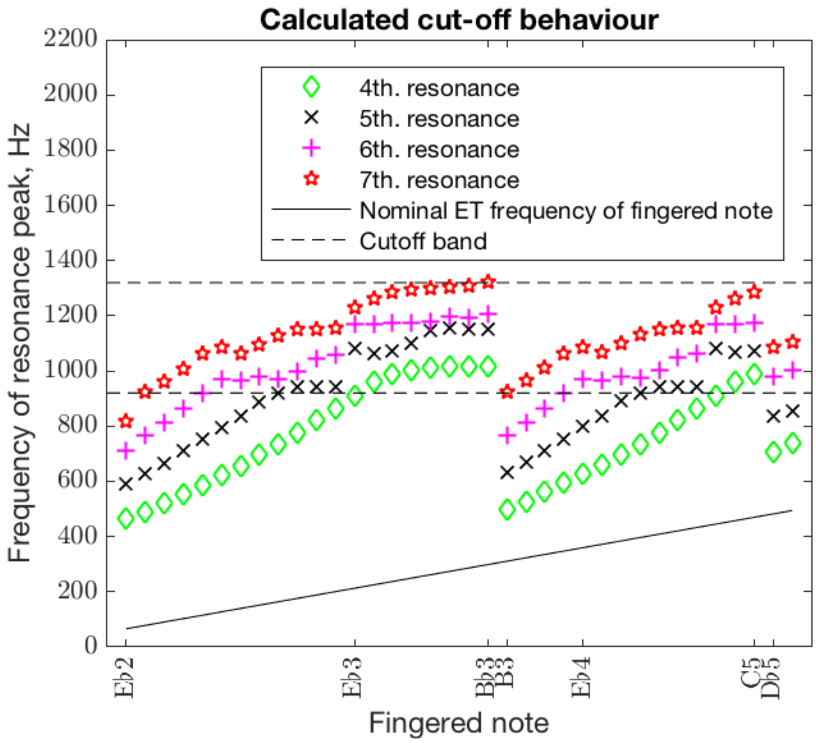

Figure 6.13. Plot of 4th – 7th resonances (supporting 7th – 13th harmonics of the played note) against the nominal ET frequency of the fingered note. Note that frequencies in this diagram are absolute, not relative as in the abscissae of the impedance spectra. The first three resonances are below cutoff on this scale. Horizontal lines are drawn at 920 and 1320 Hz, representing the cutoff band. The discontinuities at x=200 and 450 correspond to the register changes (B♭3 to B3 and C5 to C#5). Immediately after the register changes, all the resonances drop in frequency. Calculated with total embouchure correction of 20 mm, corresponding to the impedance map of Figure 6.12.

The cutoff band is seen more clearly in a simple linear plot of the individual resonance frequencies against the nominal ET frequencies of their fingerings, Figure 6.13. There is no single cutoff for the whole instrument, but each resonance individually cuts off somewhere in the band 920 – 1320 Hz. Many of them cluster around 1000 Hz, indicating that the Benade approximation (Equation 2) is reasonable and useful, though not exact. Each resonance frequency increases continuously and then saturates, except at the register changes. At register changes, all resonances drop abruptly in frequency due to the effect of the speaker key and (for the third register) first fingerhole opening. The cutoff is of course not abrupt, but a roll-off, and it is seen to depend on the fingering. The onset of cutoff for each resonance will be at a different fingering. This is understandable since it will depend on the spacing, diameters and chimney lengths of the holes. This is consistent with the observations and theory of Moers and Kergomard.[77]

Information is also available about the peak heights, which are not shown here since the plot becomes complicated and adds little insight. The peak heights near cutoff become quite small, as can be seen in, for example, Figure 6.1, and also note that the height of the resonance peak to which the fundamental aligns (abscissa 1 on the impedance maps) drops by about 50% on changing from the first to the second register ('crossing the break').

Concluding remarks

The computational model used in this study is based on small-signal, linear, plane- and spherical-wave acoustics with viscous and thermal losses at smooth walls. It does not take account of some loss mechanisms such as wall porosity, internal tone-hole edge turbulence and finger and pad resilience. Nevertheless, it is remarkably accurate for predicting the absolute values of resonance frequencies and the relative heights of resonance peaks. The method is certainly accurate enough for the purpose of reconstructing the acoustic impedance (resonance) spectra of instruments of this type. This extends the similar conclusion of Dalmont *et al.*[78] from soprano clarinets, oboes and alto saxophones to bass clarinets, and provides a reasonably accurate measurement of the embouchure equivalent length in the instrument studied.

It may eventually be possible to reconstruct the entire sound, using methods pioneered by Pierre-André Taillard and his associates,[79] which requires also the more detailed non-linear treatment of the reed/mouthpiece generator, but the preliminary step for that process is the measurement or calculation of input impedances to sufficient accuracy. The calculation of tuning and tuning accuracy (after corrections are applied) is at worst within a few cents, which is entirely adequate to measure the pitch and temperament at which an instrument was designed to play. The relative accuracy within or between instruments would be much better, so there is no problem in comparing alternative fingerings for notes, for determining the pitch and temperament in which the instrument was constructed or for comparing the overall acoustic behaviour of two different instruments. It will be extensively used in Chapter 8.

As pointed out by many others[80] the prediction of resonance peaks has utility in instrument design, restoration and modification as well as in historical research. The effect of drilling or

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[77] Moers, Elise and Jean Kergomard, 'On the Cutoff Frequency of Clarinet-like Instruments. Geometrical versus Acoustical Regularity,' *Acta Acustica United with Acustica* 97 (2011) 984–96. https://doi.org/10.3813/AAA.918480.

[78] Dalmont et al. 'Some Aspects of Tuning and Clean Intonation in Reed Instruments.'

[79] Taillard, Pierre-André, Fabrice Silva and Philippe Guillemain, 'Simulation en temps réel de l'impédance d'entrée mesurée ou calculée des instruments à vent'. In *13ème Congrès Français d'Acoustique*. Le Mans, France: Comité Français d'Acoustique, 2016, 2482-86.

[80] Benade, *Fundamentals of Musical Acoustics*. 465 ff.; Nederveen, *Acoustical Aspects of Woodwind Instruments (Revised Edition)*. 135; Scavone, 'An Acoustic Analysis of Single-Reed Woodwind Instruments, with an Emphasis on Design and Performance Issues and Digital Waveguide Modeling Techniques.'196; R. T. Schumacher, 'Ab Initio Calculations of the Oscillations of a Clarinet'; Cronin, 'Understanding the Operation of Auxiliary Fingerings on the Modern Bassoon'; Mathew Dart, 'The Baroque Bassoon: Form, Construction, Acoustics, and Playing Qualities'.

moving a hole, or of reaming the bore (for example, for removing the tenon compression induced by tenon lapping before cork came into use[81]) can be checked before material is removed. As an example, the Heckel under study in fact has a centre tenon that has a 0.1 mm constriction for a few centimetres, likely from the effect of lapping. Calculation of its effect on the impedances showed that it had a quite negligible influence and so did not need any reaming. Playing problems with a particular instrument may also be diagnosed. Again, it is clear that the Heckel instrument would play more in tune with a slightly longer neck, or at a higher orchestra pitch. Examination of the neck indicates that it might be a later replacement and not an original, and it has indeed now been fitted with a new, slide-adjustable neck.[82] The calculated impedances could also indicate how to alter a tone hole to improve the tuning, and what effect this would have on other notes. I believe, therefore, that the computational method of acoustic impedance modelling has been quantitatively validated as a research tool for investigating and restoring both historical and modern bass clarinets.

[81] McGee, Terry. *'Effect of thread wrapping on flute tenons'* http://www.mcgee-flutes.com/effects_of_thread_wrapping.htm (2011). Consulted 20/11/2017.
[82] Manufactured by Jared de Leon by 3D printing.

Chapter 7

Historical bassoon-form bass clarinets: the physical evidence

This chapter and the next seek to understand what is revealed about bassoon-form bass clarinets, and how they compare to the later straight-form bass clarinets, by the empirical evidence provided by the instruments themselves. This includes physical examination, geometric measurements and acoustic simulation. It is the first systematic study of this type for members of the clarinet family. This chapter discusses the qualitative and quantitative conclusions that may be drawn from the careful examination of a large and representative sample of the existing instruments. More than 80 bassoon-form instruments of the clarinet family, made between 1793 and 1910, are currently housed in museums and private collections, with approximately 12 more known from photographs or descriptions but lost through war or theft. Museum descriptions in catalogues or websites range from very brief entries to the detailed examination, measurement and analysis provided in the case of the German National Museum in Nuremberg.[1] Approximately thirty bassoon-form bass, alto or basset clarinets housed either in museums or private collections were examined. Where an in-person examination was not possible, information has been obtained from photographs or publications in cooperation with museum staff. Five straight-form instruments, including two by Adolphe Sax, were also studied to understand the differences between the forms. In addition, about one hundred nineteenth-century straight-form soprano clarinets, about a dozen basset horns and alto clarinets, and about twenty straight-form bass clarinets were examined to provide context and familiarity with clarinet construction from the eighteenth up to the early twentieth-century; these instruments are not reported herein. A small but representative sample of instruments of each major type (as discussed in Chapter 2) was also played or heard being played.

Strategy for examinations

Playing historical instruments

Historical instruments that have not been maintained or restored for playing can rarely be played over their whole range because of pad brittleness and leakage. It is often possible to obtain a few notes, typically G3 down to C3. In the rare instances where these instruments were able to be played, this was usually restricted to a few minutes except for the more robust metal instruments. Those instruments that had been specifically restored for playing were either played, or heard being played by a professional player. In seven cases, either playing tests were possible or a performance or recording were available. This sample is small but covers all of the different types of bass clarinet. Attention was paid to the pitch and intonation, the timbre, the volume capability and the subjective assessment of sound. Whilst ideally one

[1] Bär, *Verzeichnis Der Europäischen Musikinstrumente in GNM Nürnberg.* Band 6, *214-263.*

would need far more time to understand the playing character of an instrument these tests were used to answer specific questions, such as the effect of the butt joint on the sound or ease of playing, or to provide pointers to the directions of the acoustic study.

Physical examination and measurements

A qualitative description was noted at the time of inspection for all instruments examined. This included keywork observations noted above and an accurate measurement of the bore. The latter has a large effect upon the intonation, tone and timbre but is often not included in museum information. Measurements were taken as close as possible to the centre tenon of the instrument (i.e. just after tone hole III).

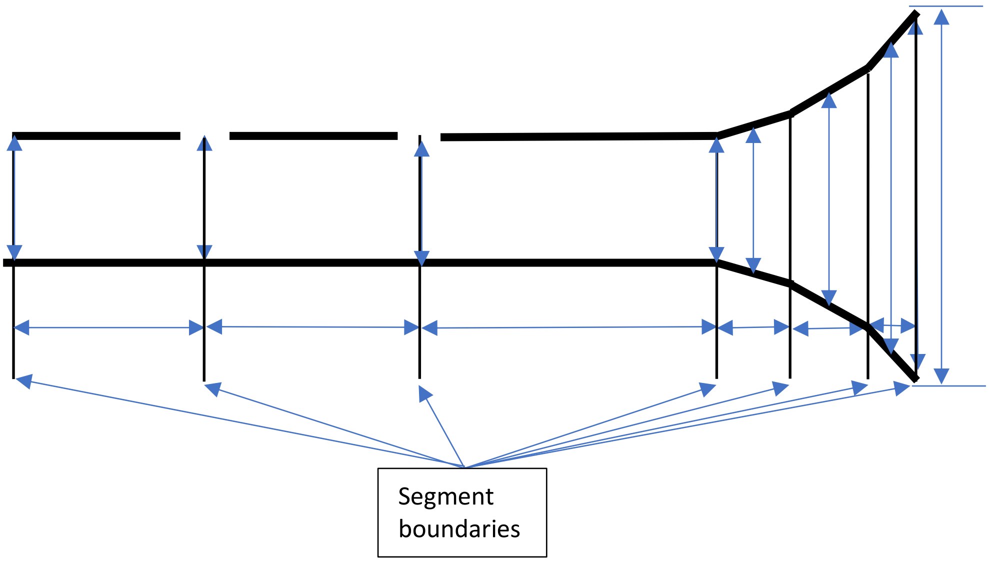
Finally, thirteen significant instruments (eight bassoon-form and five straight-form) made between 1793 and 1910 were selected for detailed geometric measurement and acoustic modelling. These were measured in enough detail to enable the computation of full impedance and resonance spectra for every note over the range of the instrument up to C5.[2] For these thirteen instruments the requirements are as follows, according to parameters which all influence the acoustic impedance; these are illustrated in Figures 7.1 and 7.2.[3]

- A complete geometric profile of the bore measured from the bell to immediately after the mouthpiece. This is divided into segments; the measurement is of the input and output diameters of the segment and its length. The choice of segment length is determined by the need for the input and output diameters to be no more than 10% different (to ensure validity of the equations used) and by the presence of tone holes. A tone hole automatically terminates a segment. Typically, 50 – 100 segments are required to describe a clarinet or bass clarinet.
- Tone hole information, including the position, and diameter of tone holes, any rounding or undercutting (if possible), the presence and size of a pad and the distance between the top of a hole and the underside of the pad when open. Tone holes are not assumed to be round but measured along two directions and averaged.
- The chimney length of each tone hole, averaged where there is an oblique intersection with the bore or outer surface.
- The outside diameter of the body at each tone hole, which affects its radiation impedance.
- The volume of the mouthpiece where possible.

Typically, 300-400 measurements are recorded for one instrument. These are essentially also the measurements that should be taken in order to make a physical replica of the instrument apart from final voicing by undercutting tone holes and the mouthpiece design.

[2] The results are presented and interpreted in Chapter 8.

[3] Bowen et al. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played.'



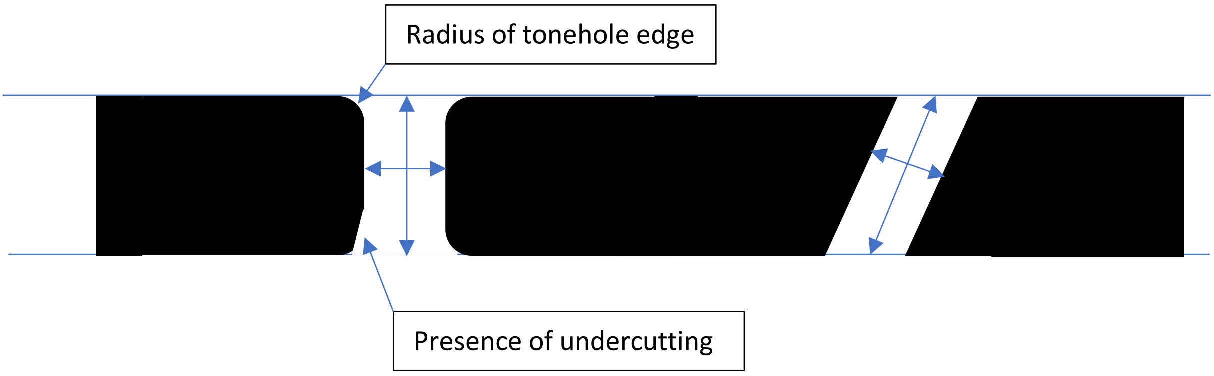


Figure 7.1 (upper). Measurement of the bore profile. Each double-headed arrow shows a dimension that must be measured. Distances along the instrument are measured from the end of the bell.

Figure 7.2 (lower). Measurement of the tone holes. Each double-headed arrow shows a dimension or feature that must be measured if present.

Tone hole positions were measured with a certified tape measure[4] that was further checked against an industrial calibrated 600 mm vernier height gauge. Measurements were made to ±0.5 mm. always referenced from the end or shoulder of a joint.[5] Tone hole diameters and depths and bore disc diameters were measured with a SPI 30-440-2 caliper with accuracy ±0.1 mm.[6] In addition to the tone hole centres and diameters (measured both along and across the clarinet axis), the chimney depth, diameter of the body at the tone hole position, the diameter of the tone hole keypad (where fitted) and its opening (venting) height at mid-pad were measured with the same tools. The radius of curvature of the outer tone hole edges was estimated at 0.5 mm for wooden finger holes and 0.1 mm for metal lined holes. I estimate that the parameters most affecting the tuning (the tone hole positions) are measured to approximately 0.3%, corresponding to an average tuning accuracy of ~5 cents. Since each length measurement is independent, this error applies separately to each note, and is not

[4] EC (European Community Standard) Class II
[5] Occasionally, interferences with keywork made this less accurate, but rarely worse then ±1.0 mm
[6] Super Polymid-Fiberglass Reinforced Plastic

cumulative. The same set of measuring tools was used for all instruments measured. Data sheets were printed for recording of all relevant data for a particular joint, and an overall sketch recorded the datum points used.

Bore diameters were measured with a large set of graduated circular Tufnol discs on the end of aluminium tubes, made by myself, illustrated in Figure 7.3. The discs are sized so that the diameter change between one disc and the next is at most 10%, with much closer spacings in the range 18 – 24 mm to accommodate typical bass clarinet bore sizes. Tufnol was chosen for its dimensional stability and for its relatively non-damaging contact properties on wood. Two 300 mm aluminium tube holders are provided for extending into the bore; these may be joined together to provide a 600 mm probing capacity. After inserting the probe with a given diameter disc until contact is just made, the crossbar is locked in position at the end of the tube, serving as the reference point for the particular joint. The whole is then carefully withdrawn and the distance from the crossbar to the farthest side of the disc is measured with the calibrated tape measure.

Figure 7.3. The set of discs and holders used for bore measurements.

The volumes of the mouthpiece and crook were measured in the case of the Heckel by filling with water, then weighing the water with a calibrated scale. The average of ten measurements was taken, giving an estimated accuracy of ±0.5%. For museum specimens this was not possible, and many instruments had replacement or missing mouthpieces. For consistency, in all cases the volume was estimated from the computation results, choosing the volume that gave the most even intonation across the range of the instrument; essentially an 'ideal' mouthpiece volume for that instrument. Empirically, this was found to scale quite well to the area of the bore in the crook.

The calculation must be performed separately for each fingering combination used, thus information on which tone holes are open or closed for the production of a given note, i.e. the result of the fingering and key operations, is required.

X-ray examination

Whilst X-ray examination has long been used by organologists to reveal internal details of musical instruments, this has normally consisted of two-dimensional imaging.[7] More recent work has included Computerised Tomography scans allowing a three-dimensional image of the structure to be computed from a large set of rays passed through the specimen at many angles.[8] Very few CT scanners are routinely available in museums, and whilst cooperation with local medical or industrial facilities would normally be possible, this was prevented by the Covid pandemic. However, it has been possible to use on trial an instrument developed in the UK that utilises digital tomosynthesis (DT) to obtain images of slices through the object as a function of depth, see Figure 7.4.[9]

Figure 7.4. Catterini (GB.O.ub.496) undergoing Adaptix digital tomosynthesis (DT) inspection

When used to inspect the Bate Collection Catterini instrument the DT images revealed hitherto undetectable details. A great advantage of the tomosynthesis method is that it allows one to focus on a single slice of the object, with limited interference from layers above and below. However, the metal keys do obscure details of the wood, and were removed when possible. An example is shown in Figure 7.5 and below in the discussion of the Catterini instrument. Measurements can be made to the pixel resolution,(0.099 mm). Bore diameters measured in this way agreed well with the measurements made by the disc tool.

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[7] See e.g. Bär, *Verzeichnis Der Europäischen Musikinstrumente in GNM Nürnberg.* Band 6, 122.

[8] Godfrey N. Hounsfield, A method of and apparatus for examination of a body by radiation such as X or gamma radiation, UK Patent 1283915. 1968/1972.

[9] Adaptix. 'Home'. www.adaptix.com accessed 28 July 2021. I am Chief Scientist at Adaptix Ltd. and thank Kate Renforth for cooperation in these measurements, Andrew Lamb for permission to use the Catterini instrument and my Adaptix colleagues for permission to use the data in this thesis. See Maria Klodt and Raphael Hauser, '3D Image Reconstruction from X-Ray Measurements with Overlap,' in Computer Vision – ECCV 2016, ed. Bastian Leibe et al. vol. 9910, 'Lecture Notes in Computer Science.' 9910. Cham: Springer International Publishing, 2016, 19–33.

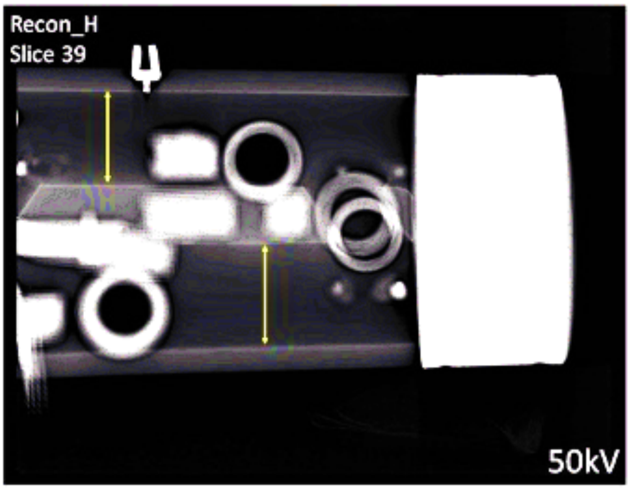

Figure 7.5. X-ray DT of the lower end of the Catterini instrument, focused on the central slice containing the two bores. Yellow arrows are used to measure dimensions. The connecting tube between the bores is obscured by the brass end-band.

Conclusions and indications from the playing tests

Table 7.1 below shows details of those instruments which were played or heard. Table 7.2 shows conclusions about common features and comments on playing properties. Images of the instruments and some individual comments are given after the table, where these are not included in the discussion of the physical examination later in the chapter.

Table 7.1 Instruments that were played or heard.

Maker/ location	Type/ pitch	Date	Museum siglum	Performer
Catterino Catterini, Padua	Bassoon with LH keys, in C	1838	GB.O.ub.496	DKB Played for 1 hour
Adolphe Sax, Paris[10]	Straight, in B♭	1840	B.B.mim.2601	Recording by Guy van Waas
Franz Losschmidt, Olomouc[11]	Ophicleide, in B♭	1852	US.NY.mma.89.4.2459	DKB played for 15 min
Johann Simon Stengel, Bayreuth[12]	True Bassoon, in B♭	1860-80	I.F.ga.1988/170	DKB played for 2 min
Stengel[13]	Straight, in A	1880	D.Düsseldorf.Robert Schumann School.stengel	Recital by Kerstin Grötsch, 2013; DKB played for 20 min
Josef Josefovich Schediwa, Odessa[14]	Half-bassoon, in B♭	1900-14	GB.O.ub.401	DKB played for 10 min
Wilhelm Hermann Heckel, Biebrich	Straight, in A	1910	GB.Warwick.bowen	DKB uses regularly in concerts

[10] © Mim 2013. My thanks to Géry Dumoulin for providing this recording and for permission to include it in this thesis.
[11] By kind permission of the curator, Dr Ken Moore
[12] By kind permission of the curator, Dr Arianna Soldani.
[13] By kind permission of Prof Kerstin Grötsch
[14] By kind permission of the curator, Dr Andrew Lamb.

Table 7.2. Comparative results of the playing tests

Maker, location and tonality	Quality of seal	Comments
Catterini, GB.O.ub.496 C at A4 = 448 Hz	A2 to B♭3 only	• Notes spoke easily, and were subjectively comparable in sound with those of a modern bass clarinet. • Playing position with reed below was more appropriate to standing or marching. For seated operatic or concert use (documented for this maker), the reed-above position was more comfortable for the player. • Instrument pitch for these notes, approx. A4 = 466, was much higher than in contemporary North Italian operas, hinting that this instrument may have had a town or church band use.
Sax, B.B.mim.2601 B♭ at A4 = 464 Hz	Good , having been partially restored	• Recording of performance by Guy van Waas of the bass clarinet solo from Act V of *Les Huguenots* by G. Meyerbeer. I also listened to him rehearsing this piece. • Pitch of the notes was analysed and found to be in B♭ but at about A4=464 Hz, almost a semitone higher than A4=440, with flatness in the lower register. • Timbre was fairly full but with some harshness at *fortissimo* levels of playing. Very good dynamic range.
Losschmidt, US.NY.mma.89.4.2459 B♭	Good down to F2	• Played easily and well with a full tone. • In very good condition, perhaps due to its rigid brass construction • No significant differences perceived compared with a modern bass clarinet.
Stengel, I.F.ga.1988/170 B♭ at A4 = 440 Hz	C2 to A3 only	• The left hand sealed well, having finger holes not plateaux. • Sound and feel of the notes in the range C3 – G3, was clearly different from those of the Catterini and of more modern instruments. • The notes appeared to be lacking in the upper harmonics and not to blend so well with other notes. • This raised the suspicion that the relatively long and narrow diagonal tone holes in the wing joints, compared to the Catterini or to a modern instrument, were causing a marked difference in the acoustic behaviour.
Stengel D.Düsseldorf.Robert Schumann School A at A4 = 440 Hz	Very good, fully restored by Peter Wolf of Kronach	• Played well and easily across entire range, with superior tone (for my taste). • Significantly less volume than a modern bass clarinet; perceptible in the performances with the same operatic bass singer and different bass clarinets. • Very different sound and feel from the bassoon-form Stengel, above.
Schediwa, GB.O.ub.401 B♭ at A4 = 440 Hz	Very good	• The only folded instrument experienced that could be played over the whole range, down to C2. • No perceptible difference was felt or heard in notes emitted from tone holes either side of the butt joint. • A very well-made instrument with an excellent tone. The top joint and 'down' tube of the butt joint are essentially

		identical to a straight form German system bass clarinet, so this is to be expected. Limited volume possible.
Heckel, GB.Warwick.bowen A at A4 = 440 Hz	Very good	• In regular use whenever a bass clarinet in A is called for, e.g. in workshop performances of Wagner *Siegfried* and Mussorgsky/Ravel *Pictures at an Exhibition*. • Plays very well with good intonation, slightly sharp at A4=440 • Sound is perceptibly different from that of a B♭ bass; similar to the way a soprano clarinet in A compares to a B♭ instr-ument. Sound is mellow and round. Capable of high volume. • This is also the instrument used for the verification of the acoustic modelling (Chapter 6).

Table 7.2 shows that all of the main sub-types of the bassoon-form class were either played or heard being played. Those with larger bore diameters (22 – 30 mm, see below) were generally comparable to modern instruments in their dynamic levels, but those with smaller bores (typically 20 mm) were significantly limited dynamically. It was surprising to find that the Catterini and Sax instruments played at such a high pitch, at least in their upper registers. The playing or listening tests will next be discussed for each instrument.

Sax B.B.mim.2601

This instrument had recently been partially restored for playing, for the Adolphe Sax Festival SAX200 in 2014 at the Musée des instruments de musique, Brussels. The extract was recorded in 2013. The instrument was not available for personal playing but this recording was kindly provided in lieu. The recording from *Les Huguenots* covered the first eleven bars of the bass clarinet solo in Act V, Trio, (a) *Interrogatoire*, which are unaccompanied, see Figure 7.6.[15] The recording was analysed[16] to find the pitches of selected notes to an accuracy of ±1 cent.[17]

In the recording, the arpeggio in bar 5 only rises to G4 rather than G5 as written in the original (shown in the ossia stave for bars 5 and 6). Presumably, this was because of difficulty in sounding the altissimo G5 on the original instrument, which had been only partially restored. In order of appearance in the score the pitches of notes shown in Figure 7.6 were analysed and compared with equal temperament at A4 = 464 Hz, which was found to be the closest pitch, at least in the upper register; see Table 7.3. The intonation at this playing pitch in the upper register is quite good, but becomes flat in the lower parts of the range. This result will be discussed further in Chapter 8 in comparison with the computed impedance data for this instrument. The tone of the instrument is fairly full but appears to be lacking harmonic content, and sounds a little harsh when played fortissimo.

[15] Giacomo Meyerbeer, *Les Huguenots*. Paris: Maurice Schlesinger, n.d. [1836].
[16] The recording was imported to the Audacity program, the indicated notes extracted, then analysed for pitch by the de Cheveigné YIN algorithm introduced in Chapter 5.
[17] Alain de Cheveigné and Hideki Kawahara, 'YIN, a Fundamental Frequency Estimator for Speech and Music'
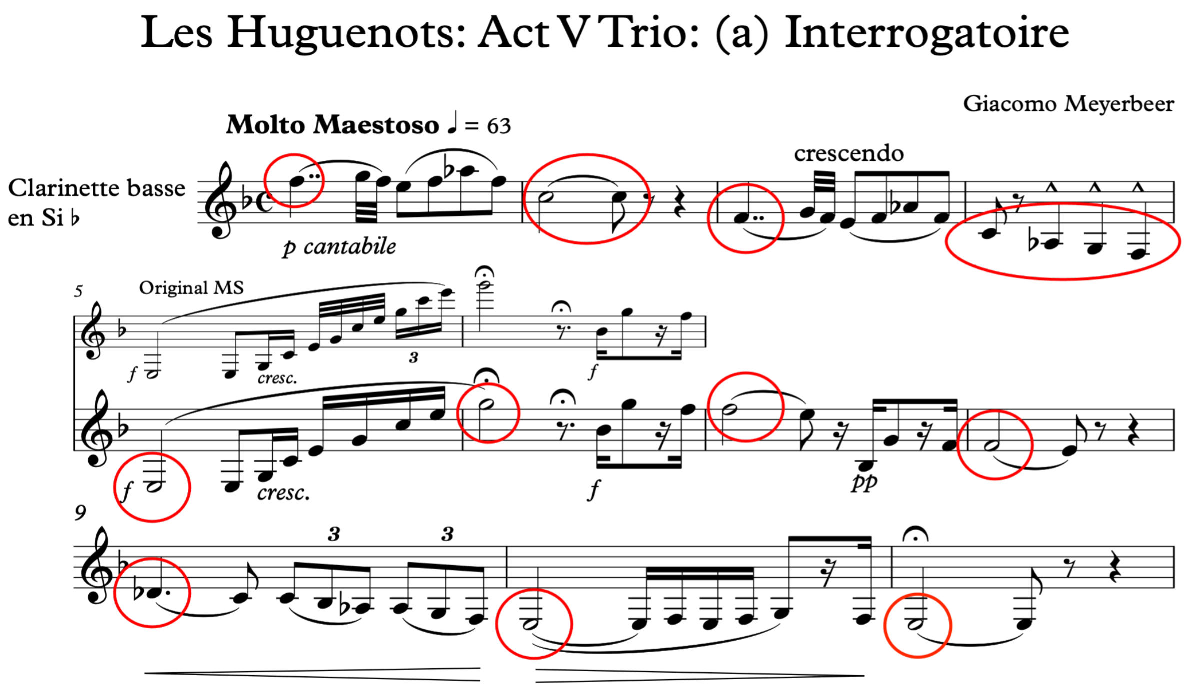
Figure 7.6. Interrogatoire, *Les Huguenots*, Act V, as recorded by Guy van Waas. The notes indicated by red circles were analysed for pitch. © Brussels Musée d'Instruments de Musique. To hear the recording, click the sound icon below, or play the external file Trio (Bass clarinet solo) from Les Huguenots.mp3.

Written Note	Sounding pitch at ET for A4 = 464 Hz	Measured pitch, Hz
F4	328.1	329.9
C4	245.8	245.3
F3	164.0	166.1
C3	122.9	122.9
A♭2	97.5	96.26
G2	92.1	90.8
F2	82.0	80.5
E2	77.4	76.4
G4	368.3	369.2
F4	328.1	328.4
F3	164.0	165.1
D♭3	130.2	129.7
E2	77.4	76.8
E2	77.4	76.8

Table 7.3. The measured pitch of selected notes of the performance of the excerpt from *Les Huguenots*, compared with equal temperament sounding pitches based on A4 = 464 Hz.

Stengel I.F.ga.1988/170

The very short playing test on the Stengel had a significant influence on the project, as noted in Table . Figure 7.7 below shows the open, long finger holes drilled obliquely through the wing joint. A feature used by all makers of true bassoon-form bass clarinets, these holes have a substantial influence on the acoustics (see Chapter 8).

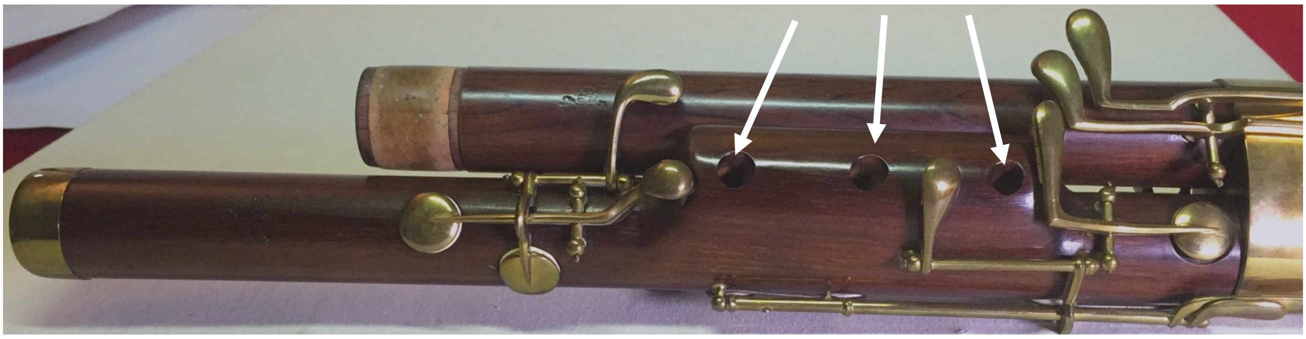

Figure 7.7. The upper or wing joint of Stengel I.F.ga.1988/170 showing the long finger holes; the white arrows indicate their approximate direction.

Stengel D.Düsseldorf.Robert Schumann School

This straight-form instrument originally belonged to the Bayreuth Festival Orchestra and was used in the first Bayreuth performance of *Tristan und Isolde*.[18] Following Kerstin Grötsch's recital in Düsseldorf in 2013 (see Figure 7.8), I played the instrument for about 20 minutes. The instrument responded very well indeed, with good sound and intonation but limited volume. To quote from my review of the concert:

> The instrument does have limitations; at times one would have liked some more volume from the bass clarinet to balance the power of the bass singer, but this may indicate the changing nature of the instruments and performances.[19]

A performance of the same work later in the programme on a modern Wurlitzer bass in B♭ gave a very different dynamic, with this bass clarinet easily able to match the powerful bass voice of Thorsten Grümbel.

[18] Email from Prof. Kerstin Grötsch, 28 February 2013 quoting oral history from the late Hans Klüppel, member for 25 years in the Bayreuth-Festival-Orchestra, who was given the instrument by Wolfgang Wagner and provided the instrument on permanent loan to the School.
[19] Bowen, 'Vergessene Klänge Und Kommende Sounds.'

Figure 7.8. Kerstin Grötsch playing the Stengel bass in A. Robert-Schumann-Hochschule Düsseldorf 2013 (Permanent lender: Klüppel family, Düsseldorf). Photograph by Daniel Springwald. Reproduced by permission of Kerstin Grötsch.

Schediwa GB.O.ub.401

Figure 7.9. Schediwa GB.O.ub.401

Of the half-bassoon Schediwa, shown in Figure 7.9, the lower range, F2 and below, was tested for any change in the sound quality or in the player's sensation for notes emitted from tone holes down to E2 in the 'down' tube and those down to C2 in the 'up' tube, see Figure 7.10. Whilst I had suspected that additional reflecting surfaces at the bottom of the tubes could significantly impact the standing waves in the instrument and hence the timbre of the sound, the Schediwa demonstrated no difference. Its basset notes were equally as good as those above the bend. It therefore appears that the cork used to stop the ends of the tubes does not introduce any additional standing waves in the tube; a useful finding.

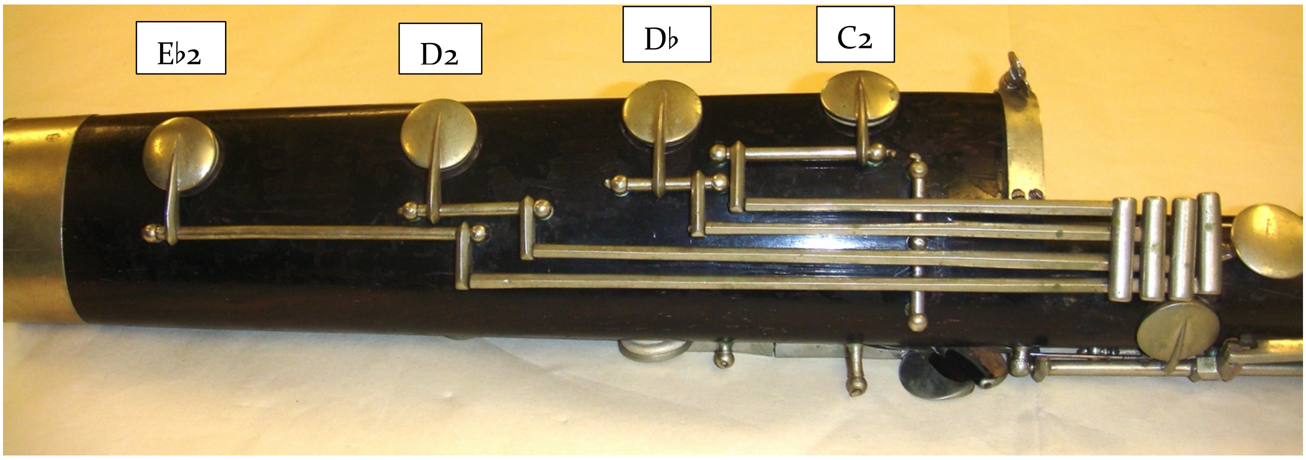

Figure 7.10. The butt joint and tone holes of the Schediwa GB.O.ub.401 showing notes from E♭2 down to C2 in the 'up' tube.

This conclusion is supported by experts in playing and making the baroque bassoon, which normally had a similar construction, either with tubes joined by a lateral hole or (less commonly) by scraping out the septum and using an oval cork plug; both of these methods are found in the bass clarinets studied. The late Dennis Godburn[20] commented that there was no perceptible difference in notes emitted either side of the bend in a well-made instrument.[21] Wouter Verschuren[22] commented that some classical instruments did have a brass U-tube connecting the two bores but that this made little difference to the sound. The well-known period bassoon maker Mathew Dart[23] provided a list of high-quality bassoon makers from the earliest times who used either the lateral hole or the oval plug: Richard Haka *c.*1645-1705, Johann Christoph Denner 1655-1707, Thomas Stanesby *c.*1688-1721, Johann Poerschman *c.*1680-1757, Johann Heinrich Eichentopf *c.*1686-1769, Thomas Stanesby Junior 1692-1754, Carl August Grenser 1720-1807, Jakob Friedrich Grundmann 1727-1800 and Johann Heinrich Grenser 1764-1813. It was therefore a very well-established technique.The two Grensers are the builders of the first (Heinrich) and second (Augustin) bassoon-form bass clarinets known.

It is therefore reasonable to conclude that the structure of the boot joint and fold does not on its own affect the acoustics of the bassoon-form instrument.

[20] 'Musicians > Dennis Godburn // The Helicon Foundation : World-Class Chamber Music in an Intimate Setting,' accessed August 28, 2021, http://www.helicon.org/musicians/dennis-godburn
[21] Private communication, 2011.
[22] Professor of Historical Bassoon, RCM.
[23] 'Mathew Dart - https://mathewdartbassoon.com accessed November 16 2021.

Examining historical instruments

An examination of these instruments is guided by considering notable milestones in the organological development of the bass clarinet. To enable more straightforward comparison, these instruments are classified by structure into six groups, shown in Table 7.4 below:

- Early instruments
- Bassoon or dulcian-form instruments made between 1835 and 1850
- Bassoon-form instruments made after 1850[24]
- Ophicleide and half-bassoon instruments made after 1855
- Straight form instruments
- Bassoon-form soprano clarinets

Table 7.4. Instruments examined in detail, in approximate chronological order. Red typeface indicates that full measurements for acoustic calculations were made, see Chapter 8 and Appendix B. The dates are those proposed by the museums unless modifications are argued in the discussions that follow. B-F = bassoon form; H-B = half-bassoon form; O-F = ophicleide form; S-F = straight form.

Maker/ location	Type	Date	Museum siglum	Comments
Early instruments				
Friedrich Lempp, Vienna	B-F; basset horn	1789	A.Ll.m.Mu.28	Examined from photos. earliest extant B-F clarinet
Heinrich Grenser, Dresden	B-F;	1793	S.S.m.M2653	earliest extant B-F bass clarinet
J.A.A. or C.J.J. Tuerlinckx, Malines	B-F; Alto	1800 - 15	B.B.mim.0933	Examined in museum.
Bassoon-form instruments, 1835 - 1850				
Johann Heinrich Gottlieb Streitwolf, Göttingen	B-F	1835	D.N.gnm.MIR477	Streitwolf was a major maker with an excellent reputation
Streitwolf	B-F	1835	D.LE.u.1539	
Catterino Catterini, Padua	B-F	1838	GB.O.ub.496	First folded bass with well-positioned and vented tone holes
Paolo Maino, Milan	B-F	1838	B.B.mim.0941	Examined in museum
Giacinto Riva, Persiceto	B-F	c.1850	US.NY.mma.89.4.3124	Examined in museum
anonymous	B-F	1840-50	US.NY.mma.89.1635	Examined in museum
anonymous	B-F	1840-50	US.NY.mma.89.1636	Examined in museum
Pietro De Azzi, Padova	B-F	1848	D.Uhingen.reil.	Examined in collection
Bassoon-form instruments, after 1850				
anonymous but attr. Stengel, Bayreuth	B-F	1850	D.M.dm.46262	Examined from photos

[24] chosen as the date after which bassoon-form instruments do not appear in Art music.

Stengel Bayreuth	B-F	1855	B.B.mim.0943	Maker made both B-F and S-F types
Stengel Bayreuth	B-F	1860-80	I.F.ga.1988/170	Maker made both B-F and S-F types
Losschmidt, Olomouc	B-F	1852	I.TS.mt.1013	Examined in museum
Ludwig & Martinka, Prague	B-F	1860-70	CZ.P.cmm.E.135	Examined in museum
Ophicleide and half-bassoon instruments, after 1855				
Losschmidt	O-F	1852	US.NY/mma.89.4.2459	Examined and played in museum
Georg Ottensteiner, Munich	H-B	1860	D.M.sm.79-28	Examined in museum
Franz Carl Kruspe, Erfurt	H-B	1865-75	CH.B.hm.1999-136	Both B-F and S-F types
Josef Josefovich Schediwa, Odessa	H-B	1900-14	GB.O.ub.401	Examined and played in museum
anonymous	H-B; basset horn		D.M.dm.43336	Examined from photographs
Bohland & Fuchs, Graslitz	H-B; basset horn		D.Nauheim. heimatmuseum. BohlandFuchs	Examined from photographs
anonymous, bell engraved 'Buffet Crampon/Paris'	H-B; basset horn		I.M.Carbonara. bassethorn	Examined from photograph
Straight-form instruments				
Sax, Brussels	S-F	1840	B.B.mim.2601	First successful straight-form type
Sax, Brussels	S-F	1840	B.B.mim.0175	ditto
Kruspe	S-F	1865-75	D.LE.u.4479	Both B-F and S-F types
Kruspe	S-F	1865-75	D.L.E.u.4478	Examined in museum
Stengel	S-F	1880	D.Düsseldorf. Robert Schumann School	Restored for playing
Stengel	S-F	1880	GB.E.U.4932	Both B-F and S-F types
Wilhelm Hermann Heckel, Biebrich	S-F	1910	GB.Warwick. bowen	model for acoustic calculations. recently repadded with leather pads, in excellent playing condition
Bassoon-form soprano clarinets				
Alessandro Ghirlanda, Verona	B-F Soprano	1868	I.R.ms.3130	Examined in museum
Francesco Chiesara, Venice	B-F Soprano	1889	I.R.ms.3254	Examined in museum

The results of the examinations of each of the instruments in Table 7. are now presented by group where a new table shows features appropriate to that group.

Early instruments

Maker	Bell position relative to player	Bore, mm	Pitch
Lempp	Right	15.5	F
Grenser	Right	15.2	B♭
Tuerlinckx	Left but instrument left-handed	15.2 – 15.5	F (probably)

These are the earliest extant bassoon-form instruments and show the first design in which they were made. It is notable that they all have similar narrow bores, not much larger than contemporary soprano clarinets, even though two are alto and the third a bass instrument. The bore is an important part of the acoustic design and its area should in principle scale with the length of the instrument (see Chapter 5). The consequence is that the Grenser bass clarinet would sound more like a narrow-bore basset horn.

The instrument by **Friedrich Lempp**, illustrated in Figure 7.11, was inspected from photographs and from the description in Piddocke.[25] This instrument is the earliest extant clarinet of any type to have been made in a bassoon form. It is interesting to note that the bell would be on the right of the player, as viewed from their playing position.

This feature is similar to the **Heinrich (and Augustin) Grenser** bass clarinets but different from all later bassoon-form instruments, which put the bell on the player's left. Placing the bell on the right means that the down tube or top joint is the same form as on a straight-form instrument. At the bottom of the instrument, the player has to stretch somewhat to reach the finger holes, which are now angled in with longer chimneys. This geometry works on a basset horn or a narrow bore bass clarinet but not on larger bass instruments, since most players' hands cannot accommodate such a large stretch over the butt joint. No other bassoon-form basset horns are extant until those dating from the second or third quarter of the nineteenth century. Note, however, that it is a very practical design, since it avoids the bulk and complexity of the box to accommodate the extra length, and is more compact.

Heinrich Grenser's innovative bassoon-shaped bass clarinet of 1793 is shown in Figure 7.12 and the wing joint is pictured in Figure 7.13. The bell is on the right-hand side of the player, as in the earlier Lempp, but the different design of the wing joints suggests it was unlikely that these makers were in contact with each other. The Lempp has a plain tube but the Grenser has a carved wing joint like a bassoon although there is no practical need for this feature. The left hand can easily reach the top joint holes in a plain tube and in fact it is acoustically more suitable in respect of the value and uniformity of the cutoff frequency (discussed in Chapter 8). The butt joint, also shown in Figure 7.12, is clearly made to be fingered by the right hand. The wing joint could therefore have been the much simpler plain tube. Moreover, Grenser's own bassoons were made as usual with the bell on the player's left. There is no obvious reason for this anomalous design.

[25] Melanie Piddocke, 'Theodor Lotz: A Biographic and Organological Study'. PhD thesis, University of Edinburgh, 2011.

Figure 7.11. Basset horn in F by Lempp. A.LI.m.Mu.28, front and dorsal views. OÖ. Landes-Kultur GmbH (formerly OÖ Landesmuseum), Sammlung Musik, Inv. Nr. Mu 28.

Figure 7.12. Grenser bass clarinet. S.S.m.M2653. Image courtesy Scenkonstmuseet/Swedish Museum of Performing Arts, Stockholm. Photograph Sofi Sykfont.

Figure 7.13. Wing joint of the Grenser instrument. Image courtesy Scenkonstmuseet/Swedish Museum of Performing Arts, Stockholm. Photograph Sofi Sykfont.

The Tuerlinckx alto clarinet, shown in Figure 7.14, is in some ways reminiscent of the Lempp basset horn. It does not have keys for tone holes below written low F, not even for E. Its bell is on the left of the player but, very unusually, the instrument is designed to be played left-handed, that is, with the right hand on the upper joint. There is no room to manoeuvre the left hand onto the upper joint, the tone holes in the butt are angled towards the left hand, and the keywork on both joints is laid out so as to be operated with the right hand on the top joint. Thus it is the same layout as the Lempp and Grenser except that the hand positions are reversed. Indications that it is an experimental instrument are the three tone holes that have been filled in, shown in Figure 7.15. As seen in Figure 7.16, the plug at the end of the butt joint is not two separate corks. This shows that the down and up tubes are connected not by a lateral hole, but a continuous cork cover. This suggests that the end of the gap between the bores (the septum) has been excavated to form a channel connecting the bores. This is the construction method of the older racket or dulcian,[26] but is also used by Streitwolf. The mouthpiece, probably contemporary with the rest of the instrument, is socketed. Whilst the instrument is unstamped, documentation held in Brussels records that the instrument was donated by the Tuerlinckx family. However, it is almost impossible to distinguish instruments made by Jean Arnold Antoine 1753 – 1827 and by his eldest son, Corneille Jean Joseph Tuerlinckx 1783-1855, whose firm was active between 1782 and ca. 1840.[27] In view of the experimental nature of the instrument, the simple construction, and the small number of keys, I suggest that this is an early instrument, 1800 – 1815.

Figure 7.14. Tuerlinckx B.B.mim.0933 alto clarinet.

[26] Kopp, *The Bassoon*, 47.
[27] William Waterhouse, *The New Langwill Index,* 404; Jane M. Bowers, 'Tuerlinckx', *Grove Music Online* 2001. Accessed 9 Nov. 2021.
https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000028565

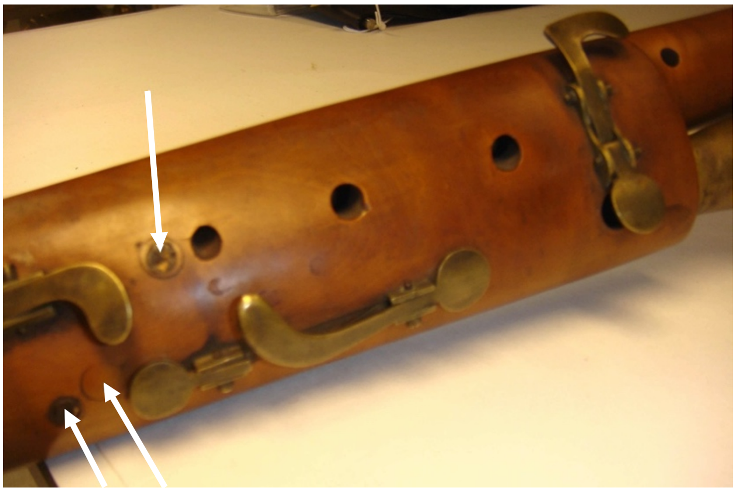

Figure 7.15. Detail showing tone holes that have been filled in, indicated by arrows.

Figure 7.16 Detail of end of butt joint showing continuous cork cover

Bassoon-form instruments, 1835 - 1850

Maker	Bore, mm	Pitch	Top joint system
Streitwolf	24.5	B♭ at A4 = 440 Hz	Wing joint
Streitwolf	25.2	B♭ at A4 = 440 Hz	Wing joint
Catterini	22.55	C at A4 ≥ 444 Hz	Keys
Maino	22	C at A4 = 435 Hz	Wing joint
Riva	19	B♭	Wing joint
anonymous	30	B♭	Keys
anonymous	25	B♭	Keys
De Azzi	23	C (very sharp)	Keys

For these, and indeed all other extant bassoon-form instruments, the bell is on the left of the player. The top joint is operated by the left hand as usual, and the dimensions of the tubes require that either a wing joint with diagonal holes or a key mechanism is required to close the tone holes of the top joint. It would be very difficult for most players to reach round to operate plain finger holes at the centres of the tubes for both LT and I, II and III tone holes. The choice of method is an important point in the acoustical behaviour of the instruments, discussed below in Chapter 8.

The two **Johann Heinrich Gottlieb Streitwolf** instruments examined are in B♭ although five of his surviving instruments are in C. Examining two from the same workshop affords the opportunity to assess the repeatability of a maker's instruments, particularly since Streitwolf had a large output and enjoyed a high reputation. These instruments are shown in Figures 7.17 and 7.18. The position of the A♭ key is significant and is discussed in the following sections. The noticeable increase in quality displayed by the instruments in this group is manifest in the accuracy and consistency of their manufacture. Both instruments are contemporary and quite similar despite the Nuremberg instrument having 19 keys, one more than the Leipzig instrument. The Leipzig instrument, however, has the doubly-curved crook, which makes it more compact. This is particularly relevant since Streitwolf was known to have supplied instruments to military bands.[28]

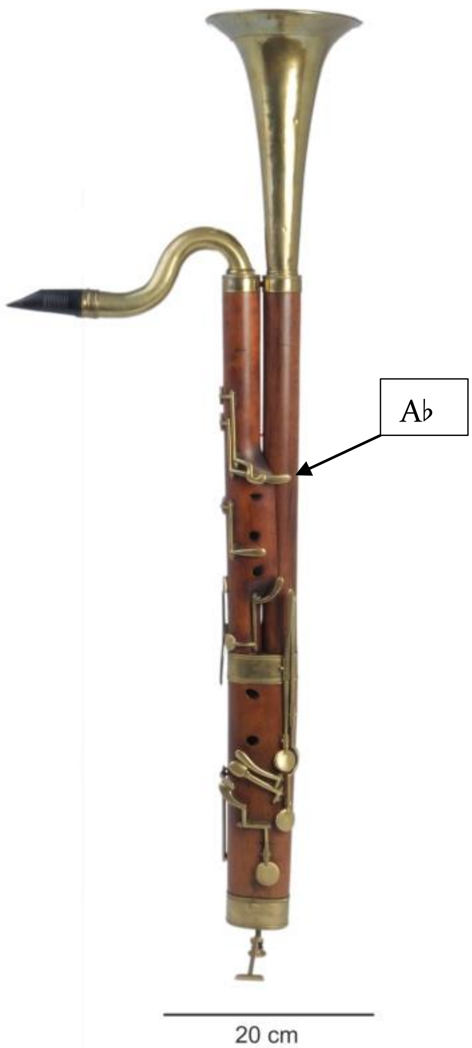

Figure 7.17. (left) Streitwolf D.N.dnm.MIR477 (dorsal view). Image from MIMO.

Figure 7.18. (right) Streitwolf D.LE.u.1539 (front view). Image from MIMO.

[28] As noted above in Chapter 3.

Notably, Streitwolf used the 'true' bassoon form of the Grensers where the tone holes I, II and III are fingerholes drilled obliquely through the wing. The diameter of these fingerholes is limited by the need to cover them with finger tips rather than pads. He appeared to make them in this style throughout his career. This practice continued through to the third or fourth quarter of the nineteenth century, and became popular amongst many makers, including Wilhelm Beck, Josef Franz Seidel, H. Douglas, Georg Jacob Berthold and Giacinto Riva. Several unstamped instruments also show this construction.

The next six instruments in the early bassoon-form group are associated with the northern Italian peninsula and display equally important similarities and differences. The front and dorsal views of the **Catterino Catterini** instrument from 1838 are shown in Figures 7.19 and 7.20. Given that the reed-above embouchure for soprano clarinets persisted longer in Italy than in most countries it is possible that these instruments were also designed with that position in mind.[29] The mouthpiece is, however, not contemporary with the rest of the instrument. An important innovation of Catterini was the use of plateau keys for all holes, allowing them to be larger size than is possible with plain finger holes. This has significant advantages in raising the cut-off frequency.

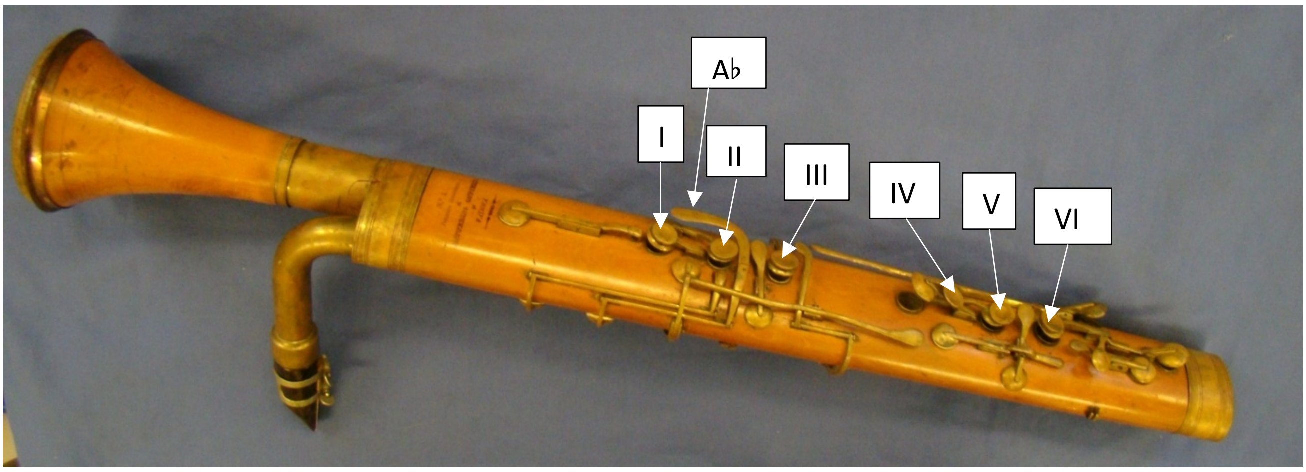

Figure 7.19. Catterini GB.O.ub.498 showing plateau keys for all tone holes, and location of the A♭ key.

Figure 7.20. Catterini GB.O.ub.496, dorsal view.

The instrument's acoustic qualities are a direct consequence of its innovative construction. The main tone holes on the down tube, I, II, III, IV, V, VI are placed centrally along the

[29] Ingrid E. Pearson, 'The Reed-above Embouchure: Fact or Fallacy?' *Australian Clarinet and Saxophone.* 2 (1999), 8-13.

instrument, necessitating a sideways angle to reach the down or up bores. However, the holes do not enter the bore centrally, but at the side. so that the outer edge of the hole is tangential to the outer edge of the bore, as shown in Figure 7.21. All the tone holes are terminated in short brass chimneys, about 4 – 5 mm long, with 1 mm walls, shown in Figure 7.22. These were usually perpendicular to the surface of the instrument but sometimes placed parallel to the angled tone hole. The bore varied between 22.3 and 22.7 mm at the top of the down tube.

Using an endoscope to examine the internal bore revealed no rounding of the inner edges of the tone holes. Undercutting was not apparent from either normal or endoscopic inspection, but see the X-ray images below. Connection between the two bores was made with a neat hole, slightly narrower than the bore, and these bores were plugged with corks.

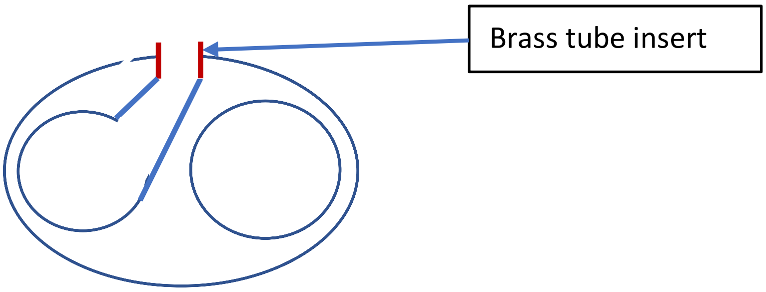

Figure 7.21. Sketch of the structure of the main tone holes, which taper outwards towards the bore.

Figure 7.22. Detail of a tone hole on the instrument.

The internal diameters of the brass tubes lining the main tone holes were in the range 14 - 16 mm, about 50% larger than many of the tone holes used by Grenser and Streitwolf, and too large to be covered by players' fingers. Whilst this range allows proper venting and acoustic termination of the air column it necessitates more complicated keywork with even more keys (20) than the Streitwolf instruments. It does, however, liberate the bassoon-form instrument from the need for long and relatively thin chimneys on the wing joint. The tone holes are now mostly accurately positioned and well-vented with wide chimneys.[30]

This Catterini instrument was also examined by X-ray inspection using the novel Adaptix instrument described above. To study the bore and tone hole profiles, a few keys were removed. It was not possible to detach all keys for a complete examination, nor could the brass inserts in the tops of the tone holes be removed. Attention was given to the holes near the butt, with two views of the middle of the instrument. The reconstruction gave 100 slices

[30] Note, however, that the group of holes I, II and III are rather widely separated from the group IV, V and VI. This usually indicates inaccurate tuning, and is explored below and in chapter 8.

through the instrument, each of which is a true-scale image with no distortion effects as are present in conventional radiography. The pixel size is 0.099 mm and this corresponds to the spatial resolution of features that can be seen and to the accuracy of measurements. The full 3D images were exposed and reconstructed in a few minutes.

The details near the butt were studied by supporting the instrument on its side, so that the main tone holes were approximately parallel to the reconstructed slices and seen in cross section, as shown in Figure 7.23 to Figure 7.27. It is noticeable how all the holes are strongly tapered, with some as much as twice the diameter at the inside as at the outside. The consequences for acoustic calculations are discussed in Chapter 8. This taper could not be determined from the external examination since it is hidden by the upper part of the tone holes and by the plateau keys if not removed.

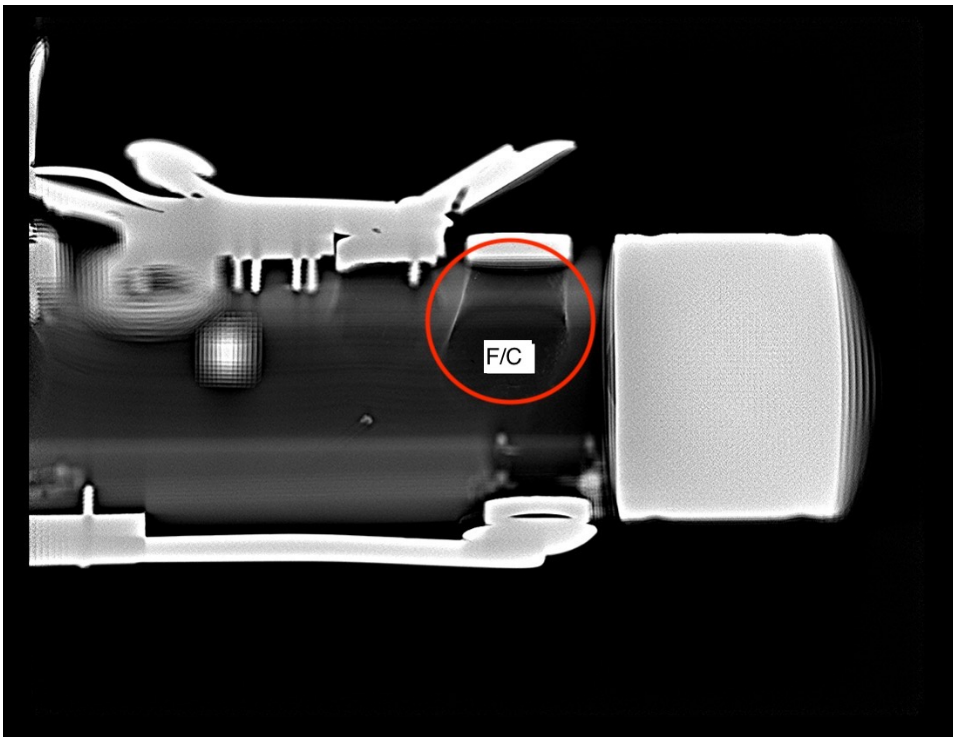

Figure 7.23. Cross section X-ray side view of Catterini GB.O.ub.496 showing slice intersecting the F/C tone hole in the down tube (inside the red circle). The strong taper (undercut) of the hole is seen.

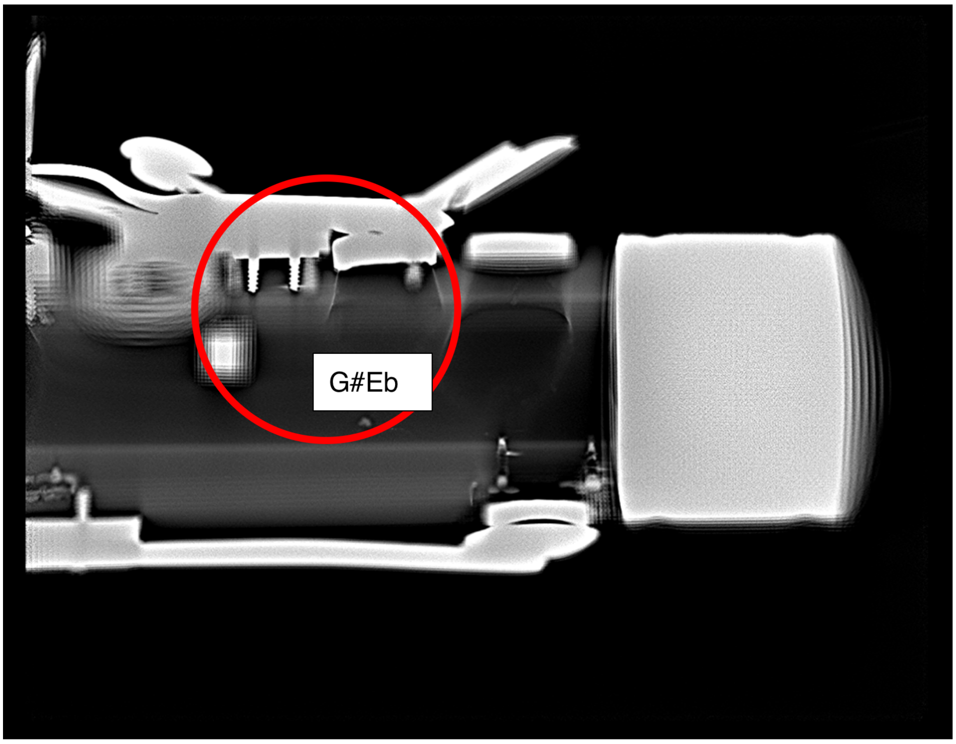

Figure 7.24. Cross section side view of Catterini GB.O.ub.496 showing slice intersecting the G#/E♭ tone hole. This hole is also in the down tube but slightly displaced in angular position from the F/C hole. This hole is also strongly tapered.

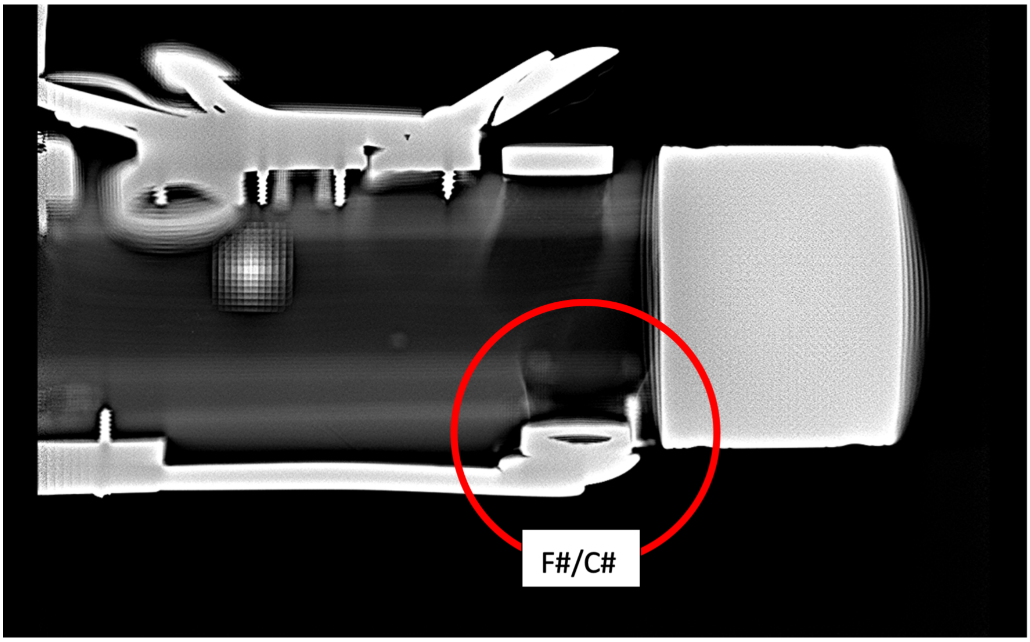

Figure 7.25. Cross section of Catterini GB.O.ub.496 showing slice intersecting the F#/C# tone hole. This hole (inside the red circle) is in the up tube and is tapered a little less strongly.than the two previous examples.

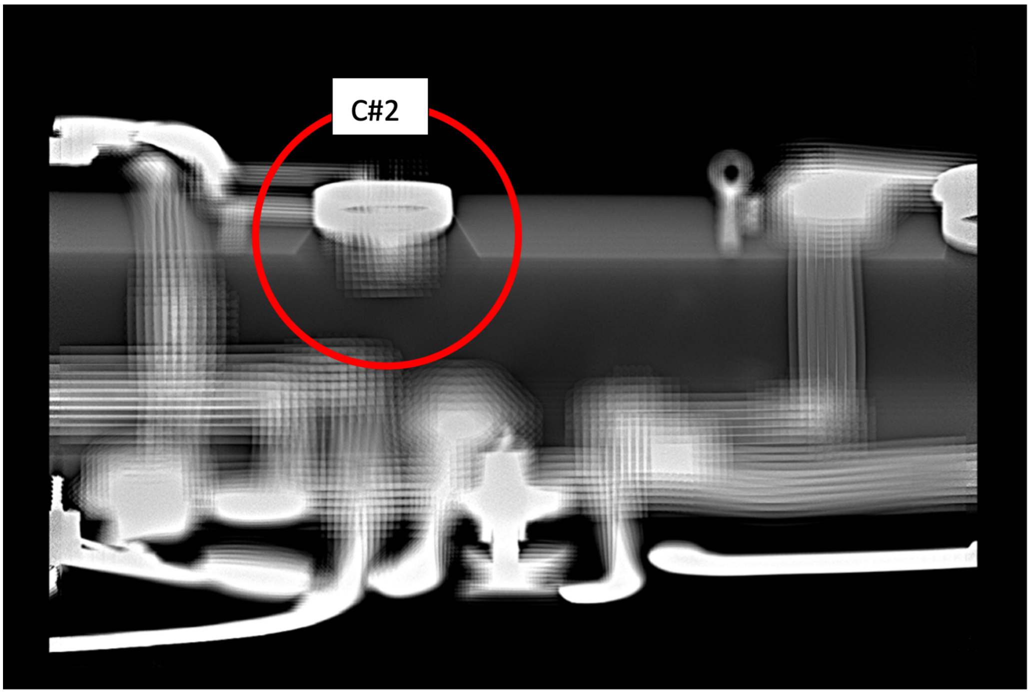

Figure 7.26. Cross section of Catterini GB.O.ub.496 showing slice intersecting the C#2 tone hole and some keys removed. This hole is in the up tube and is tapered very strongly. The wall is also thinner in this part of the tube.

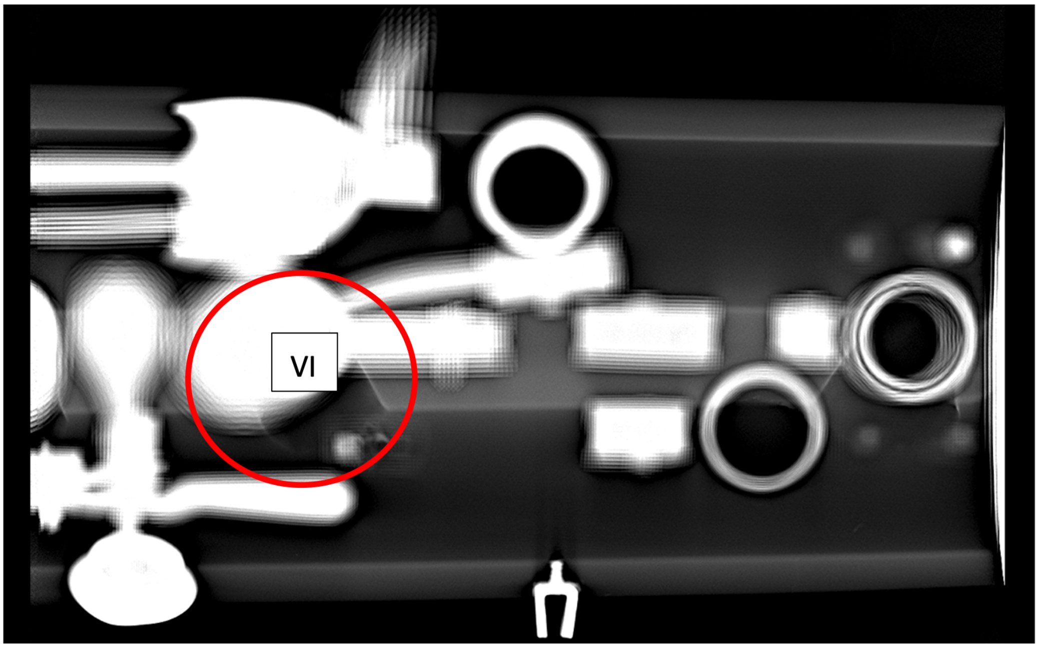

Figure 7.27. Cross section top view of Catterini GB.O.ub.496 with the slice intersecting the VI tone hole selected. This hole is in the down tube and is tapered very strongly as it runs obliquely into the bore. Lower keys removed.

Catterini's instrument, first announced in 1833, represents a landmark invention in bass clarinet design, comparable with design principles adopted for bass clarinets by Adolphe Sax, albeit on an instrument with narrower bore and a more complex construction. Catterini's design was quite successful in Italy, in both operas and bands, but the longevity of Sax's design may also owe much to his prowess in marketing and promulgating his own bass clarinet in bands, with the government, in the opera house and later in concert orchestras.

Paolo Maino established his workshop in Milan in 1836 and provided an instrument to the Modena theatre in 1838. He was thus a contemporary of Catterini.[31] The instrument is shown in Figure 7.28. Whilst Catterini used a one-piece form with mechanisms to reach the tone holes, Maino adopts the true bassoon form with a wing joint to allow the left-hand fingers to reach the tone holes. In contrast to Grenser and Streitwolf, Catterini used plateau or lever keys, with large tone holes for all holes, but Maino only used pads for tone holes I, IV and VI. The other main tone holes are open; for II and III they have to be drilled obliquely through the wing and are necessarily of smaller diameter. Maino's instrument is much more similar to the earlier German constructions of Grenser and Streitwolf. Curiously his instrument shows little influence from Catterini, despite both being located in the then Kingdom of Lombardy, which was at that time part of the Austro-Hungarian Empire. The position of the A♭ key is noted in Figure 7.28 and is positioned quite differently to 13-key soprano instruments. This placement renders the touchpiece quite inconvenient for the execution of fast passages involving the throat notes. These features suggest that the instrument was made early in his career, *c*.1840.

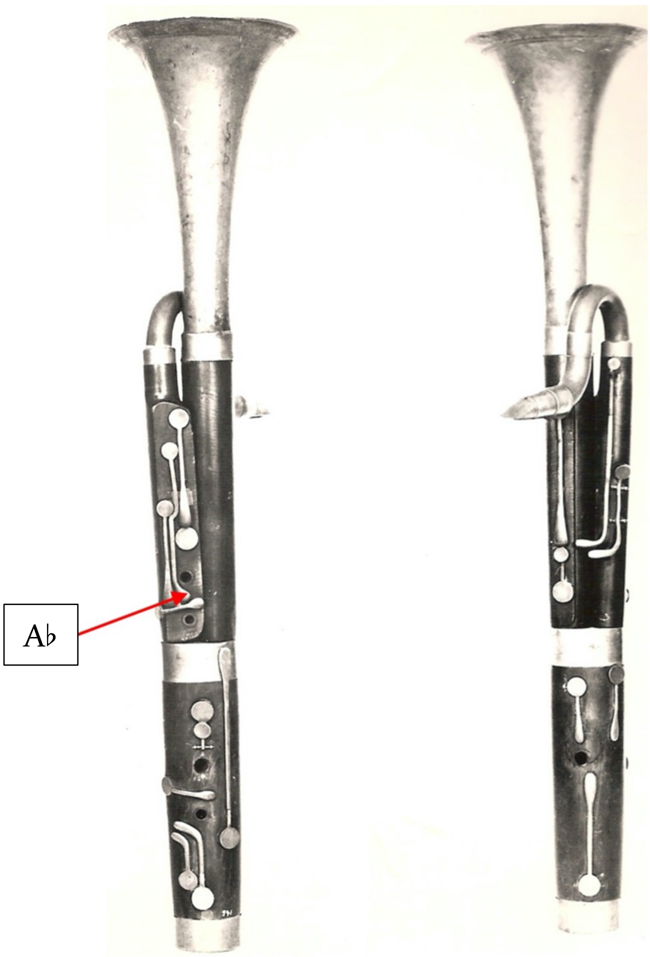

Figure 7.28. Front and dorsal views of Maino, B.B.mim.0941. Image courtesy Muséd des Instruments de Musique, Brussels.

[31] Waterhouse, *The New Langwill Index*, 250. Catterini announced his instrument in 1833.

Another North Italian instrument, by **Giacinto Riva**, shown in Figure 7.29, is clearly a more developed design. We notice later style key cups rather than plain plates, the hinge-rod keywork and the brille for fingers R2 and R3. The brille allows one to obtain accurate tuning on the B/F# notes without needing an additional key, and is adopted from soprano clarinet design. However, it is still based on a bassoon form with a wing joint, with its likely acoustic disadvantages. It is very likely that Riva was acquainted with Catterini and his instrument, since he was associated with the Persiceto band that owned a Catterini 'glicibarifono'.[32] But Riva did not adopt Catterini's design, nor is it likely that Riva manufactured Catterini's instrument.[33]

The instrument is stamped (on the butt and bass joints) G. RIVA/DI/PERSICETO. Riva's workshop in Persiceto was active between 1839 and 1861 when he moved to Ferrara. The right-hand brille was invented by Theobald Boehm and William Gordon in 1831 and adopted by Eugene Albert in 1840 for soprano clarinets.[34] Presumably it took some time to become established on bass clarinets; it is absent on Sax's Brussels examples, discussed below, dated 1840. A date between 1840 and 1861 is thus established for this instrument, and my assessment of the general style would suggest a date c.1850.

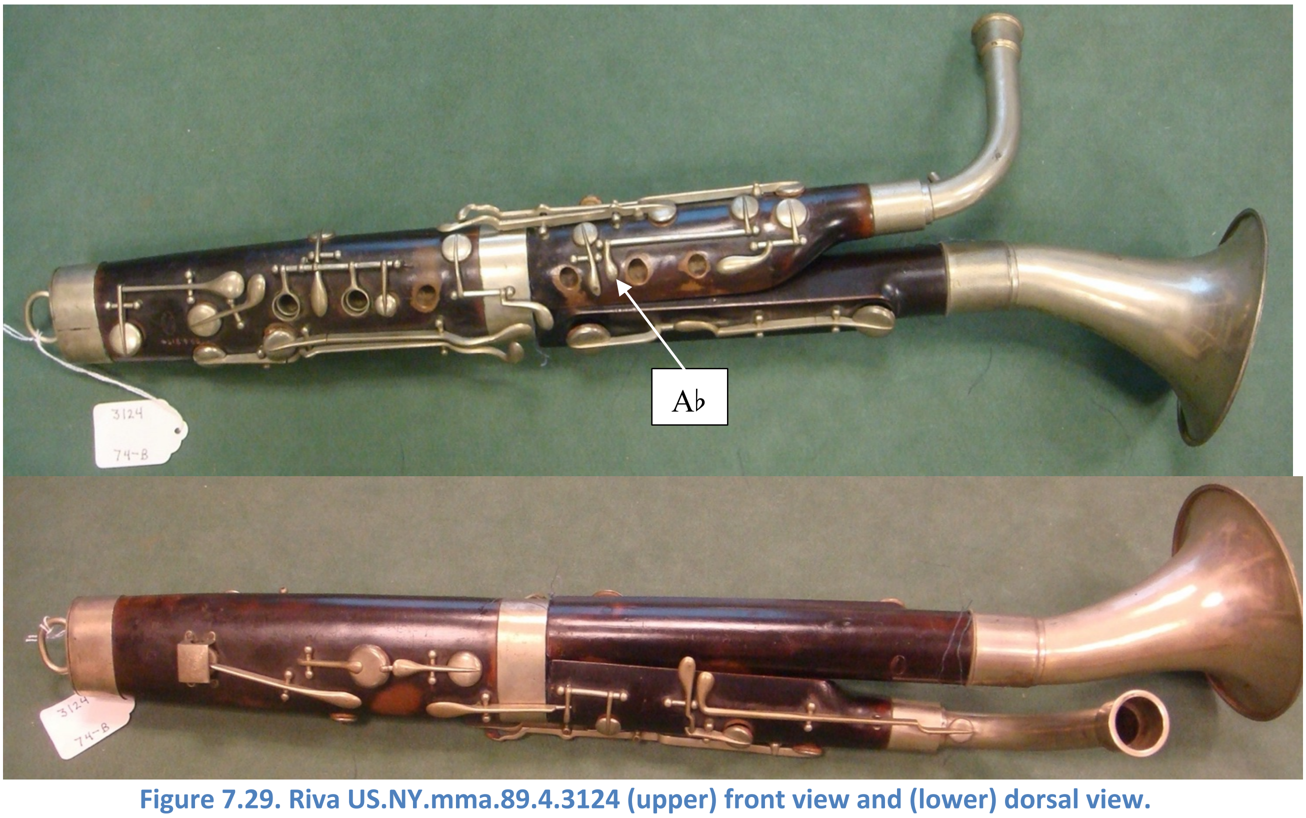

Figure 7.29. Riva US.NY.mma.89.4.3124 (upper) front view and (lower) dorsal view.

Two very similar **anonymous** instruments housed in New York also probably originated in Lombardy, see Figures 7.30 and 7.31 (shown without mouthpieces or bells). Metropolitan Museum records indicate without source that #1661 is said to have been constructed by

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32 Valentini, "L'Orchestra a San Giovanni in Persiceto e Le Istituzioni Musicali Dell '800."
33 Despite the suggestion to the contrary in Waterhouse, *The New Langwill Index*, 59.
34 Voorhees, *The Development of Woodwind Fingering Systems*, 2003, 21.

Fornari, of Venice, in the 18th Century. The Fornari of Venice discussed in Chapter 3 was Catterini's successor at the Teatro di Fenice in the mid-nineteenth century.

The size of their tone holes, which are covered with pads and use intricate keywork, strongly resembles the instrument by Catterini. They do not possess the RH brille mechanism. These anonymous instruments have very large bores, 30 mm for 1635 and 25 mm for 1636.. The only other difference between these two instruments appears on the front of the top joint, holes I, II and III. Unlike the Catterini instruments, these are of conventional bassoon construction, with butt, wing and bass joints rather than the one-piece dulcian construction. This may have been for practical and economic reasons. The piece of boxwood used by Catterini, unusually large, both then and now, would have been expensive to obtain, and time-consuming to season. Any mistake in construction would mean either patching the error or starting again with an expensive and rare piece of wood. There was thus a strong motivation towards a multi-piece construction, which was the norm for the rest of the nineteenth century.

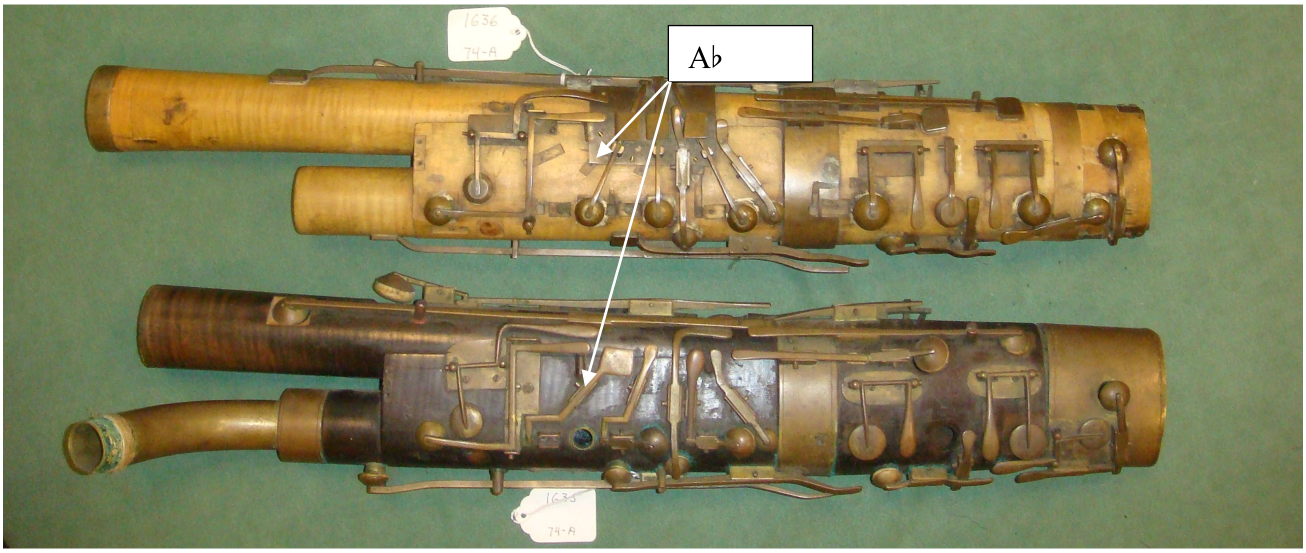

Figure 7.30. anon. US.NY.mma.89.1635 (lower) and anon. US.NY.mma.89.1636 (upper), front views

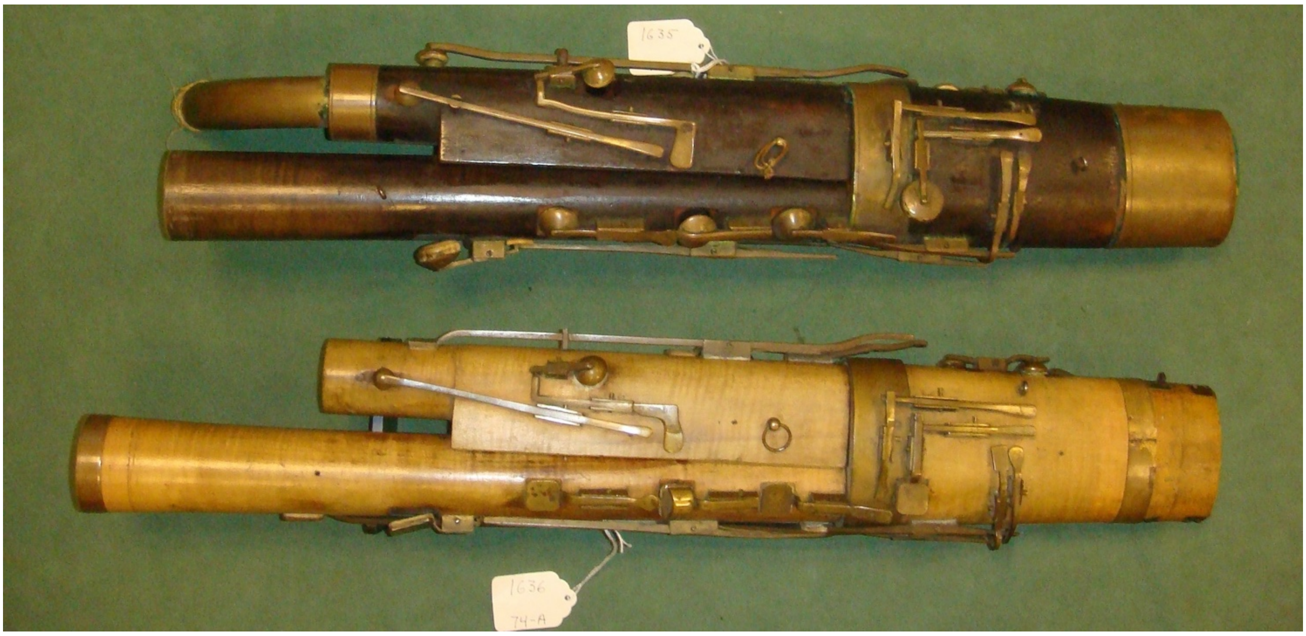

Figure 7.31. anon. US.NY.mma.89.1635 (upper) and anon. US.NY.mma.89.1636 (lower) dorsal views

It is useful to examine the construction of tone holes I, II and III more carefully, see Figure 7.32. The touches for these tone holes are positioned on the wing of the wing joint, with the tone holes themselves centrally over the bore in the two anonymous examples. This is acoustically even more favourable than the angled holes from the instrument centre into the bores of the Catterini. The touches themselves are laid out in a more convenient location for the left-hand fingers, and in US.NY.mma.89.1636 the touches are of uniform size.

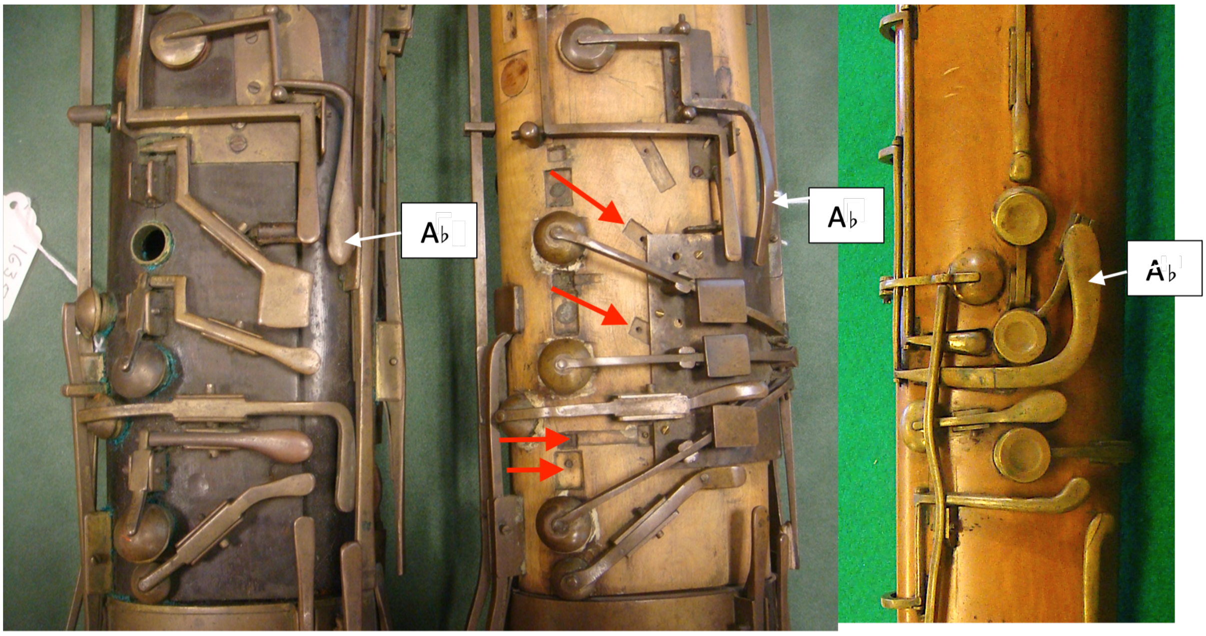

Figure 7.32. anon. US.NY.mma.89.1635 (left), anon. US.NY.mma.89.1636 (centre) and Catterini GB.O.ub.496, front view of tone holes I, II, III and their mechanisms. The red arrows on the centre image show examples of recesses in 1636 in positions where saddles or mechanisms were originally fitted as on 1635. The keys on 1636 are a simpler and neater mechanism.

The location of the A♭ key is a little better in the anonymous examples, and more similar to that of the soprano clarinet. In all three, it is possible to make a quick transit to this key using the side of L1 by rotating the wrist, a common technique for the soprano clarinet.[35] This enables something that is not possible on the true bassoon form such as the Streitwolf, since the up tube is in the way.[36] In the Maino and Riva instruments, it is actually operated by a touch for L2 as annotated on the images, see Figures 7.28 and 7.29.

The differences in the mechanisms for the left-hand tone holes are instructive. Clearly the maker or makers wanted to improve on the idiosyncratic Catterini layout and possibly to conform to Müller-system fingering patterns. The spacing of I, II and III holes is wider than on the Catterini, which probably would give better tuning; the holes in the Catterini are rather too closely spaced as a group, relative to the lower tone holes. Therefore, it seems that US.NY.mma.89.1635 is earlier than US.NY.mma.89.1636, as the keywork of the former is less elegant, involving awkward key shapes with articulation to close the key pad. The mechanism on US.NY.mma.89.1636 has been replaced by a more direct lever although one may see

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[35] Michele Gingras, *Clarinet Secrets: 100 Performance Strategies for the Advanced Clarinetist*, 2nd edition. Washington, DC: Rowman & Littlefield, 2017.

[36] I am grateful to Thomas Reil for drawing my attention to the significance of the positioning of the A♭ key on bassoon-form instruments.

recesses in the wood which correspond to the positions of saddles in 1635, as indicated on Figure 7.32. It appears that the same mechanism was originally installed on 1636 but then removed and replaced by the simpler mechanism, which also appears on the De Azzi instrument discussed below. The touches for these keys are also more neatly and uniformly laid out on 1636.

Therefore it seems most likely that these anonymous instruments are in fact completed prototypes. Whilst less well-finished than the Catterini or Riva instruments they display significant advances in acoustic and ergonomic design and economy of manufacture. The Metropolitan Museum dates these instruments to the period 1840 to 1860, although the features mentioned above suggest that a date of *c*.1840-1850 is probable. The Catterini is the only precedent for this design of instrument at least until the more elaborate ophicleide form. There is little doubt that these anonymous instruments are of North Italian manufacture and may have been made by apprentices from Catterini's workshop.

The final instrument in this North Italian group, attributed to **Pietro De Azzi** is contemporary with the two anonymous bass clarinets.[37] As shown in Figure 7.33 this is an excellently crafted instrument. Though made in bassoon form, the tone holes are all covered, as in instruments by Catterini and the two anonymous instruments. De Azzi, however, uses a simpler and more elegant mechanism, shown in Figure 7.34, similar to US.NY.mma.89.1636 but better executed. De Azzi's tone holes are correctly placed above the centre of the upper joint bore, and the wing is only used to support the mechanism and to look elegant. The A♭ key for the side of L1 is well-positioned, and there are no brilles, indicating an earlier date, *c*.1848.

[37] Alfredo Bernardini, 'Woodwind Makers in Venice, 1790 - 1900.' *Journal of the American Musical Instrument Society* 15 (1989) 52–73.

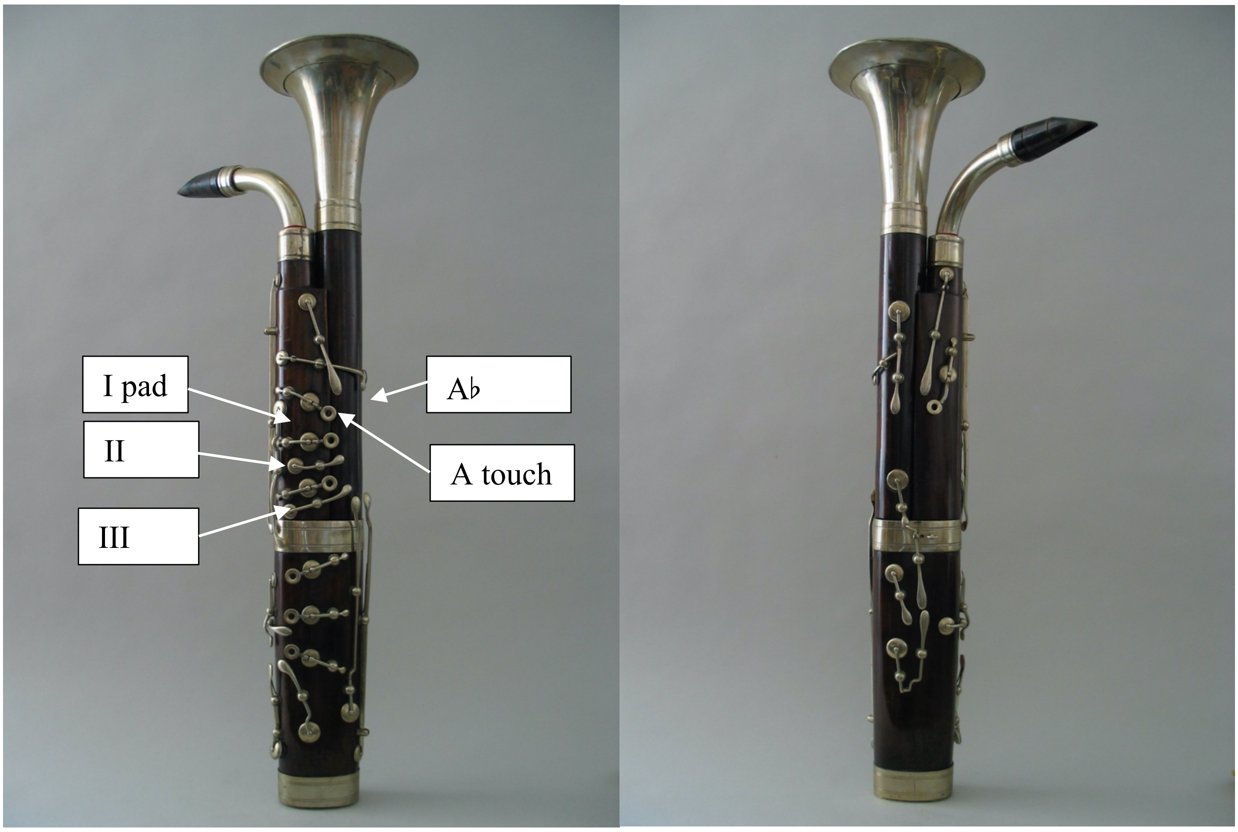

Figure 7.33 Front (left) and dorsal (right) views of De Azzi D.Uhingen.reil. Images courtesy Thomas Reil.

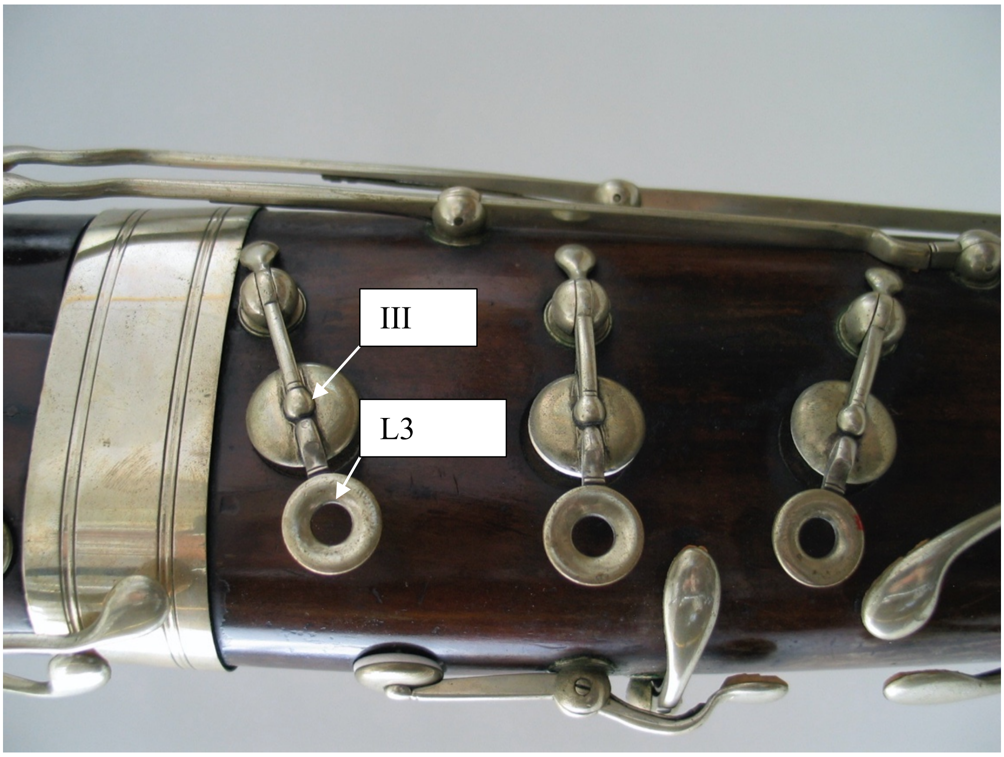

Figure 7.34. Detail of keywork of holes I, II and III in De Azzi D.Uhingen.reil. Image courtesy Thomas Reil.

De Azzi probably knew of Catterini's instrument and possibly even the two anonymous specimens. Whilst it is tempting to suggest a North Italian approach to instrument design, Maino and Riva are in fact closer to Streitwolf in their designs.

Bassoon-form instruments, after 1850

Maker	Bore, mm	Pitch	Top joint system
NN attr. Stengel D.M.dm.46262	20.7	B♭	Wing joint, fingerholes
Stengel B.B.mim. 0943	19.9	B♭ at A4=440 Hz	Wing joint, fingerholes
Stengel I.F.ga.1988/170	20.0	B♭ at A4=440 Hz	Wing joint, fingerholes
Losschmidt I.TS.mt.1013	22.7 – 23.4	B♭	Wing joint, keys
Ludwig & Martinka CZ.P.cmm.E135	20	C at A4=435-440 Hz	Wing joint, keys

From about 1850 there is very little evidence of the use of the bassoon-form instrument in operas or concert orchestras, as discussed in Chapter 3. Composers such as Richard Wagner, Franz Liszt, Gustav Mahler and Richard Strauss wrote extensively for bass clarinet but did not write below E2, with very few exceptions: Liszt uses low E♭2 in four places in *Purgatorio* from *Eine Symphonie zu Dante's Divina Commedia* (1859), though the prominent solo for bass clarinet only descends to E2.[38] It seems that by this time the straight-form instrument (sometimes with E♭2) had largely superseded the bassoon-form in civilian orchestras and opera houses.[39] At least 40 folded-form instruments made after 1850 are extant, which must be a small proportion of instruments in use during the second half of the nineteenth century. Therefore it is likely that bassoon-form instruments were popular in bands. In support of this is the presence of stamps indicating military ownership, for example on the half-bassoon Ottensteiner in Munich, shown in Figure 7.55.

Instruments by **Johann Simon Stengel** are difficult to date because of his long life and consistent high-quality workmanship. He is an important maker for this study having made bass clarinets in both bassoon and straight forms, of which several are extant. Stengel's association with the Wagner Festspielhaus late in his life suggests that his instruments were used by players in Bayreuth. Clustered in the period 1850 – 1866 Stengel's bassoon-form bass clarinets are more advanced than the examples discussed so far. Two examples of his bassoon form instruments have been chosen for detailed measurement, to study his consistency. The instrument in Brussels is shown in Figure 7.35, and the keywork of the front and dorsal sides is shown in Figure 7.36.[40]

38 D. Keith Bowen, *The Rise and Fall of the Bass Clarinet in A*. (2009).

39 Noting that the English player J.H. Maycock probably did use either a bassoon or an ophicleide form instrument as discussed in Chapter 3.

40 B.B.mim.0943

Figure 7.35. Stengel B.B.mim.0943, left and right views. Images from MIMO.

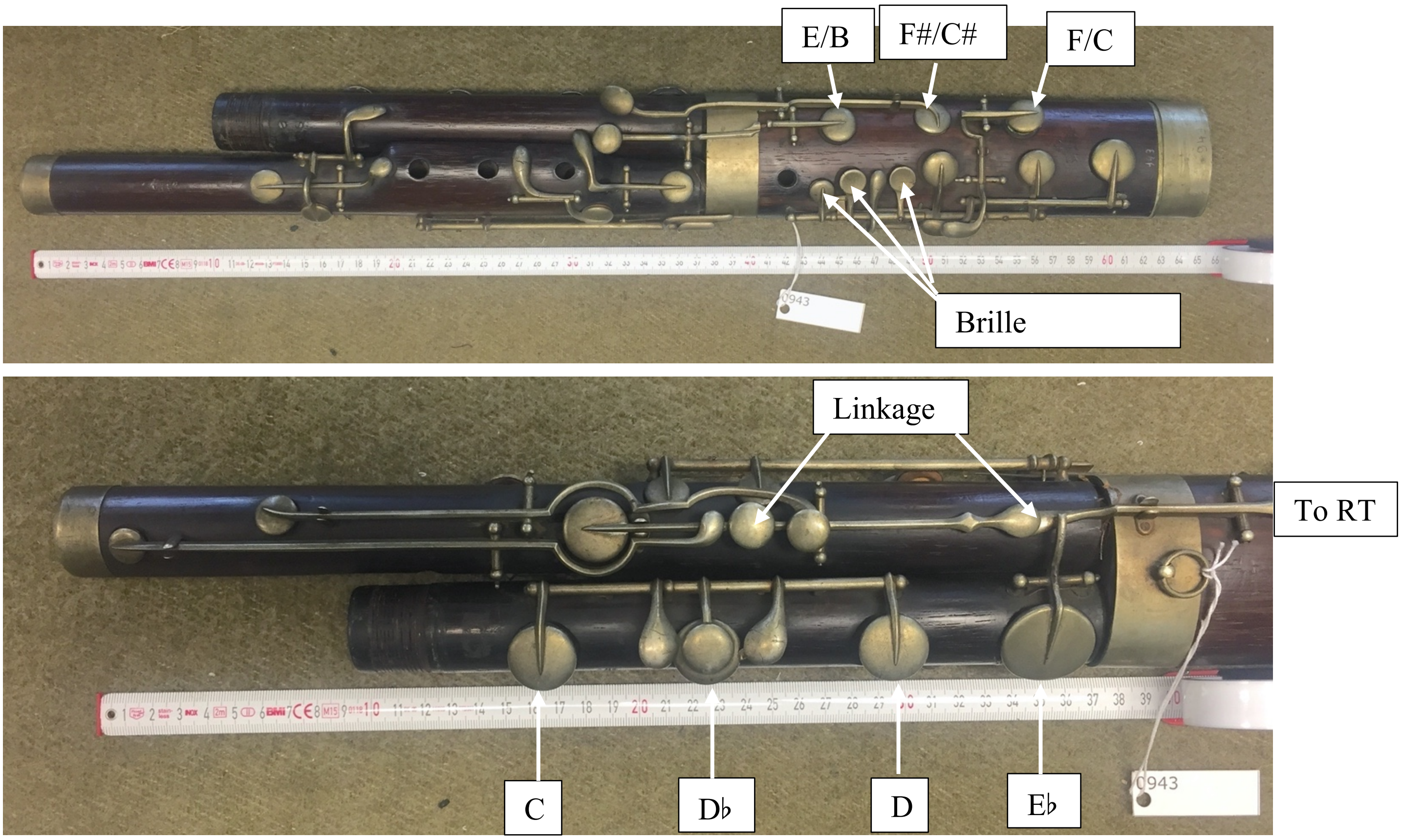

Figure 7.36. Front (upper) and dorsal (lower) views of Stengel B.B.mim.0943

Inspection reveals that spacing of the bass tube holes is quite similar between those labelled E♭, D, D♭ and C, indicating that these notes are chromatic. If the first two holes were D and C rather than E♭ and D then the spacings between these two holes would be double those between the next three holes labelled D, D♭ and C. It is true that the spacing between the hole here labelled E♭ and that labelled E/B on the top joint is somewhat greater than that of the next three holes, which may have led to previous misassignments.[41] This was necessitated by the mechanism of the tenons and the butt joint. But it is seen in Figure 7.36 that Stengel compensated for this by making the E♭ tone hole much larger than the next three, which corrects the intonation.[42] Detailed acoustic modelling, reported in Chapter 8, confirmed this conclusion.

The contemporary Stengel, housed in Florence, is very similar to the last example in Brussels particularly in terms of keywork, see Figures 7.37 and 7.38. This suggests that its range is also fully chromatic to C2. The only real difference in the keywork is that this instrument has a water or spit key, as shown on the bottom key on the side view in Figure 7.37, probably added to get round the problem of condensation near the bottom of the tubes.[43]

Figure 7.37 Stengel I.F.ga.1988/170 Cherubini, front and side views. Images from MIMO.

[41] e.g. Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 312. Rice suggests that the notes on the bass joint are B♭, B, C and D with D♭ and E♭ missing.

[42] This conclusion is confirmed by the detailed acoustic modelling of both instruments, shown in Chapter 8.

[43] Rendall, *The Clarinet: Some Notes on Its History and Construction*, 1954, 143.

Figure 7.38. Details of keywork on dorsal side of Stengel I.F.ga.1988/170 Cherubini. Left: wing and bass joints, right: butt joint.

Note for comparison that the bassoon-form Stengel in Nuremberg, has a larger bore of 24 mm. This instrument can be placed earlier in date, since it lacks the brille mechanism on the right hand; it is a 13-key soprano mechanism down to E2. The keywork is also less elegant than the Brussels and Florence models, which appear to be his stable product. The butt joint of the Nuremberg instrument is shown in Figures 7.39 and 7.40 and shows the keywork in normal and X-ray illumination. In the X-ray view the oblique drilling of tone hole V is clearly seen; however, unlike in the Catterini discussed above, there does not appear to be a significant taper or undercutting.[44]

[44] D.N.gnm.MIR479; described in Bär, *Verzeichnis Der Europäischen Musikinstrumente in GNM Nürnberg.* Band 6, 249.

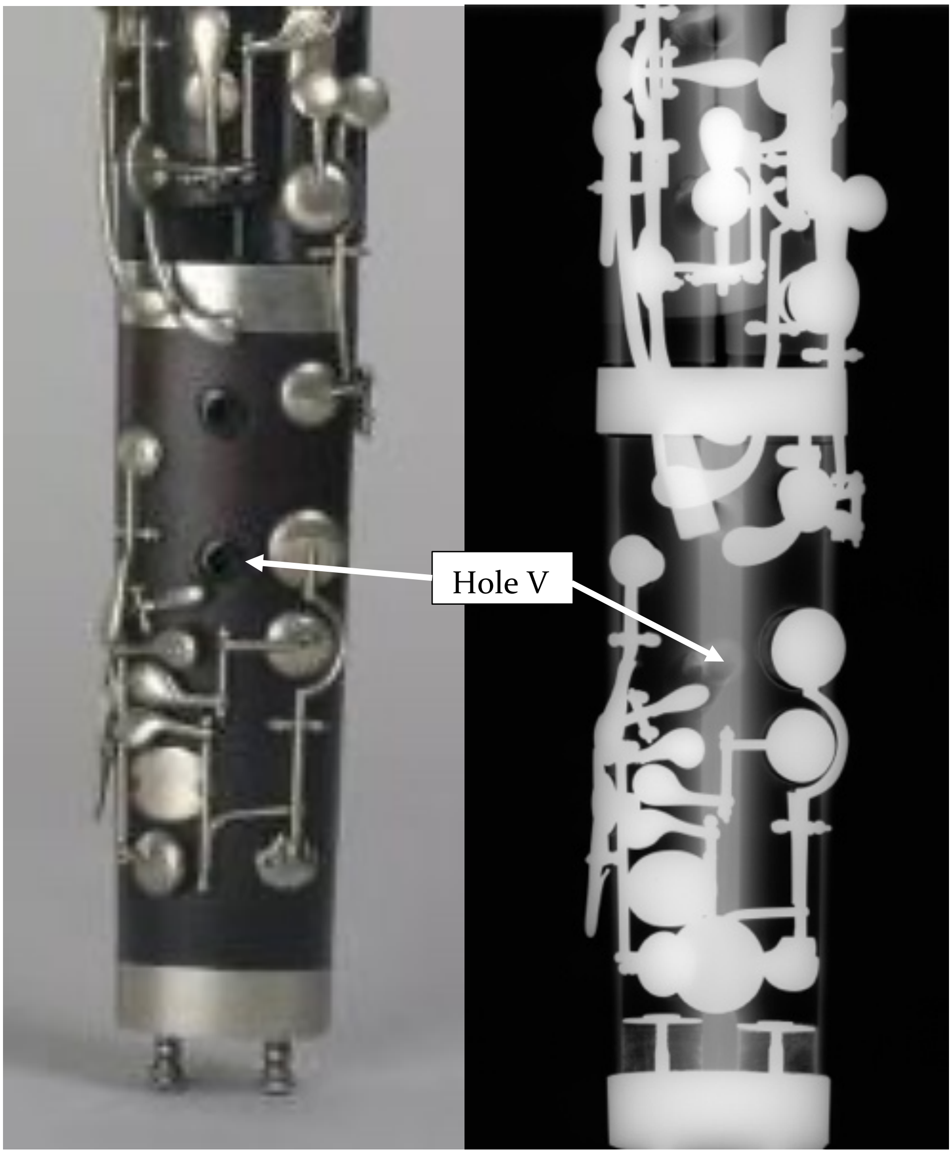

Figure 7.39. Front view of butt joint of D.N.gnm.MIR479 showing details of tone holes and keywork for the right hand. Note the absence of a brille. Left: normal illumination. Right: X-ray radiograph. Images from MIMO.

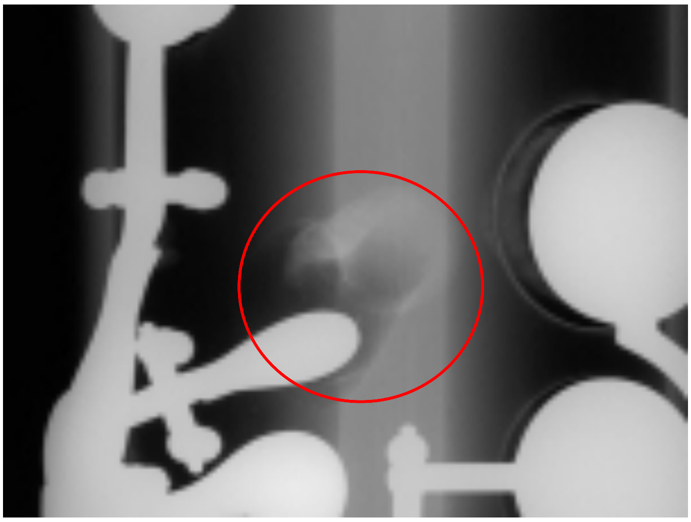

Figure 7.40. X-ray radiograph enlarged to show details of the tone hole V, which is bored at a sideways and downward angle to intercept the 'down' tube at the correct position. Image from MIMO.

We now turn to the unstamped instrument located in the Deutsches Museum, Munich, shown in Figures 7.41 to 7.43.

Figure 7.41 Instrument anonymous D.M.dm.46262. Quarter view. © Deutsches Museum, Munich, Archive, CD81767, reproduced with permission.

Figure 7.42. Instrument anonymous D.M.dm.46262. Front view. © Deutsches Museum, Munich, Archive, CD81768, reproduced with permission.

Figure 7.43. Instrument anonymous D.M.dm.46262. Dorsal view. © Deutsches Museum, Munich, Archive, CD81770, reproduced with permission.

This instrument was examined by means of detailed photographs and discussion with the curator.[45] It is very strongly reminiscent of stamped instruments by Stengel. In comparison with the Brussels and Florence instruments, themselves alike, we note the following similarities:

[45] I thank Dr Silke Berdux and Anna Krutsch for providing these photographs and Panagiotis Poulopoulos for measuring the bore of the instrument.

- The construction of the bass joint is comparable.
- The positioning of the F/C touch running diagonally across the butt joint to a tone hole on the 'up' tube is a characteristic later Stengel design; in the 1835 Streitwolf the tone hole is in the same position but a less elegant keywork is present.
- The brille to correct B/F# is very similar on all three.
- The bass joint and its keywork is virtually identical on all three.

These observations support the hypothesis that this unstamped instrument certainly originated in Stengel's Bayreuth workshop, which was large enough to be designated as a factory by 1860.[46] The lack of a stamp and presence of at least one tone hole correction suggest that it is a prototype instrument, made to test a new design of keywork. It has very different keywork from the 1835 Streitwolf and shows developments such as the equivalent of the brille for B/F#.

Franz Losschmidt is another maker from the former Austrian empire. The number of surviving instruments suggests that Losschmidt was quite a prolific maker. Whilst most of his extant bass clarinets are in the ophicleide form and made of brass, one wooden instrument survives in bassoon-form, see Figures 7.44 to 7.46. The keywork and bore/tone hole design is not as complex as that on the Oxford Catterini glicibarifono. The latter, and the two anonymous prototype examples, discussed above, seem to have been designed to maintain a constant length of the tone hole chimneys along the instrument. In contrast, the Losschmidt, in common with most wooden bassoon-form bass clarinets, places the tone holes for A, G#, I, II and III in the thick part of the wing joint where it curves towards the left hand, even though keys are used, which could have placed these holes more centrally to the tube. Losschmidt's design seems intentional to facilitate finger placement on the tone hole plateau keys, but it means substantially increased chimney lengths for these holes. We may benefit from a comparison with the bassoon, where the long chimneys are known to be a major feature of the characteristic tone production, and indeed the length and diameter of the chimneys are an important feature of the characteristics of the different bassoon types.[47] One would therefore expect significant influence of the chimneys on the tones emitted by these holes, and also a significant difference in the timbre of the 'wing holes' with the C#/G# and Eb/Bb cross keys, which open holes with much shorter chimneys.

The neck is conventional, but the mouthpiece is unusual, being socketed, and inlaid with metal at the tip and framing the slot. Such an unusual mouthpiece is likely to be original. It has a very square profile across the top, and a very narrow tip opening. Playing was allowed but the condition of the instrument was too leaky to get any sounds. The condition of the instrument, with many pads sticking to their holes, also meant that I was unable to make the accurate measurements that would be required for an acoustic model. A number of measurements were taken for study purposes.

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[46] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 311.

[47] James B. Kopp. 'The Not-Quite-Harmonic Overblowing of the Bassoon', 2006. http://koppreeds.com/harmonic.html accessed 17 October 2021

Figure 7.44. I.TS.mt.Losschmidt. Upper: front view, lower: dorsal view

Figure 7.45. Wing joint, front

Figure 7.46. Wing joint, dorsal

The **Ludwig & Martinka** instrument shown in Figure 7.47 was erroneously labelled by the Czech Music Museum as a bass clarinet in A.[48] However, with more advanced methods for calculating the pitch it has been possible to ascertain that the instrument is actually in C,

[48] CZ.P.cmm.E.135. For this reason it is discussed in Bowen, The Rise and Fall of the Bass Clarinet in A, 2009.

pitched at between A4 = 435 – 440 Hz.[49] The keywork is full plateau keys with so-called salt-spoon pads but without a brille mechanism, which support the museum's dating.

Figure 7.47. Ludwig and Martinka CZ.P.cmm.E135)left) front, (right) dorsal

Ophicleide and half-bassoon instruments, after 1855

Maker	Bore, mm	Pitch	Folding system
Losschmidt	25	B♭	U tube
Kruspe	22-3 – 22.5	B♭ at A4=435 Hz	Very short butt joint
Ottensteiner	21.3	B♭?	Short butt joint
anonymous	18	F?	Short butt joint
Bohland & Fuchs	not known	F?	Short butt joint
anonymous, ?Buffet	not known	F?	Short butt joint
Schediwa	22	B♭	Short butt joint

This relatively late group of instruments is arguably the most advanced of the folded type that were made. They all have in common a plain cylindrical top joint or down tube with no bassoon-like wing, resulting in short tone hole chimneys, and many of the tone holes are covered with plateau keys, allowing large tone hole diameters. These factors produce high

[49] The pitch was calculated from the sounding length of the E2 note plus the end correction calculated from Benade's formula, see Benade, *Fundamentals of Musical Acoustics*, 449.

cut-off frequencies and good cooperative resonance of the tones. The butt joint is short or very short and in the ophicleide form is replaced with a U tube.

The **Franz Losschmidt** ophicleide-style instrument in New York (Figure 7.48) is in excellent condition. It seems typical of Losschmidt's products after about 1852. The bore at the start of the downward-facing tube is a large 25 mm. The downward tube is parallel all the way. After the U-bend, the upward-facing tube is virtually conical, with a slight flare starting just before the lowest note, at which point the bore is *c*.44 mm. The keywork is Müller-based, with thumb keys for E, E♭, D, C, Bb; but there is no B or C#. There is an engraving of the maker's mark and also 'No. 8' is engraved, presumably a serial number.

Figure 7.48. (Upper) left and (lower) right side views of Losschmidt US.NY.mma.89.4.2459

Instruments by **Franz Karl Kruspe** are particularly important to this study, since both bassoon form and straight forms have survived. The instrument in Basel is shown in Figure

7.49 and the instrument formerly in the Stearns collection, Ann Arbor in Figure 7.50.[50] We note the similarity of construction between the two instruments, including the curiously shaped crook and bell. These and other details of the Basel instrument are shown in Figures 7.51 to 7.53. Although at first glance this appears to be a standard bassoon-form instrument, the very short butt joint is quite a surprising feature, see Figure 7.53. The purpose of this is primarily to fold the tube backwards to make the instrument more compact. It carries just one key, for F#/C#. The instrument therefore models a straight form instrument with a fold in the middle. The bore is 22.6 mm. The complexity of the bell/bass joint and crook allow considerable simplification to the manufacture of the instrument body, and also demonstrate a significant understanding of the acoustics and of the issues involved in playing the instrument.

Figure 7.49. Kruspe CH.B.hm.1999-136. ©Historisches Museum Basel.

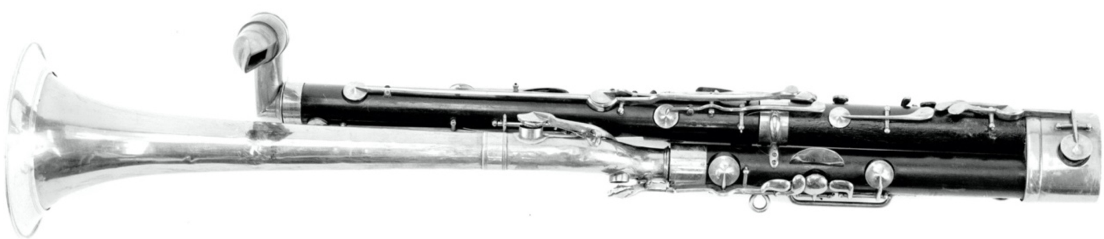

Figure 7.50. Kruspe originally US.AA.s.636, since stolen, location unlnown. Image courtesy Christopher Dempsey, Stearns Collection, University of Michigan at Ann Arbor and A.R. Rice.

[50] This instrument was stolen and therefore no further information is available.

Figure 7.51. Kruspe CH,B.hm.1999-136, view of crook and mouthpiece.

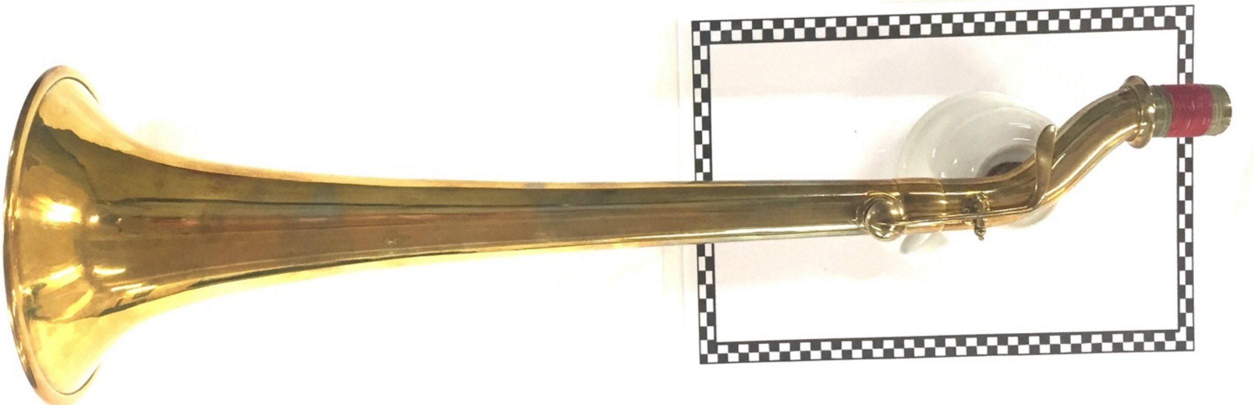

Figure 7.52. Kruspe CH.B.hm.1999-136, view of bell

Figure 7.53 Kruspe CH,B.hm.1999-136, view of butt joint, which is just the part covered by the brass banding.

The curious designs of the bell joint and crook ensure the instrument can be used ergonomically by the player, in much the same way as a soprano clarinet is played. First, the bending of the bass tube and bell below the top joint permits access to the important A and A♭ keys without interference to the left hand. The bell and crook bends, shown in Figure 7.51 and Figure 7.52, initially appear to be otiose. The bell is also very slowly flaring and is quite narrow for much of its length. Only when the instrument is correctly assembled and held as if for playing does the reason for this design become apparent. The geometry of the instrument is such that the narrow part of the bell sits below the top joint, which itself is simply a tube unencumbered by a 'wing'. This means that the fingers of the left hand can easily reach the centre point of the top joint tube in line with the correct positions for the tone holes. Despite holes I and II being fairly short open finger holes, they can be reached by the fingers without need for long oblique holes. In order that the instrument can be blown with the tubes in these fore-and-aft positions, the maker provided the dog-leg in the bell and a crank in the crook (Figures 7.51 and 7.52).

It is also quite possible that the unstamped Leipzig instrument, shown in Figure 7.54, is a slightly later ophicleide version by Kruspe.

Figure 7.54. Two views of D.LE.u.4481.NN-01. Photo of the Musikinstrumentenmuseum of the University of Leipzig.

This instrument torso was in the workshop of Max Hüller, taken over from Carl Kruspe in 1923 and sold by Max's son Kurt to the Grassi Museum in 1978.[51] The ophicleide foot is a natural development of the very short butt joint of the other Kruspe basses and the construction is otherwise similar. The instrument does not appear to be correctly assembled for playing: the crook should be rotated about 180° so that it passes over the dog-leg in the bass tube, giving the improved ergonomic style noted above. The instrument torso was damaged in WWII.

The **Georg Ottensteiner** bass clarinet shown in Figure 7.55 is a member of the 'half-bassoon' class of instruments. These first appeared in the third quarter of the nineteenth century and were produced until the early twentieth century. This effective design holds the acoustic and ergonomic advantages of the straight type for most of its length, but takes advantage of the butt joint to incorporate a bass tube, with no penalty of overall length. The Ottensteiner example descends chromatically to B♭1, with an elegant and practical mechanism for the four basset keys.

Figure 7.55. Ottensteiner D.M.sm.79-28.

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[51] Email from Wieland Hecht, Musikinstrumentenmuseum der Universität Leipzig im Grassi, 24.6.2022

That this instrument was used in a military band is shown by the ownership stamps: **I/J.R.19** on the body and **B 3.J.R**. on the butt (see Figure 7.56) and bell. 'J.R.' stands for *Jägerregiment*, a light infantry regiment in the Germanic militia.[52]

Figure 7.56. Military ownership stamp on butt joint of D.M.sm.79-28.

(a) (b) (c) (d)

Figure 7.57. Half-bassoon basset horns. (a) anonymous D.M.dm.43336, © Deutsches Museum, Munich, Archive, CD81752; (b) D.Nauheim.heimatmuseum.BohlandFuchs, image with kind permission of Hans Joachim Brugger; (c) and (d) I.M.carbonara, anonymous, with kind permissions of Rocco Carbonara and Albert Rice.

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52 Private communication, Dr Eszter Fontana, Leipzig Grassi Museum, 20 August 2009.

The three half-bassoon instruments shown in Figure 7.57, one by **Boland & Fuchs**,[53] one possibly by **Buffet** and one **anonymous** are all basset horns, as defined by their dimensions, which indicate a tonality of F and their keywork, showing that the range descends to (written) C2.[54] They have been studied by means of these photographs alone.[55] Although the photograph of the Bohland & Fuchs instrument does not show the dorsal side, all three instruments are strikingly similar in the layout of their keywork. The instrument D.M.dm.43336 does not have the LH ring keys[56] so is presumably earlier than the other two. Whilst engraved with 'Buffet Crampon/Paris' on the bell the Carbonara basset horn has no stamps on the bodywork.[57] A striking feature in at least two of the instruments is the very neat and logical mechanism of the basset keywork. The **anonymous** Munich instrument is superfically similar to Ottensteiner's bass clarinet, but the layout of the latter's basset keys is different (Figure 7.55). It is, however, similar to the basset key arrangement in the Bate Schediwa, shown in Figure 7.10. This is such a characteristic feature that it is reasonable to speculate some connection between these instruments. Schediwa trained in Bohemia with V.F. Červeny and emigrated to Odessa only in 1881.[58] Both Schediwa and Bohland & Fuchs were known chiefly as brasswind makers. The appearance of these clarinets suggests they were made by experienced hands, possible in Germany by a third party. The Edinburgh example GB.E.u.4819 has the label of seven medals marked 'WIEN, PARIS and CHICAGO', these pertain to the exhibitions held in those cities in 1892, 1889, and 1893, indicating that the design was established at least by 1892.

The anonymous Munich instrument has a wide bore for a basset horn (18 mm), and it has been suggested that it is an alto clarinet in F with extended range.[59] The other two basset horns look similar in construction, but bore measurements are currently unavailable. It would certainly be more powerful than the classical instrument and have a less characteristic basset horn sound. However, the only music available for such instruments in the nineteenth century was basset horn music. Art music repertoire is better known, but Eichborn notes that during the middle nineteenth century, basset horns were used in military bands in Germany.[60] I suggest that bands may have comprised significant markets for these more dynamically powerful basset horns.

Straight-form instruments

Maker	Bore, mm	Pitch, Hz	Range
Sax (2601)	28.8	440	E2
Sax (0175)	29.0	440	E2
Kruspe	23.0	440	E♭2

[53] Günter Dullat, 400 Jahre Musikinstrumentenbau in Graslitz, Katalog zur Somderausstellung im Heimatmuseum Nauheim. Nauheim: Heimat= und Museumsverein Nauheim e.V., 2014; 400 Jahre Musikinstrumentenbau in Graslitz: heimatmuseum-nauheim.de) https://www.heimatmuseum-nauheim.de/musik_graslitz/musik_graslitz.htm
[54] Sounding F2 (see Table C.1)
[55] My appreciation to Albert Rice for a valuable discussion on these instruments.
[56] Other photographs are available for this instrument, which show that I. II and III are open fingerholes.
[57] A.R. Rice, private communication.
[58] Waterhouse, *The New Langwill Index*, 351.
[59] Seifers, *MusikInstrumente Katalog Der Bläsinstrumente.*
[60] Eichborn, 'Studien Zur Geschichte Der Militärmusik.'

Kruspe	23.3	not known	E2
Stengel	not known	440	E2
Stengel	20	not known	E2
Heckel	23.25	440	E♭2

All these are instruments in B♭. The **Adolphe Sax** instruments, shown in Figures 7.58 and 7.59 are both relatively early, made in Brussels before his move to Paris. They differ mainly in the materials used (ebony/silver and boxwood/brass). There is one slightly earlier instrument extant, in C, US.AA.s.637, which is reported to have a bore of 22.9 mm,[61] however, the Brussels instruments in B♭ have much larger bores. 28-29 mm, as measured by myself. This is significant because it is much larger than the current *c*.24 mm used by manufacturers such as Selmer and Buffet and larger than any of the bassoon-form instruments for which data is available, except for the bassoon-form instrument US.NY.mma.89.1635 discussed above. The mouthpieces are also very large in comparison to contemporary instruments. These instruments would have produced a great volume of sound, and thus were useful for performances in French military bands, particularly outdoors. Note that that early Buffet bass clarinets were also made with a very large bore, for example the instrument D.N.gnm.MIR478 (c.1850), a straight form with upturned bell, whose bore is 28.8 – 30.4 mm.[62]

The keywork of the Sax instruments makes them relatively easy to play fluently, and they had the power to carry well under any circumstances. Any bass clarinet with a favourable reed and mouthpiece set-up is also capable of playing extremely quietly.


Figure 7.58 (left). Sax B.B.mim.0175. Image from MIMO.
Figure 7.59 (right). Sax B.B.mim.2601. Image from MIMO.

[61] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 292.
[62] Bär, *Verzeichnis Der Europäischen Musikinstrumente in GNM Nürnberg.* Band 6, 241.

Figure 7.60. Stengel GB.E.U.4932. (L) side view, image from MIMO. (R) detail of RH keys showing brille.

The straight instrument by **Johann Simon Stengel** (Figure 7.60), is likely to be later than all of his bassoon-form instruments. Its bore is identical to the two other bassoon-form instruments by this maker in the database.[63] This design of *c*20 mm diameter, long cylindrical bore with a short flare was subsequently adopted by later bass clarinet makers in the Germanic tradition, as seen in much later instruments by Fritz Wurlitzer and Stephen Fox. The keywork on this Stengel is now the 15-key Müller-derived system with both right- and left-hand brilles, with a duplicate G#/E♭ key for L4. Similar keywork is found on the Düsseldorf Stengel bass in A, shown in Figure 7.8. Applying seriation or sequence dating to features discussed above reveals the chronology for the examined Stengel bass clarinets that is shown in Table 7.5.[64]

Tab;e 7.5. Proposed chronology of the Stengel bass clarinets examined.

Sequence	Instrument	Proposed date
1	D.N.gnm.MIR479 bassoon-form in C	1860 – 1865
2	D.M.dm.46262 bassoon-form in B♭ (my attribution)	1865 – 1875
3	B.B.mim.0943 bassoon-form in B♭	1865 - 1875
4	I.F.ga.1988_170 bassoon-form in B♭	1865 – 1875
5	GB.E.u.4932 straight-form in B♭	1870 - 1880
6	D.Düsseldorf.Robert Schumann School straight-form in A	1876 - 1880

[63] B.B.mim.0943 and I.F.ga.1988/170 Cherubini

[64] Flinders Petrie, 'Sequences in Prehistoric Remains', 1899, 295–301; Colin Renfrew and P Bahn, *Archaeology. Theories, Methods and Practice*. 2008, 126-127.

Precise dating is more difficult, but we know that the Düsseldorf instrument was purchased by the Bayreuth Festspielhaus Orchestra soon after its opening in 1876.[65] It is plausible that the other straight form GB.E.u.4932 in B♭ or a similar instrument was made for the same theatre, indicating that the straight forms appeared in 1870 – 1880. D.N.gnm.MIR479, the prototype bassoon form, is probably early 1860s, giving the other two very similar instruments B.B.mim.0943 and I.F.ga.1988_170 (which has a water key also, so is probably the later) as 1865 – 1875.

Finally, the instrument used for the acoustic tests was my own **Heckel** bass clarinet in A, shown in Figure 7.61. It is a 21-key system including 5 plateau keys (holes I and IV are open fingerholes), and is the Simple pattern of tone holes. Brilles for both right and left hands operate auxiliary tuning holes, as in the straight-form Stengels, and it has a so-called patent C#.[66] In total, 22 of the 24 holes are covered by keys or plateaux.

Figure 7.61. Heckel bass clarinet in A used for acoustic trials. Image courtesy Huw Bowen

The instrument has been kept in playing condition all its life, but only lightly played, no doubt as a consequence of there being relatively few orchestral parts for the bass clarinet in A.[67] It has a straight bell.

There was no sign of ellipticity due to shrinkage and the bore demonstrates a predominantly conical flare beginning 153 mm from the bell. It is therefore a very appropriate experimental instrument for this project. The original mouthpiece was missing. A new mouthpiece was made in 2014 by Edward Pillinger using published dimensions of an original Heckel B♭ bass clarinet mouthpiece of a similar model in Nuremberg.[68]

Bassoon-form soprano clarinets

Maker	Pitch		
Ghirlanda	C at 435-440 Hz	I.R.ms.3130	Pitch calculated from dimensions
Chiesara	C at 435-440 Hz	I.R.ms.3254	Pitch calculated from dimensions

The examination of these instruments would not be complete without the inclusion of four rare and remarkable bassoon-form soprano clarinets. Two of these are shown in Figure 7.62. They are, in modern terminology, basset clarinets, descending to written C3.

To determine the pitch, the sounding length *L* of the **Tedesco Chiesara** instrument was measured from the mouthpiece tip to the bell; this was 685 mm. Both these instruments are

[65] Email from Prof. Kerstin Grötsch, 28 February 2013 quoting oral history from the late Hans Klüppel, member for 25 years in the Bayreuth-Festival-Orchestra, who was given the instrument by Wolfgang Wagner and donated the instrument to the School.

[66] Voorhees, *The Development of Woodwind Fingering Systems in the Nineteenth and Twentieth Centuries*, 2003, 163.

[67] Bowen, D. Keith. 'The Rise and Fall of the Bass Clarinet in A', 2011.

[68] D.N.gnm.MIR480, see Bär, Frank P. *Verzeichnis der Europäischen Musikinstrumente in Germanischen Nationalmuseum Nürnberg.* Band 6, 257.

about the same length including the bells. The frequency of written C3, the lowest note on the instrument, will be 129 Hz at A440, so it is very likely that both these instruments are pitched in C at A = 435 – 440 Hz. Thus it is very unlikely that they were designed to play Mozart's basset clarinet parts in either A or B♭, since they are at the wrong pitch.

Figure 7.62. Front views of Chiesara I.R.ms.3254 (L) and Ghirlanda I.R.ms.3130 (R).

Figure 7.63 Dorsal views including basset keys of Chiesara (L) and Ghirlanda (R)

A third instrument in the same museum, in metal by **Martin Tomschik** (I.R.ms.3069) is in B♭ and folded by means of a pipe soldered so as to connect the down and up tubes. This instrument was not examined. Tomschik describes the instrument in a patent as:

> 'almost more than half shorter than the usual clarinets in B♭ and therefore it is not only very comfortable for every clarinettist, but because of its compactness quite suitable for the cavalry music choirs. This clarinet can also be made in the keys A, B, C and D. [69]

It is possible that this was a prototype which never went into production. But Wilhelm Altenburg mentions similar instruments existing in Bohemia and Germanic lands. [70] Moreover, there is a fourth folded soprano basset instrument in Rome, an ophicleide form by

[69] Austrian patent 2992 filed 30 December 1857, 'Schwanerhals Clarinette', see Günter Dullat, Klarinetten, 125.
[70] Wilhelm Altenburg, *Die Klarinette: ihre Entstehung und Entwicklung bis zur Jetztzeit in akustischer, technischer u. musikalischer Beziehung*. Heilbronn am Neckar: C.F. Schmidt, 1904, 31. Cited in Dullat, *Klarinetten*, 125.

Anton Nechwalsky.[71] Except for the Tomschik, these instruments are discussed and compared with historical and modern basset clarinets by Rice.[72] Tomschik's remark suggests strongly that these instruments might have been intended for use in cavalry bands, for which the extreme compactness would be advantageous. Both B♭ and C would be useful pitches for this purpose. The 1865 Mercadante Commission on band instrumentation does not mention clarinets as a normal constituent of Italian cavalry bands. However, it is possible that they were used in some cavalry regiments in central Italy, which would account for their presence only in Rome.[73] They were part of the enormous and eclectic collection amassed by the tenor Evangelista Gorga that he gifted in 1949 to the State of Italy.

Concluding remarks

This chapter has presented a great deal of information about approximately one-third of extant folded clarinet instruments in museums, which illuminates the development and use of the instruments. The examples were chosen to include the principal forms of the instrument. Folded alto clarinets, basset horns and soprano clarinets provide supplementary context to the main theme of bassoon-form bass clarinets. The playing tests and analysis of performances has given valuable information about the pitch, accuracy of temperament, sound quality and in particular the dynamic capabilities of a selection of instruments, and has indicated qualitatively how these correlate with the bore and flare dimensions. A critical examination of tone hole positions has suggested alterations to the fingering assignments made in the literature in some cases, which are pursued by quantitative modelling in the next chapter. Inspection of the geometric design of the keywork has indicated a new assignment of one unmarked instrument, D.N.dm.46262, proposed as a Stengel.

Three general trends are evident:

- Makers were very slow to apply the Boehm system of toneholes and keywork (first fully released by Buffet in 1855) to the bass clarinet. It was never applied to the bassoon-form instrument and was not applied to any of the straight forms considered in this thesis.
- From about 1850, as shown in Chapter 3, Art music for operas and orchestras appeared to use almost exclusively the straight form instrument down to E2. But the bassoon-form instrument was made in significant quantities in the period 1850 – 1900 and even beyond and enjoyed significant developments in this period (e.g. by Kruspe). This reinforces the conclusion that they were used primarily in bands and outdoor music, for which they are arguably better fitted than the straight instrument.
- The bassoon-form instruments are considerably more complicated as woodwork designs than straight form instruments. Whereas all joints of a straight-form instrument are made with a relatively simple woodturning operation, only the bass joint of a bassoon-form

[71] I.R.ms.3072. I have seen a photograph of this instrument but it is not yet available for publication. There are also ophicleide-form basset horn and bass instruments in the museum by Nechwalsky (I.R.ms.3080 and I.R.ms.3260 respectively).

[72] Rice, 'The Basset Clarinet.'

[73] Gottfried Veit, *Die Blasmusik: Studie Über Die Geschichtliche Entwicklung Der Geblasenen Musik*. Innsbruck: Helbling, 1972, 61; Whitwell, *The History and Literature of the Wind Band and Wind Ensemble: 5. The Nineteenth-Century Wind Band and Wind Ensemble*, 90.

instrument can be made on the lathe. The wing joint and butt joint have to be made by hand shaping, carving and drilling at an angle. This is a much more laborious and complex operation. The complexity of the keywork is similar between the two forms. Therefore one would expect bassoon forms to be quite significantly more expensive.[74] The fact that such instruments persisted in military bands for at least some 50 years after they had been displaced from opera houses and orchestras by the straight form is a strong argument that they found substantial utility in this genre.

In the next chapter the acoustical properties of a critically selected set of these bass clarinets will be analysed and studied in detail.

74 Holtzapffel, Charles. *Turning and Mechanical Manipulation Vol. 1: Materials; Their Differences, Choice and Preparation; Various Modes of Working Them, Generally without Cutting Tools*. London: Holtzapffel & Co, 1843; ———. *Turning and Mechanical Manipulation Vol. 2: The Principles of Construction, Action and Application, of Cutting Tools Used by Hand; and Also of Machines Derived from the Hand Tools*. London: Holtzapffel & Co, 1846;———. *Turning and Mechanical Manipulation Vol. 3: Abrasive and Miscellaneous Processes, Which Cannot Be Accomplished with Cutting Tools*. Second. London: Holtzapffel & Co, 1884; ———. *Turning and Mechanical Manipulation Vol. 5: The Principles and Practice of Ornamental or Complex Turning*. London: Holtzapffel & Co, 1884; Holtzapffel, John Jacob. *Turning and Mechanical Manipulation Vol. 4: The Principles and Practice of Hand or Simple Turning*. London: Holtzapffel & Co, 1881.

Chapter 8

Acoustic impedance spectra of historical bass clarinets

Introduction

As discussed in Chapter 7, thirteen historically-significant instruments were selected for detailed geometrical measurements and acoustic simulations. For convenience, these instruments are shown again in Table 8.1. The measurements themselves can be found in Appendix B.

Table 8.1. Instruments for which detailed measurements and acoustic calculations were made. B-F = bassoon form; H-B = half-bassoon form; S-F = straight form.

Maker/ location	Type	Date	Museum siglum	Comments
Early instruments				
Heinrich Grenser, Dresden	B-F	1793	S.S.m.M2653	earliest extant B-F bass clarinet
Bassoon-form instruments, 1835 - 1850				
Johann Heinrich Gottlieb Streitwolf, Göttingen	B-F	1835	D.N.gnm.MIR477	Streitwolf was a major maker with an excellent reputation
Streitwolf	B-F	1835	D.LE.u.1539	
Catterino Catterini, Padua	B-F	1838	GB.O.ub.496	First folded bass with correctly positioned and vented tone holes
Paolo Maino, Milan	B-F	1838	B.B.mim.0941	Examined in museum
Bassoon-form instruments, after 1850				
Stengel Bayreuth	B-F	1855	B.B.mim.0943	Both B-F and S-F types
Stengel Bayreuth	B-F	1860-80	I.F.ga.1988/170	Both B-F and S-F types
Ophicleide and half-bassoon instruments, after 1855				
Franz Carl Kruspe, Erfurt	H-B	1865-75	CH.B.hm.1999-136	Both B-F and S-F types
Straight-form instruments				
Sax, Brussels	S-F	1840	B.B.mim.2601	First successful straight-form
Sax, Brussels	S-F	1840	B.B.mim.0175	First successful straight-form
Kruspe	S-F	1865-75	D.LE.u.4479	Both B-F and S-F types
Stengel	S-F	1880	GB.E.U.4932	Both B-F and S-F types
Wilhelm Hermann Heckel, Biebrich	S-F	1910	GB.Warwick. bowen	model for acoustic calculations. recently repadded with leather pads, in excellent playing condition

The acoustic impedance spectra showing all resonances of the air column will be shown, calculated according to the methodology described in Chapter 6. Each instrument is shown by means of spectra for each note from the bottom of the range up to C5, and by an impedance map. The individual spectra show the properties of the individual notes, and the impedance maps summarise the main acoustic features of the instrument. From these we can determine the tonality, the playing pitch, the fingering, the evenness of the intonation in both main registers, any particularly poor notes, the onset of the cutoff frequency and (in consequence) the number and alignment of harmonics that contribute to the timbre.

The methodology described in Chapter 6 is followed exactly, but practical issues must first be discussed. These are, how to account for missing or inadequately measured mouthpieces, how to determine the playing pitch of the instrument and how to account for the butt joint in the computations of the bassoon-form instruments.

The mouthpiece and the playing pitch

The parameter required in the computations is the total volume of the mouthpiece, as explained in Chapter 6. This is the most difficult of the measurements. Attempts to measure the internal dimensions and model the volume as, say, a cylinder followed by a tapered cylinder were not successful, leading to implausible extra resonances on the instrument. There are two ways known to give accurate results:

- Filling the mouthpiece with water (or some other fluid of known density) and weighing the fluid; repeating, say, 10 times for accuracy. This can only be done safely on a hard rubber mouthpiece but is unsafe on wood and is normally not permitted at all on museum specimens. It was performed for the modern mouthpiece of the Heckel instrument in my possession, discussed extensively in Chapter 6. This gave a baseline for mouthpiece size for other instruments.
- Doing a full CT X-ray scan and extracting the volume from the data. This requires a CT unit of sufficient accuracy and size, plus suitable analytical software. While these exist, they are not normally available within museums. In practice it is very difficult to organise such measurements, especially for museums in another country.

Furthermore, the mouthpiece of a historic instrument is often either a replacement or completely missing. A methodology is obviously needed to cope with this common eventuality as well as with the difficulty of obtaining accurate measurements.

Fortunately, the mouthpiece volume and the playing pitch can be determined together, on the reasonable assumption is that the maker or player provided a mouthpiece that played well in tune at the specified playing pitch. The intonation of the instrument and mouthpiece together is a feature easily derived from the computer models displayed as an impedance map. Thus we may vary the mouthpiece volume and the playing pitch in the computer model and select the values that provide the best overall intonation. This is not a strictly mathematical operation of minimising errors; some judgement is required, bearing in mind that players prefer a slight sharpness overall. Unlike flatness, it is fairly easy to correct slight sharpness with reduced embouchure pressure and oral cavity voicing, especially near the top of each register. This volume, optimised for tuning and intonation, can be regarded as an 'ideal' mouthpiece for the instrument. It is used in this chapter for all museum instruments, whether or not they have mouthpieces. It is also reasonable to assume that the mouthpiece volume should scale approximately with the bore area of the crook. Therefore, as a starting value, for the modelling, the measured volume of the Heckel, 29 cm^3 at a bore of 23.25 mm diameter, was used. This instrument is known to play very well and in tune, For an instrument with a crook diameter of D, the initial trial value V was therefore taken as

$$V = 29\,D^2/(23.25^2)\quad \mathrm{cm}^3$$

or

$$V = 0.0536D^2\quad \mathrm{cm}^3$$

This often needed no changing and is a useful empirical law. There are of course, several more subtle aspects of mouthpiece design, such as the curvature of the chambers and the length and shape of the baffle, which mainly affect the ease of playing and the detailed timbre. The model is not at present sensitive enough to distinguish such effects and besides, they are also strongly dependent on the individual player's embouchure and oral cavity. Such optimisation is shown in detail for one of the Sax instruments (B.B.mim.2601). It was performed on all instruments other than the Heckel, but for brevity the details are not presented for the other instruments.

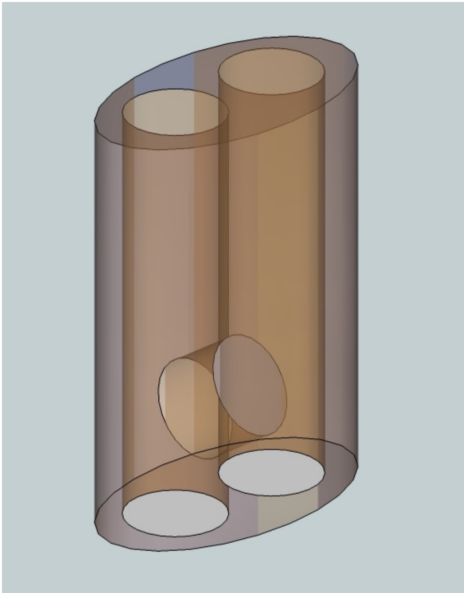
Treatment of the butt joint

The structure of the butt joint is shown in Figure 8.1a and a diagrammatic 'straightened out' representation in Figure 8.1b. Whilst a number of acoustical treatments of a curved tube have appeared, none treats this particular geometry.[1] The mathematics are complicated but a main conclusion for low frequencies is that a sharp U-bend will reduce the inertance slightly. Only low frequencies need to be considered, since only low notes utilise the up tube. However, the inertance is also increased by the dead space at the bottom of each tube between the side hole and the cork bung, as illustrated in the figure.

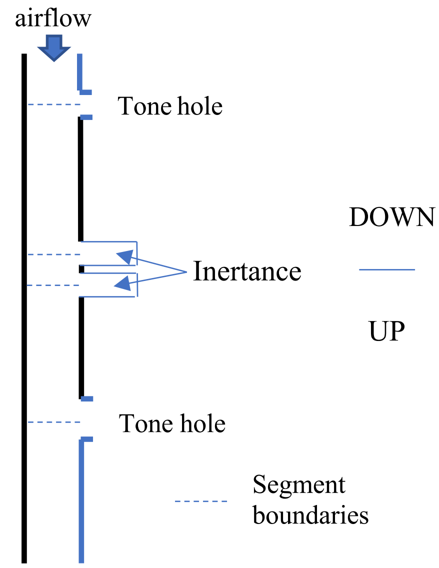
The butt joint is therefore modelled as follows, starting from the up tube (bell side) :

1. A segment from the previous tone hole leading up to the centre of the side hole;
2. An inertance, modelled as a closed fingerhole, from the centre of the side hole to the cork bung;
3. A short segment corresponding to the width and diameter of the connecting hole;
4. Another inertance, modelled as a closed fingerhole, from the cork bung of the up tube to the centre of the side hole;
5. A segment running from the centre of the side hole to the next tone hole.

[1] G.S. Brindley, 'Speed of Sound in Bent Tubes and the Design of Wind Instruments,' *Nature* 246 (1973) 479–80; D. H Keefe and A.H. Benade, 'Wave Propagation in Strongly Curved Ducts,' *J. Acoust. Soc. Am.* 74 (1983) 320–32. https://doi.org/10.1121/1.389681; C.J. Nederveen, 'Influence of a Toroidal Bend on Wind Instrument Tuning,' *J. Acoust. Soc. Am.* 104 (1998) 1616–26. https://doi.org/10.1121/1.424374; Félix, Dalmont, and Nederveen, 'Effects of Bending Portions of the Air Column on the Acoustical Resonances of a Wind Instrument.'



(a)



(b)

Figure 8.1 (a). Cutaway diagram of the butt joint in a bass clarinet or bassoon. After drilling the holes, the side connecting hole is cut and shaped by hand. Finally the open ends are plugged with cork. (b) Diagram of cross section showing how the joint is modelled in the computer.

These are illustrated in Figure 8.1b. This procedure appears to work effectively and the impedances are not very sensitive to the exact values. The impedance maps do not in general show any discontinuity between notes either side of the join.

Illustration of the analysis of spectra

The resonances (impedance peaks) and their consequences are discussed in detail in Chapter 6. The summary and interpretation of the data will be illustrated by means of the Heckel bass clarinet in A, used as a test instrument for the software verification. The Heckel is a high-quality instrument made in *c.*1910, using the Simple pattern of keywork and tone holes, i.e. very similar to most of the nineteenth-century instruments examined.

The calculated impedance (resonance) spectra for each note of the Heckel are shown in Figure 8.2 and Figure 8.3 for the first and second registers, respectively. Red lines are also drawn at the values of the odd harmonics of the actual resonance peak used in that register.[2] In the first register this is simply the first resonance; the peak position is evaluated automatically, and lines drawn at 1, 3, 5, 7, 11 and 13 times this value.

[2] As discussed in Chapter 5, the even harmonics of a stopped pure cylindrical tube are absent and even in a practical instrument are very weak.

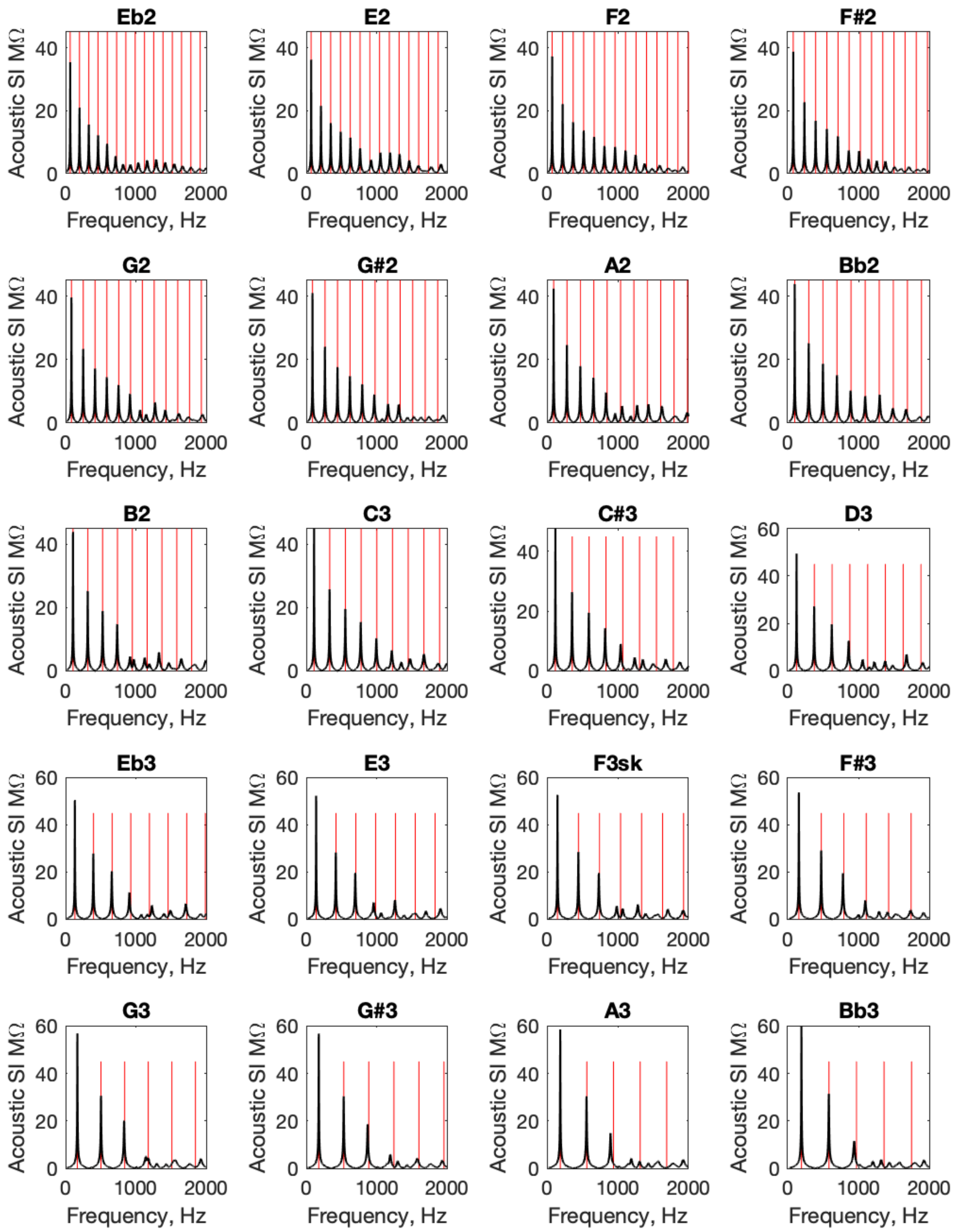


Figure 8.2. Impedance spectra for the GB.Warwick.bowen.Heckel for the first register, from E♭2 to B♭3.

The more of these frequencies there are that coincide with actual resonance frequencies of the air column, the more harmonics there are that appear in the sound of the note. This in turn strengthens and stabilises the note through the phenomenon of mode locking as discussed qualitatively in Chapter 5 and also by Nederveen and Dalmont.[3]

The positions of the acoustic resonances (peaks in the impedance spectra) are properties of the air column itself, which in turn are the consequences of the design of the bore, the sizes and shapes of the fingerholes, pad venting and other details of manufacture. That is why they

[3] C.J. Nederveen and J.-P. Dalmont, 'Mode Locking Effects on the Playing Frequency for Fork Fingerings on the Clarinet,' *J. Acoust. Soc. Am.* 131 (2012) 689–97. https://doi.org/10.1121/1.3653966

may be computed from acoustic theory. There is no physical necessity that they be in a harmonic relationship. This is down to the skill, experience and knowledge of the maker. It is not possible to satisfy all demands of perfect intonation, tone quality, etc., right across the instrument, and the maker is also free to choose where the compromises occur. In this instance, the multiple resonances are well aligned with harmonics of the fundamental in the lower register; there is a slight misalignment of the third resonance (fifth harmonic) for the notes A3 and B♭3, which will slightly flatten the tuning of these notes.

Moving to the second or upper register, Figure 8.3, we see that the main effect of the speaker key is to shift the first resonance towards higher frequencies so that it will no longer couple with resonances at harmonic positions. Resonances overall are weaker in this register. The fundamental of the played note is now based upon the second resonance frequency. Three or four such resonances are available for mode locking at least up to G4. At higher frequencies, above about 1000 Hz, it is seen that the resonances become very much weaker. These are above the cutoff frequency (see Chapters 5 and 6) at which the waves are not reflecting just after the first open finger hole but are penetrating further down the instrument and may be lost at the bell. The resonances now become weak and appear in apparently random positions. They are caused by weak reflections from the bell and oscillate about the wave impedance for the tube itself.[4] The position of reflections from the bell depends both upon the bell shape and on the frequency, hence these reflections do not give rise to uniformly-spaced peaks. Above about G3, the vibration is sustained by essentially only one resonance, the higher harmonics being above the cutoff frequency. This is the reason why embouchure and oral cavity control is so effective and necessary at the top of the second register, and why a clarinettist may easily bend or glissando over notes in this region.

Although the third register may also be calculated, the impedance spectra are now much less informative. The first fingerhole is used as an additional speaker key, the fundamental of the played note is now based upon the third tube resonance frequency and there are normally no other strong resonance peaks below cutoff. The stability and accuracy of intonation now depends very largely on the player's control of embouchure and oral cavity, with little help from the instrument resonances. Discussion of all instruments in this chapter is therefore limited to notes from the bottom of the instrument up to C5.

Although impedance spectra will be shown for the other instruments discussed in this chapter, this detailed discussion will not be repeated. Rather, we shall discuss highlights from the impedance spectra then focus on the summary of the resonance properties provided by the impedance map, discussed in detail in Chapter 6. The impedance map for the Heckel is shown in Figure 8.4, which is here annotated to show the features of interest.

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[4] Benade, *Fundamentals of Musical Acoustics*, 435.

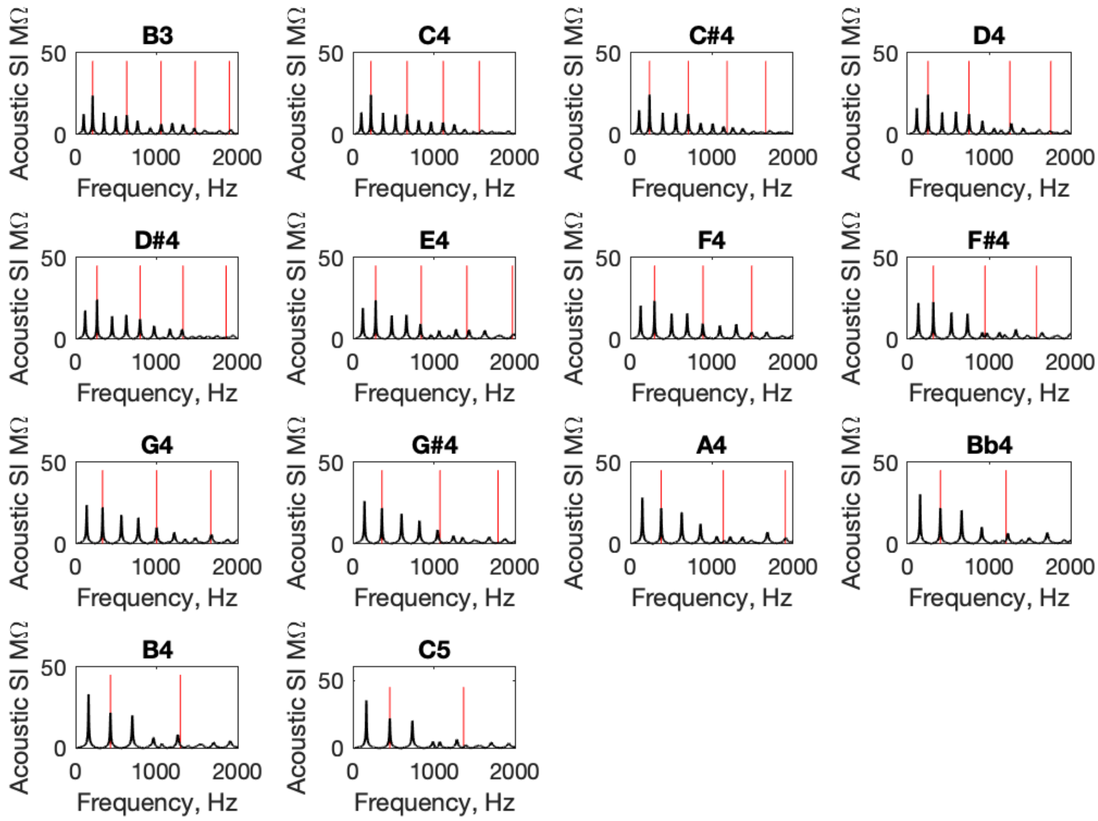

Figure 8.3. Impedance spectra for the Heckel for the second register, from B3 to C5.

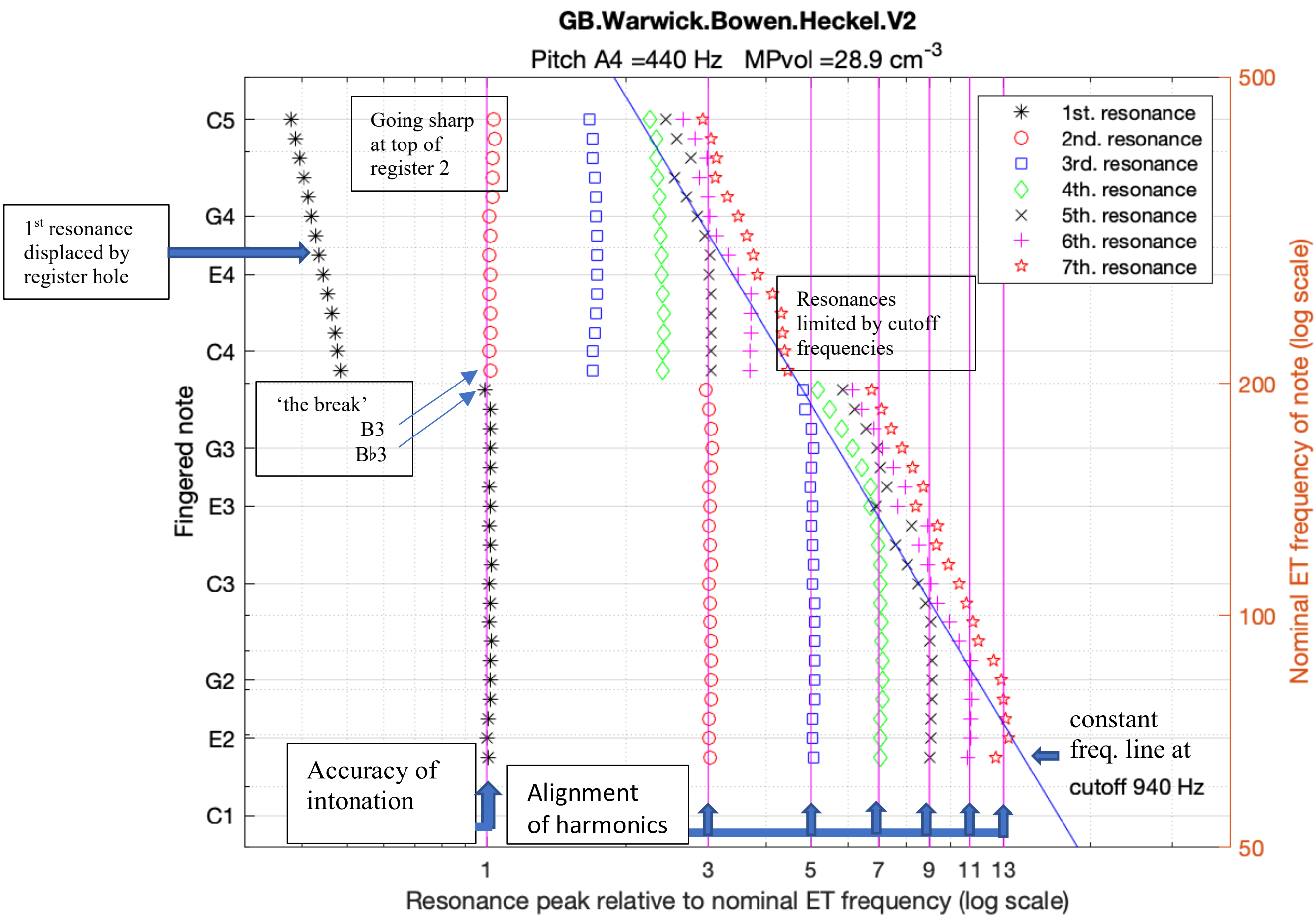

Figure 8.4. Impedance map of the Heckel bass in A.

- The intonation is shown by the closeness and regularity of the points representing single notes to the vertical line at an abscissa of 1 (which represents perfect equal temperament). In this case the map is drawn to represent a pitch of A4 = 440 Hz. Other examples that will be seen later fit better at other pitches, e.g. A4 = 435 Hz. Thus we may determine the pitch, the temperament and the overall intonation.
- The points representing the resonances first rise vertically with the fingering up the chromatic scale, then bend over to run parallel to diagonal lines, which are at constant frequency on this plot. This is the cutoff phenomenon, discussed in Chapter 6. Above a certain frequency, the acoustic waves do not reflect at or near the first open tone hole, but pass through to the bell and may be either emitted or weakly reflected (at frequency-dependent points); they may accidentally reinforce the standing waves in the instrument.[5] This is an important feature of the acoustics of a woodwind instrument. Benade points out that once intonation and alignment of resonances for cooperative oscillation are satisfied,

  > … specifying the cutoff frequency for a woodwind is tantamount to describing almost the whole of its musical personality.[6]

- However, the map shows that different harmonics cut off at somewhat different frequencies; the cutoff frequency therefore does depend on the fingering, and it should be referred to as a cutoff band. For purposes of quantitative comparison of instruments, I propose that a sensible choice of a single value is the onset of cutoff for the third resonance of the fundamental, which should align with the fifth frequency harmonic.This can be read directly from the impedance map. This indicates whether three harmonics are available to cooperate to stabilise the vibration of the fundamental note. It is about 940 Hz for the Heckel (as opposed to *c*.1000 Hz read from the impedance spectra or from the Benade formula) and is noted on the maps simply as 'cutoff'.
- The alignment of impedance peaks with harmonics is easily seen, and is very accurate in this instrument even up to the 13th harmonic. Most instruments shown in this chapter are much less accurately aligned and we shall see that the impedance maps provide an excellent and informative summary of the acoustic properties of the instruments.

The impedance maps have proved to be an invaluable way of condensing several hundred dimensional measurements, several complicated computations and one or two million resulting numbers onto a single diagram.

Spectra of selected historical instruments

The discussion will begin with the important straight form instruments. These were the instruments that eventually succeeded in displacing the bassoon form for Art music, beginning with the Sax instruments of about 1840, and are still in use today. It is valuable to enquire into the similarities and differences that they show with bassoon-form instruments, and in which ways the latter may have been more appropriate for the band music in which they survived much longer.

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[5] such as the round red circles from the 13th resonance, reinforcing the top few notes of the 3rd resonance.

[6] Benade, 435.

Sax B.B.mim.2601 c.1840

The impedance spectra for this B♭ instrument are shown in Figures 8.5 and 8.6.

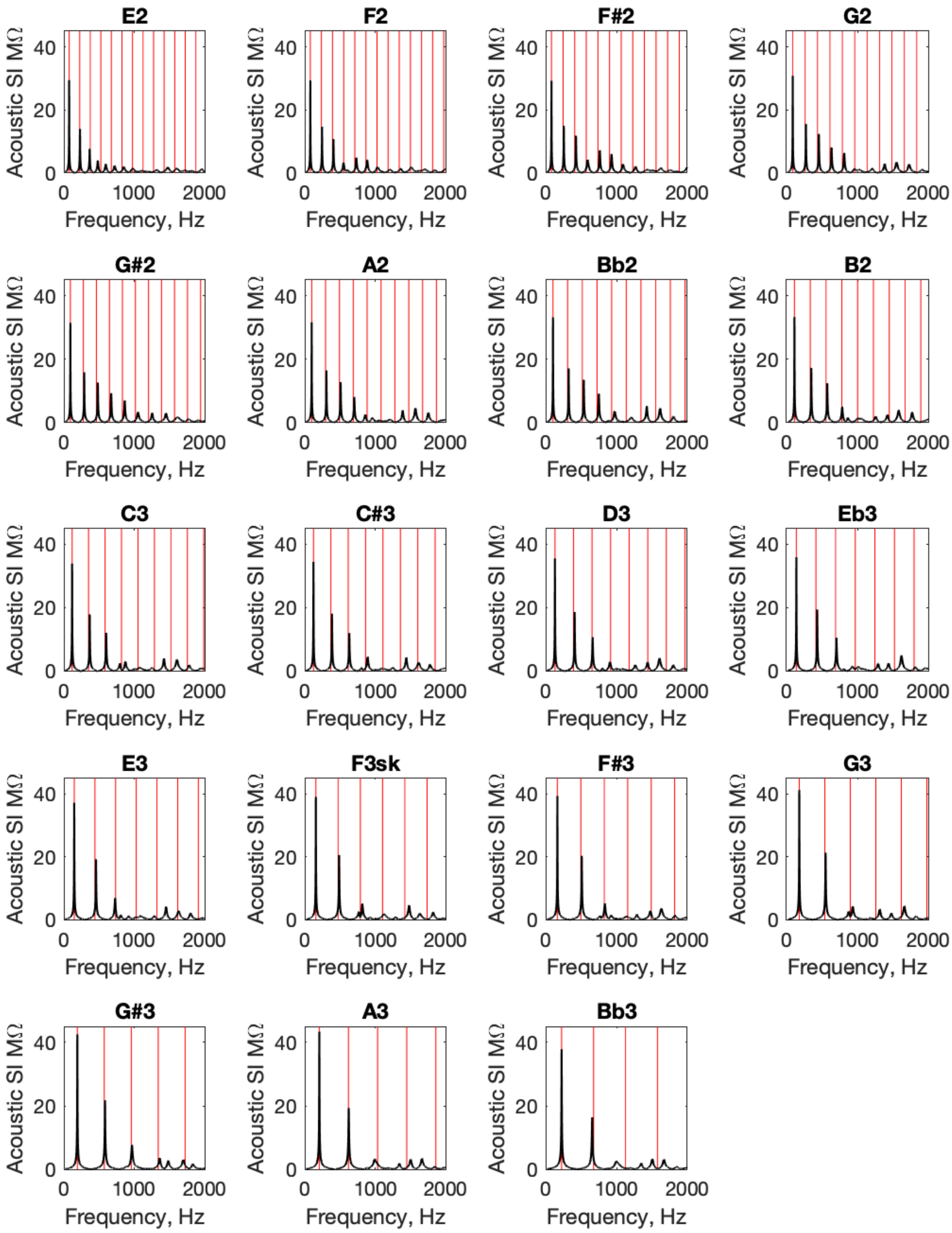

Figure 8.5. Impedance spectra for the Sax B.B.mim.2601 for the first register, from E2 to B♭3.

It is immediately seen that the resonance amplitudes decay much more rapidly with increasing frequency than in the Heckel. The fit to the harmonics is good, but for the throat notes at the top of the register only two strong harmonics are fitting. The sound quality would not be expected to match other notes in the register, and the intonation would be less stable. This is likely to be a consequence of the more flaring bore.

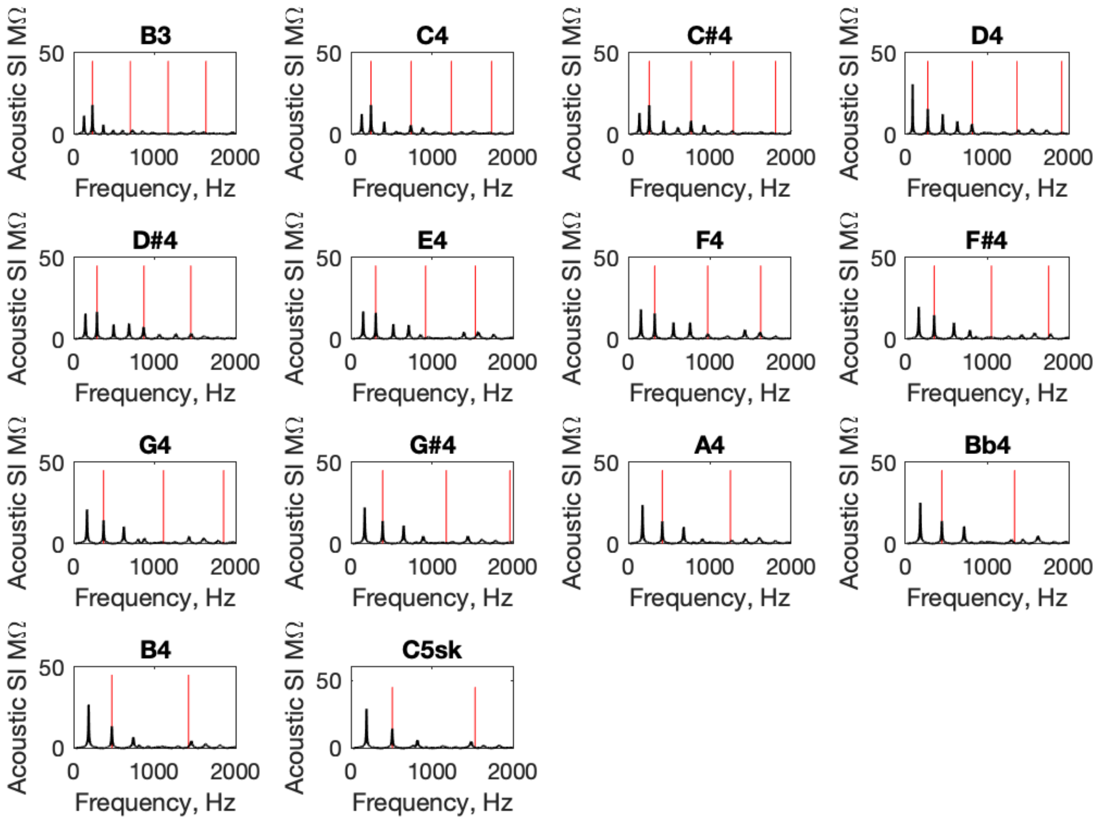

Figure 8.6. Impedance spectra for the Sax B.B.mim.2601 for the second register, from B3 to C5.

This trend continues in the second register. The mode locking will be weak and the intonation more flexible. Of course, there are situations in which this is an advantage, such as in correcting problems of intonation.

Turning now to the impedance map (Figure 8.7), we see that at a pitch of A4 = 440 Hz the temperament is even, since the points representing each note in the first register are generally varying smoothly from note to note. This was noticed by Berlioz, as remarked in Chapter 1.[7] The agreement of the points with the line representing the fundamental (abscissa = 1) is fairly good, though not as good as the Heckel shown earlier. Therefore the intonation is fairly good in the first register, though it tends to sharpness in the top of the register. The second register is quite sharp. As noted above, these notes will not be strongly mode locked and it will be possible to play the instrument generally in tune.

The cutoff frequency band begins at 780 Hz, significantly lower than the Heckel. This is likely to explain the probable limited harmonic content of the notes. However, the very wide bore should provide plenty of volume.

[7] Berlioz, 'Instrumens de musique'. 1842

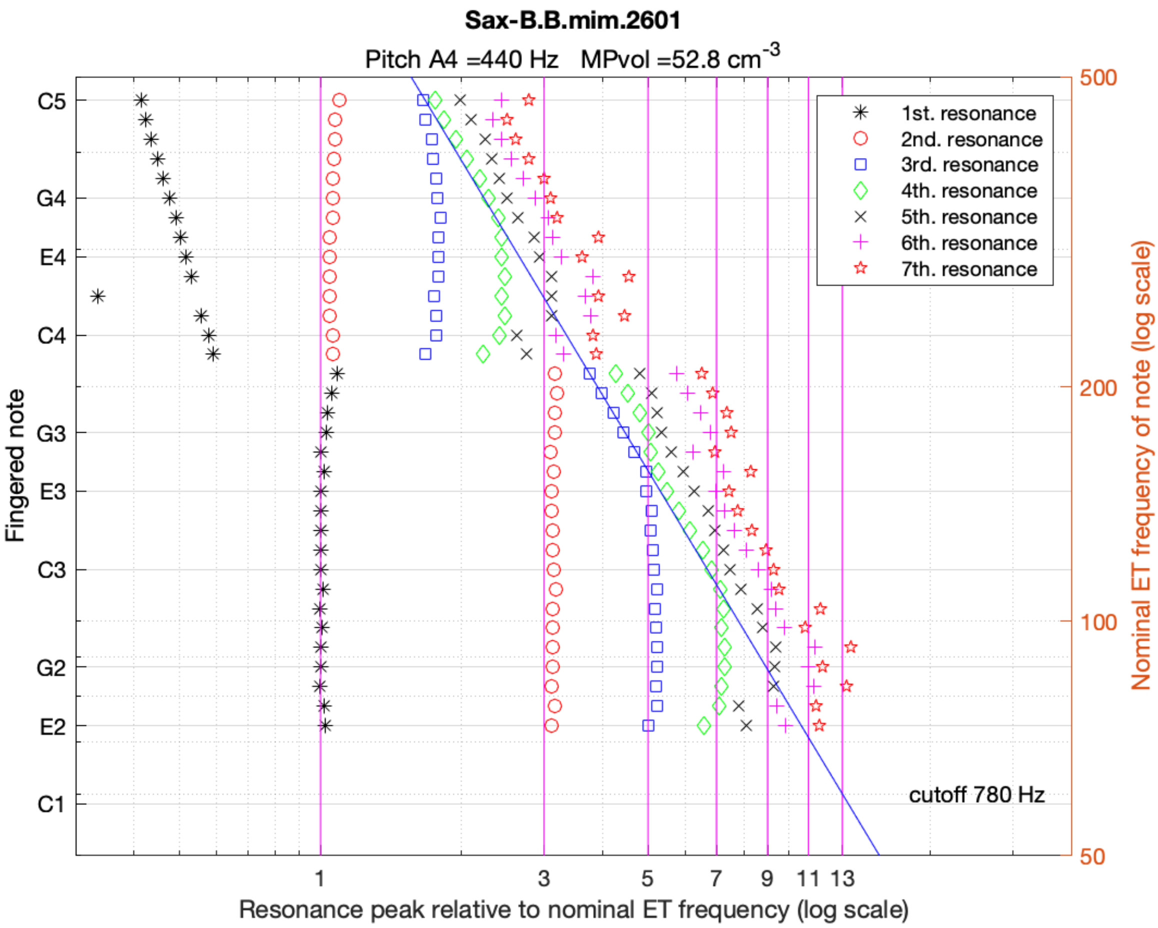

Figure 8.7. Impedance map of the Sax B.B.mim.2601

The likely playing pitch and mouthpiece volume are determined by examining the linearity and regularity of the fundamental resonance. In general, getting the mouthpiece volume correct means getting the points on the fundamental resonance in as straight a line as possible. For example, at smaller mouthpiece volumes, the computations showed that the notes at the top of the first register were very much sharper; but, at larger volumes, most of the notes in the first register went too flat by the time the throat notes were corrected. This of course is observed in normal clarinet playing when the mouthpiece is pulled in or out.

Once the mouthpiece volume is adjusted in the computation to be as ideal as possible, the pitch at which the impedance map is plotted can be adjusted. This does not need any more computation since the 'instrument' is now fixed. Figure 8.8 shows at greater enlargement the region around the fundamental resonance on the impedance map, calculated for various plausible pitches. Inspection shows that the best selection of pitch overall is A4 = 440 Hz, especially for the lower register. The latter would play quite well at 438 Hz but the sharpness in the upper register would be worse. At 440 Hz, the notes should be more playable in tune. One can see however, that deciding the pitch is not simply a process of mathematical minimisation of some error function, such as the well-known 'least squares' method. Knowledge of the behaviour of instruments and the preferences of players is needed, and it is not surprising that different makers make different choices over how to distribute the inevitable errors.[8] In the recording of this instrument, discussed in Chapter 7, the piece was mainly in the upper register and the tuning was consequently placed very high, A4 = 464 Hz, with low notes allowed to be flat.

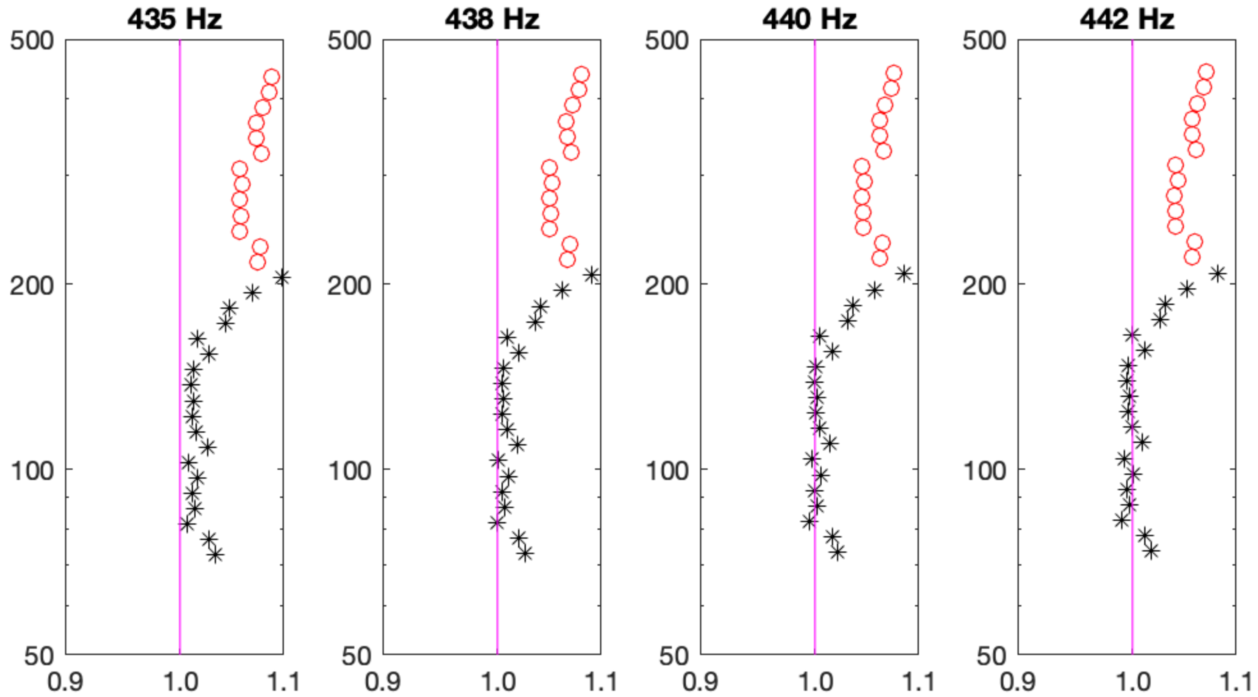

Figure 8.8. Enlargement of region around the fundamental resonance in the impedance map for different values of tuning. For axis labels see Figure 8.7.

Similar adjustments in the computation were made for all the instruments discussed in this chapter. However, the details will not be presented in further examples; for brevity, only the best fits obtained are shown.

[8] Dalmont et al. 'Some Aspects of Tuning and Clean Intonation in Reed Instruments.'

Sax B.B.mim.0175

This specimen was examined to see if there were significant differences with B.B.mim.2601. It is very similar in dimensions except that the crook is less strongly curved and the bell is a little shorter (Figure 8.9).

Figure 8.9. Comparison views of B.B.mim.2601 (with paler wood and brass fittings) and B.B.mim.0175 (with dark wood and nickel-silver fittings).

The results of the calculations are shown in Figures 8.10 to 8.12. The instruments are very similar, and the date of both instruments is given as c.1840 by the museum; they were both made in Sax's early Brussels period. Model 0175 is probably a little later than 2601:

- Unlike 2601. it does not contain any plugged and redrilled holes;
- 0175 has one extra key, a side E♭/B♭ key positioned for RH1;
- The temperament is somewhat better in 0175. The upper register is improved at first but again drifts to become sharp towards the top;
- The cutoff is slightly higher in 0175, at 810 Hz cf. 780;
- The decay of the impedance peaks is less severe than in 2601, resulting in more contribution of harmonics to the sound;
- However, the twelfths are again wide, slightly more so in 0175.

It has already been noted that these instruments have an exceptionally large bore diameter, 28 – 29 mm. This was echoed in early Buffet instruments (Chapter 7) but not by other manufacturers, nor by modern makers, where *c*.24 mm is the norm. This would compensate in volume for the somewhat lower resonance peaks. It should also be noted that these are quite early instruments by Sax, made in his Brussels period before he moved to Paris in 1840. It is probable that they were further improved over his career.

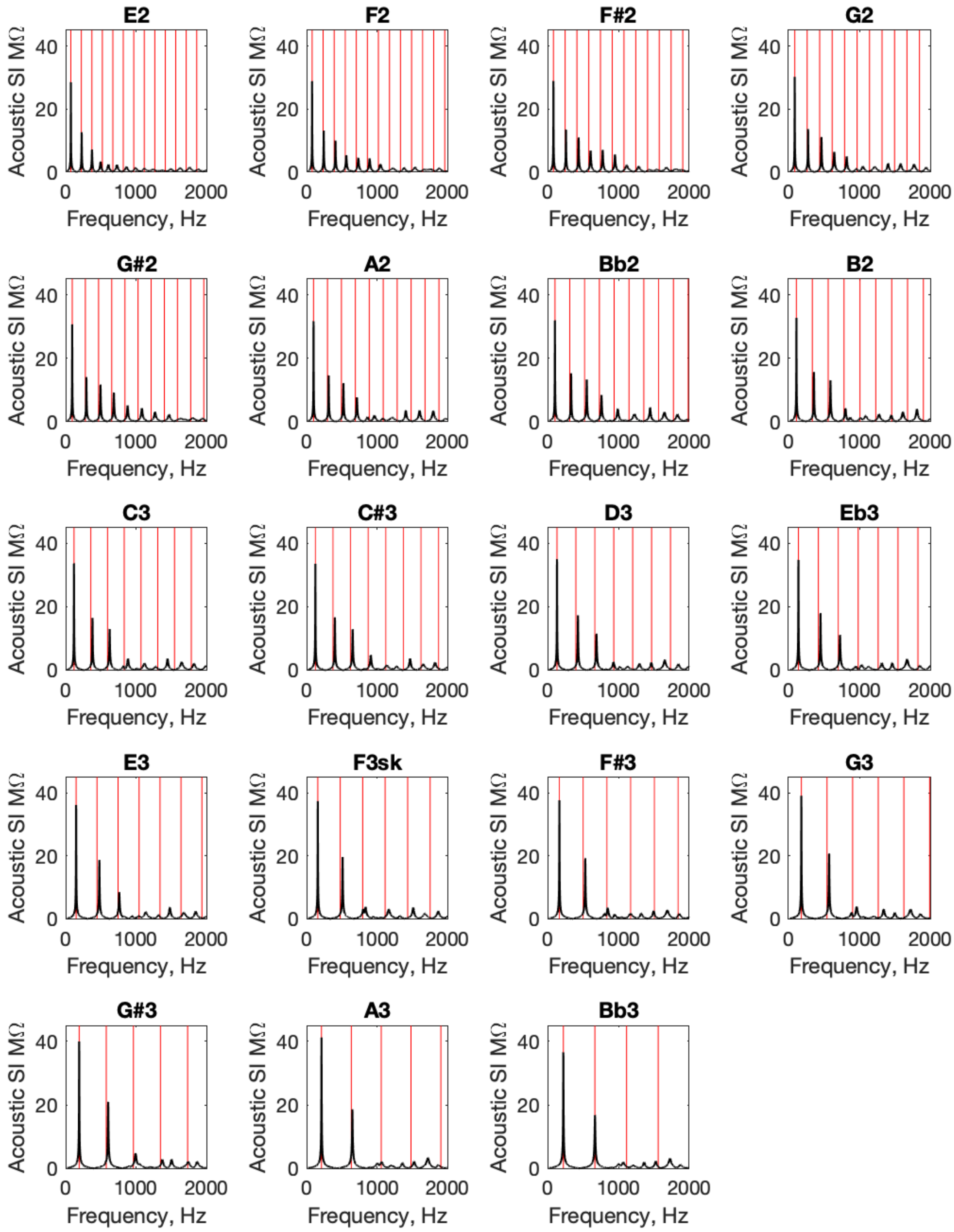

Figure 8.10. Impedance spectra for the Sax B.B.mim.0175 for the first register, from E2 to B♭3.

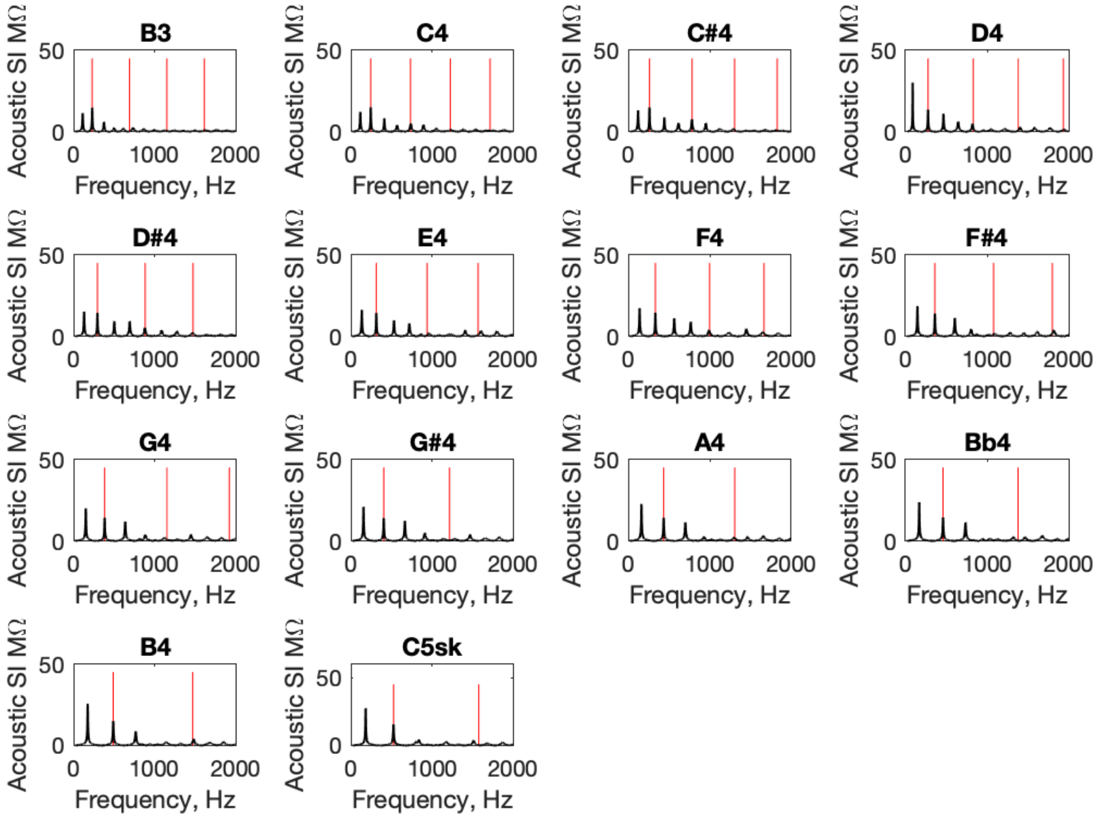

Figure 8.11. Impedance spectra for the Sax B.B.mim.0175 for the second register, from B3 to C5.

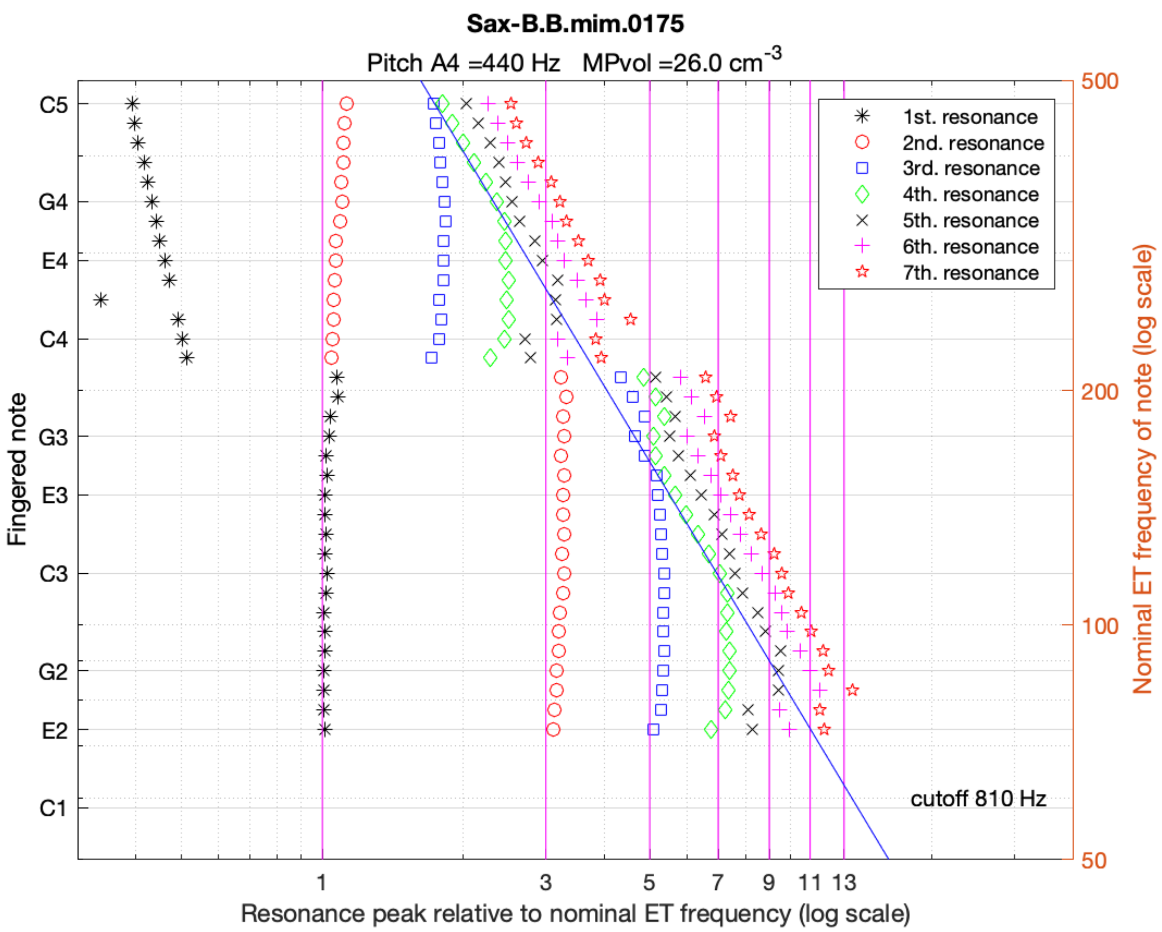

Figure 8.12. Impedance map of the Sax B.B.mim.0175

Kruspe D.LE.u.4479

The spectra for this straight instrument, dated 1865 – 75, are shown in Figures 8.13 to 8.15.

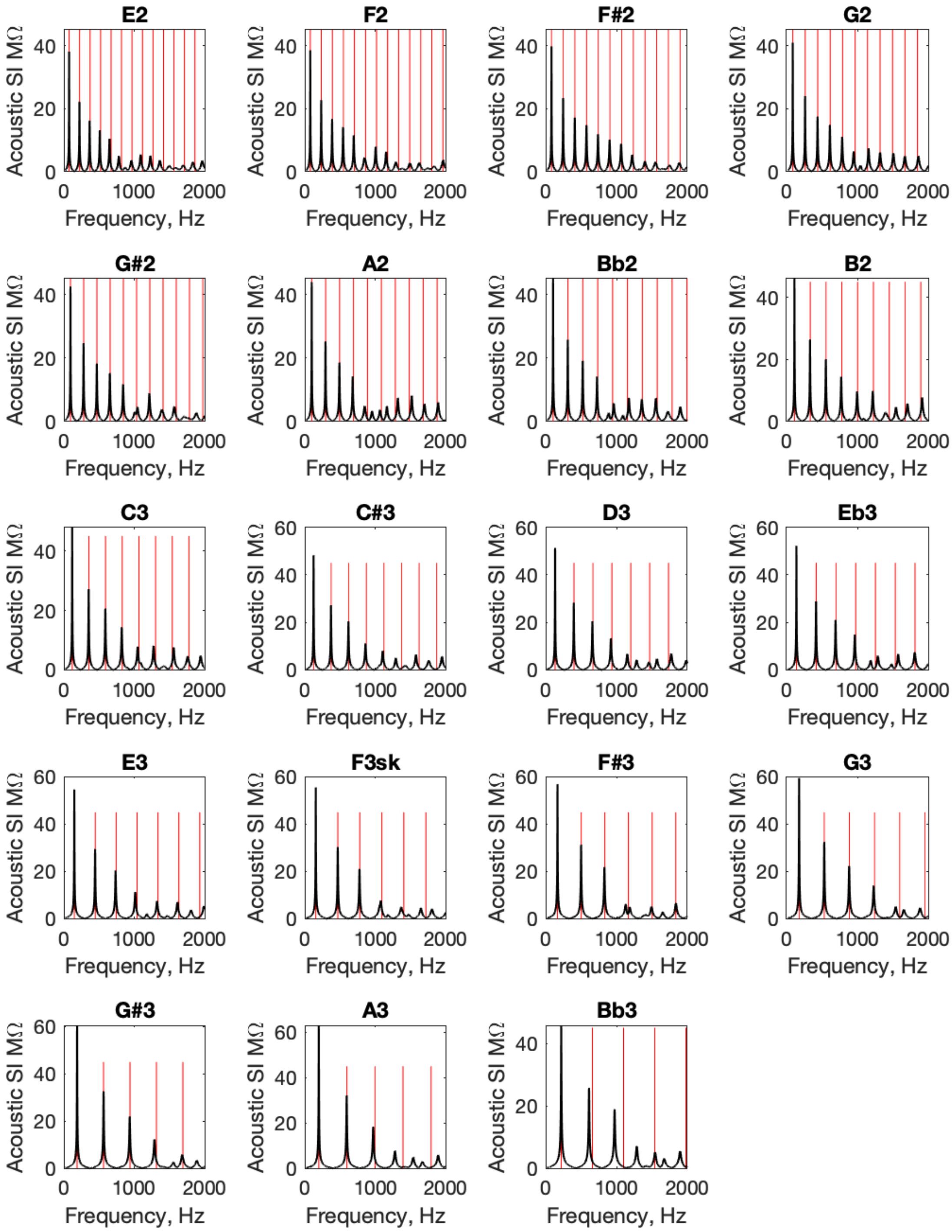

Figure 8.13. Impedance spectra for the Kruspe D.LE.u.4479 for the first register, from E2 to B♭3.

These graphs show that the Kruspe is a very good instrument. The intonation and temperament at A4 = 440 Hz are just about ideal except for slight sharpness of B♭3 and B3. Even these will be pulled a little flatter by mode locking with the slightly flatter higher harmonics. The spectra show significantly stronger resonance peaks in both registers than the Sax instruments; they also decay more slowly with increasing frequency and are very well aligned with the harmonics. The bore diameter is 23 mm, in contrast with the Sax instruments at 28-29 mm.

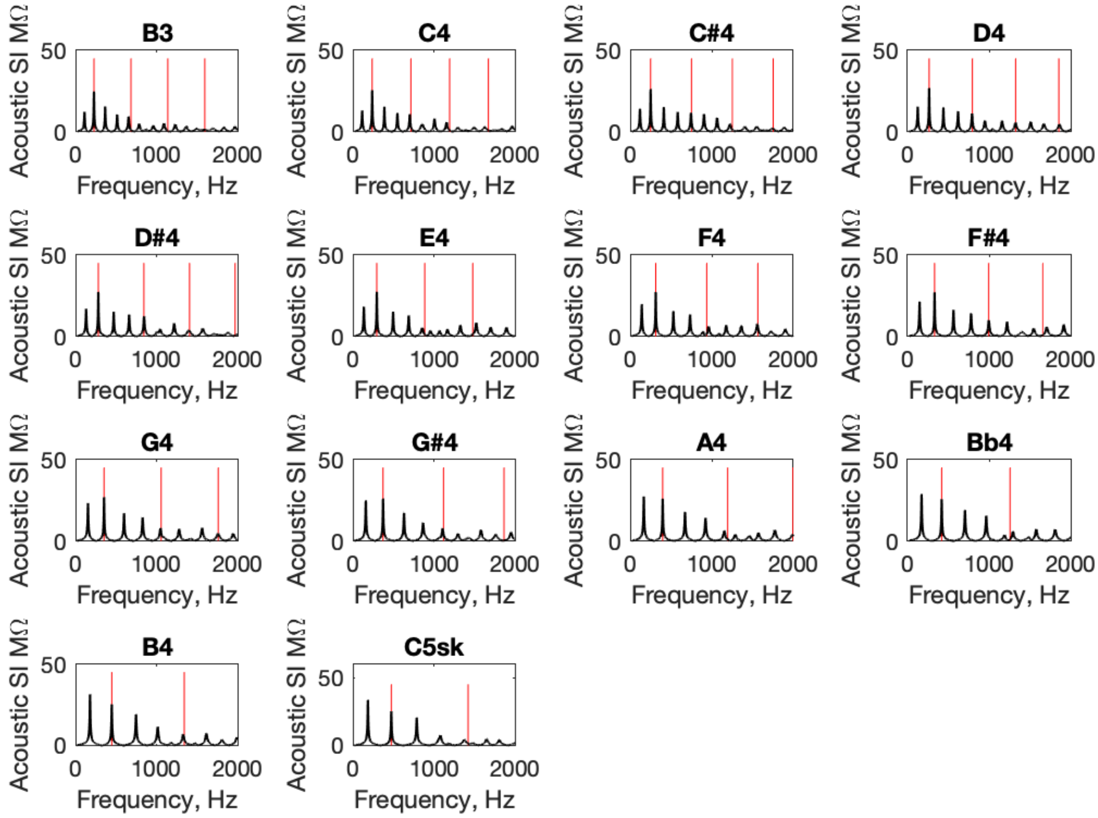

Figure 8.14. Impedance spectra for the Kruspe D.LE.u.4479 for the second register, from B3 to C5.

The impedance map of the Kruspe shows the excellent alignment between resonances and harmonics. The cutoff at the third resonance of 970 Hz is higher than in the Sax instruments, and is comparable with the Heckel at 940 Hz. It should, however be noted that the Heckel is pitched in A and is therefore a longer instrument.[9] I consider that the high cutoff frequency (and consequently, many potential resonances reinforcing the harmonics and stabilising the intonation) is a property of the long, largely cylindrical bore and limited bore diameter that is typical of German clarinets and bass clarinets to this day. In contrast, starting with Sax, and perhaps even earlier with prototype instruments, the French tradition is of wider bore instruments with a more pronounced flare; this inevitably results in a more limited harmonic content but more flexibility in tuning.

Of course, the maker still has to position the tone holes accurately and make them of appropriate sizes in order to succeed with the temperament and intonation. Kruspe has succeeded very well in this instrument. It is interesting that Kruspe instruments were probably those suggested by Wagner for performances of *Lohengrin* in Vienna, following those in Dresden.[10] Kruspe also made bassoon and ophicleide form bass clarinets, discussed later.

[9] The cutoff frequency for a clarinet in A should be increased by about 6% (the frequency ratio between semitones) to compare with a B♭ clarinet. The Heckel thus has a slightly higher relative cutoff.

[10] D. Keith Bowen, 'The Rise and Fall of the Bass Clarinet in A'. 2009.

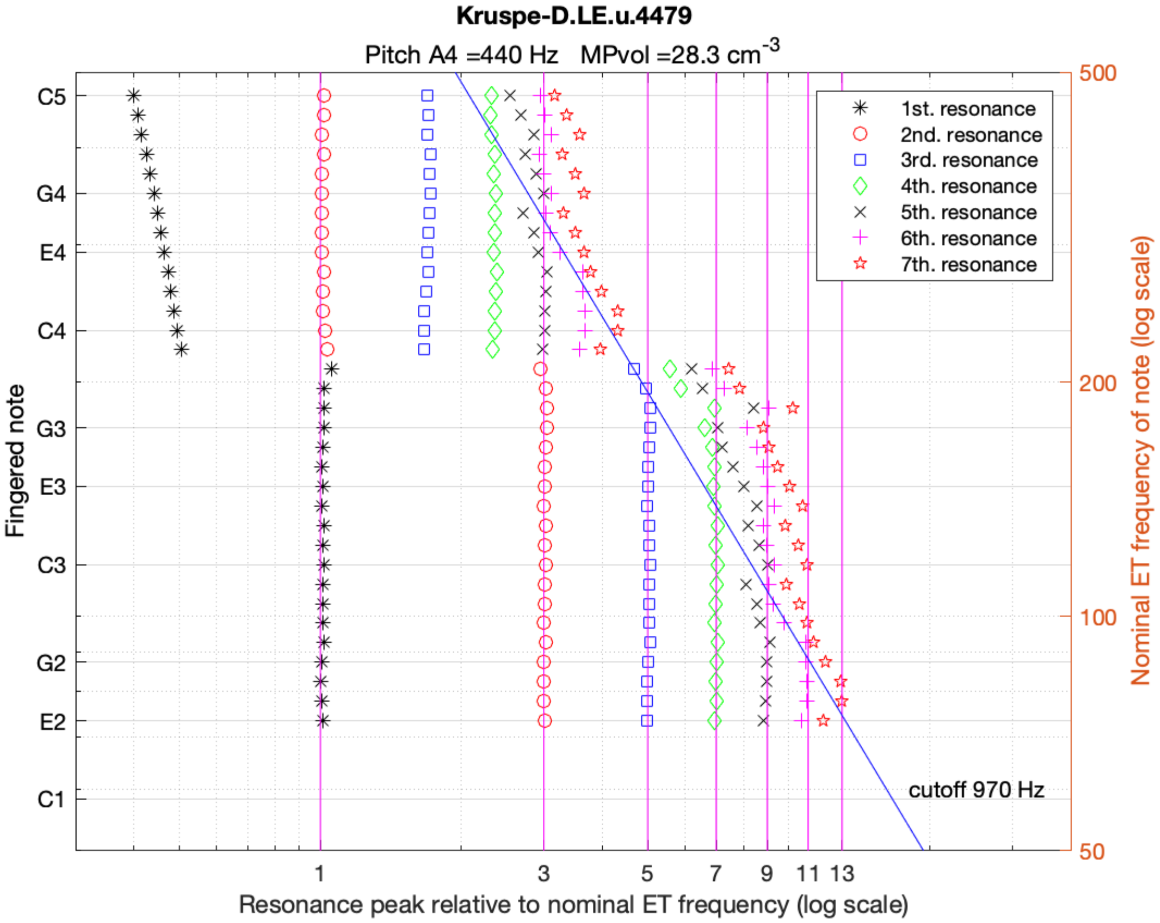

Figure 8.15. Impedance map of the Kruspe D.LE.u.4479.

Stengel GB.E.u.4932

The final straight-form instrument shown is in B♭, dated c.1880, and has a 20 mm bore. It is generally similar in acoustic properties to the straight-form Kruspe. The graphs for this instrument are shown in Figures 8.16 to 8.18. Stengel is another of the few makers from whom both bassoon-form and straight instruments survive. The average intonation is good, with accurate twelfths and no drift towards sharpness in either register, but the temperament is a little uneven. The resonances are notably stronger in the upper register than are those of the wider-bore instruments. The onset of cutoff is similar at 980 Hz. A very similar instrument (but restored, and pitched in A) was played in Darmstadt at the Robert Schumann School of Music, and is reported in Chapter 7. It is a high-quality instrument with excellent tone and intonation but without the power of modern instruments.

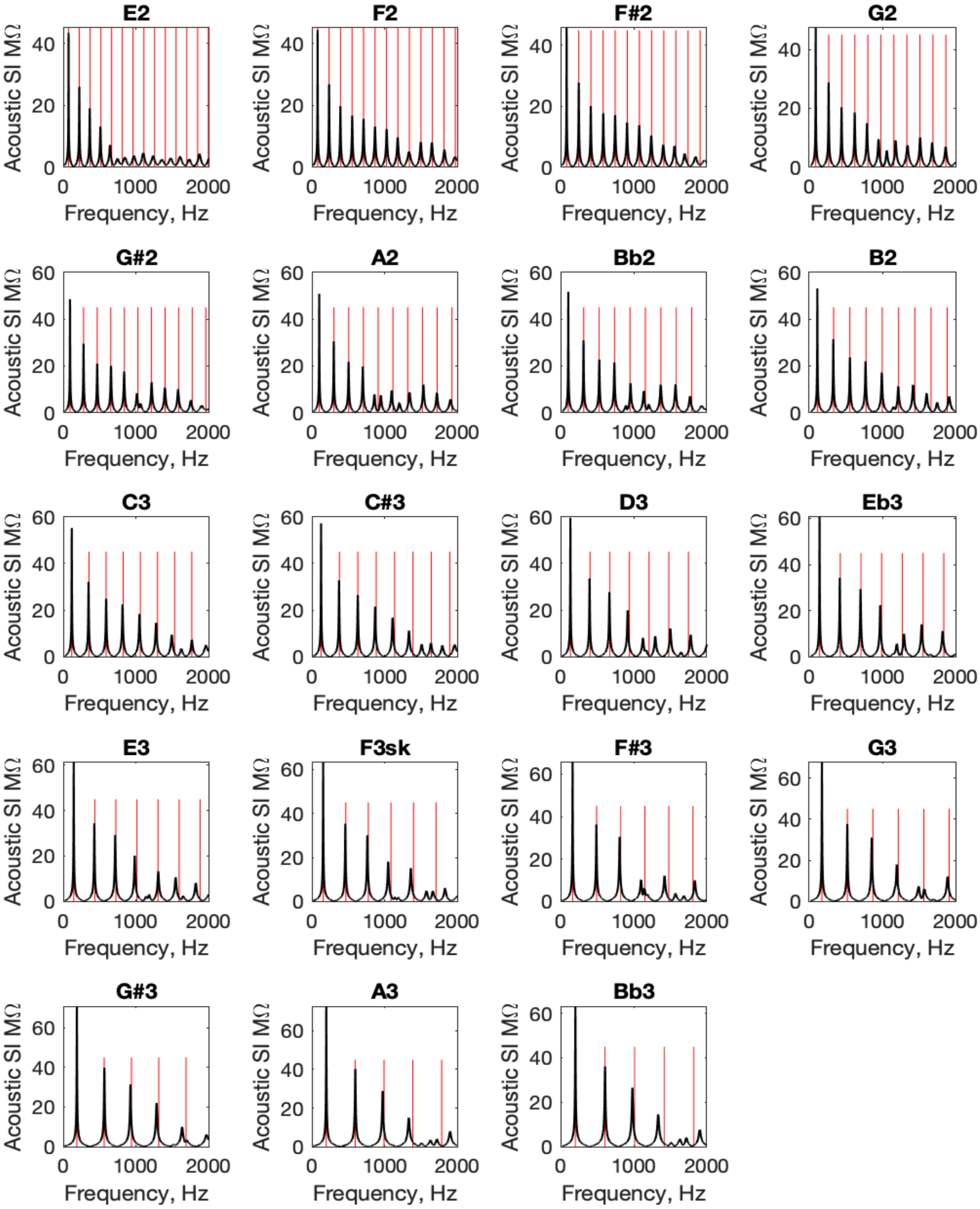

Figure 8.16. Impedance spectra for the Stengel GB.E.u.4932 for the first register, from E2 to B♭3.

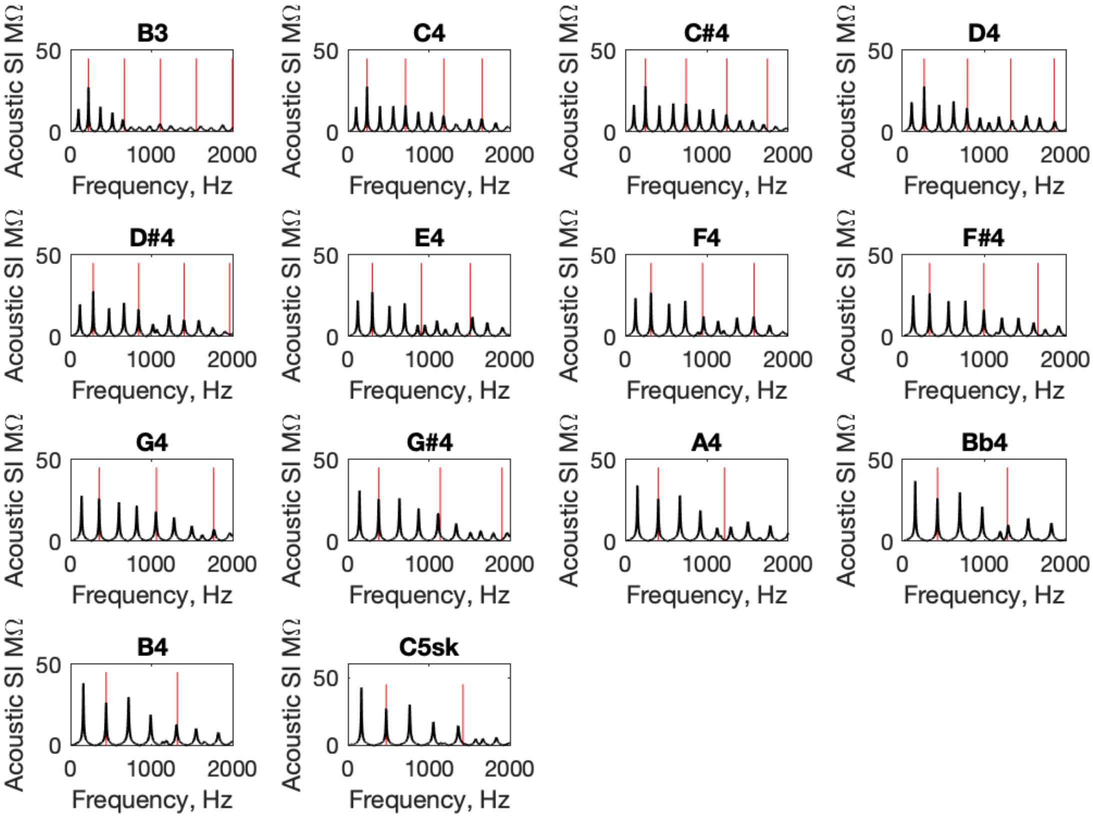

Figure 8.17. Impedance spectra for the Stengel GB.E.u.4932 for the second register, from B3 to C5.

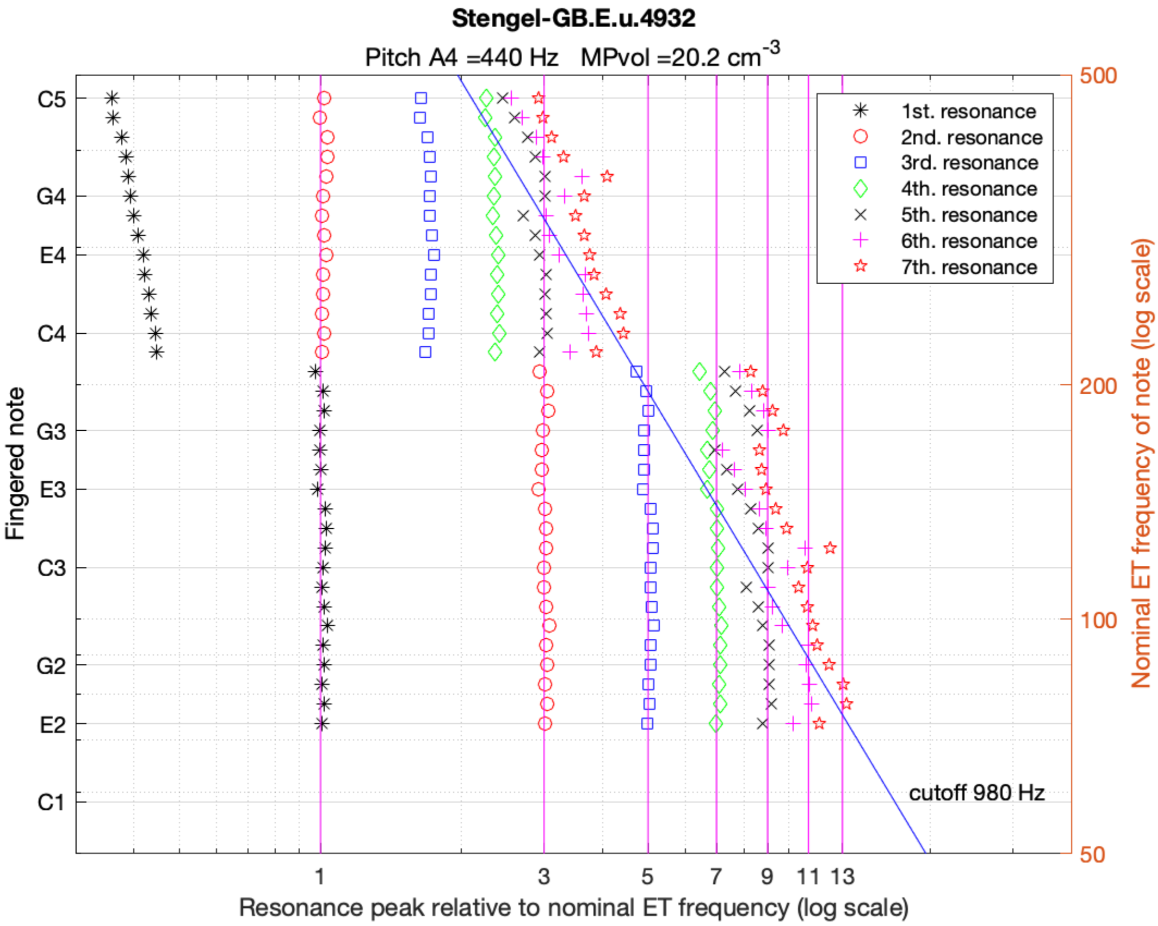

Figure 8.18. Impedance map of Stengel (straight form) GB.E.u.4932

Grenser S.S.m.M2653

The bassoon-form instruments are now discussed in approximate chronological order. This Grenser, the first successful bass clarinet of any form, was built and signed by Heinrich Grenser and (unusually) dated, at 1793. It is probable that there were some experimental precursors and there was also the bassoon-form basset horn by Lempp, as discussed in the previous chapter. There is also documentary evidence that the instrument was ordered direct from Grenser for the Swedish court.[11] Interestingly, the Lempp basset horn has the same geometry as the Grenser instrument, with the bell on the player's right, contrary to all later bassoon-form bass clarinets known (Figure 8.19) except that of Augustin Grenser, Heinrich's uncle, father-in-law and master.

Figure 8.19. Rear view of the Grenser S.S.m.M2653. Image courtesy Scenkonstmuseet/Swedish Museum of Performing Arts, Stockholm. Photograph Sofi Sykfont.

The spectra and impedance map are shown in Figures 8.20 to 8.22.[12] A glance at the impedance map shows that the intonation is far inferior to the instruments discussed so far, indicating the improvement that took place in the following century. The Grenser has only 8 keys, which are described in Rice;[13] he here describes the instrument as in C but in a later publication states that it is in B♭.[14] The latter is correct, as shown in the impedance map, which is drawn for an instrument in B♭ at a pitch of A4 = 445 Hz. No C#1 tonehole is present. The lowest note is, as stated by Grenser himself, B1, not B♭1 as has been stated in the literature.[15]

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[11] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009; Rice, 'The Earliest Bass Clarinet Music (1794) and the Bass Clarinets by Heinrich and August Grenser.' 2011.

[12] My measurements of tone hole positions and sizes agreed well with existing measurements and drawings provided by the museum.

[13] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 259.

[14] Rice, 'The Earliest Bass Clarinet Music (1794) and the Bass Clarinets by Heinrich and August Grenser.' 2011.

[15] e.g. Shackleton, 'Bass Clarinet,' 2001.

In the first register the resonance peaks are mostly quite well aligned with harmonics and the instrument would play quite acceptably in this register. The second register is much less satisfactory, with poor alignment of peaks and harmonics until the note E4. However the resonances in this register are weak, and would not provide strong stabilising feedback.

Turning now to the impedance map, we see that with three exceptions the lower register peaks are quite well in tune at A4 = 445 Hz. The exceptions are the forked notes E♭2, B♭2 and C#3, which are all sharp and have poor alignment with resonances. This is not unexpected on forked notes, since the nodes of the standing waves will have a quite different relationship with the open and closed holes for a forked fingering than for a simple fingering. Hence the note may sound but the timbre will be badly affected and the intonation uncertain. B♭3 is extremely sharp and not really usable, while no fingering could be found that was anywhere near G#3; this note has been omitted from the chart. In this and other impedance maps, fingering corrections have been applied (e.g. to flatten sharp forked fingerings); these are specified in the listings in Appendix B. Many of the future innovations in bass clarinet keywork were directed at improving the intonation and timbre of forked notes, or at avoiding their necessity by providing specific holes for each semitone.[16]

Considering now the second register, we see that the notes from F4 to C5 are acceptably in tune, but that notes from E4 down to B3 become progressively very sharp indeed. We have seen that the register key is in the wrong place for a reasonable B♭3; it needs to be further away from the reed end. It is also obviously in the wrong place for good intonation of the notes from B3 to E4. An advantage of the simulation method is that it is possible to move the positions of the holes in the model and investigate the effects on the intonation. Some trial computations showed that the register key would play the notes B3 to E4 quite well in tune if it were moved about 80 mm downstream (away from the reed); in fact the existing A key would work quite well as a register key for these notes. But then the upper notes of the second register, previously quite well tuned, would become hopelessly sharp. The only speaker key available on this instrument is that on the crook.

[16] Voorhees, *The Development of Woodwind Fingering Systems*, 2003.

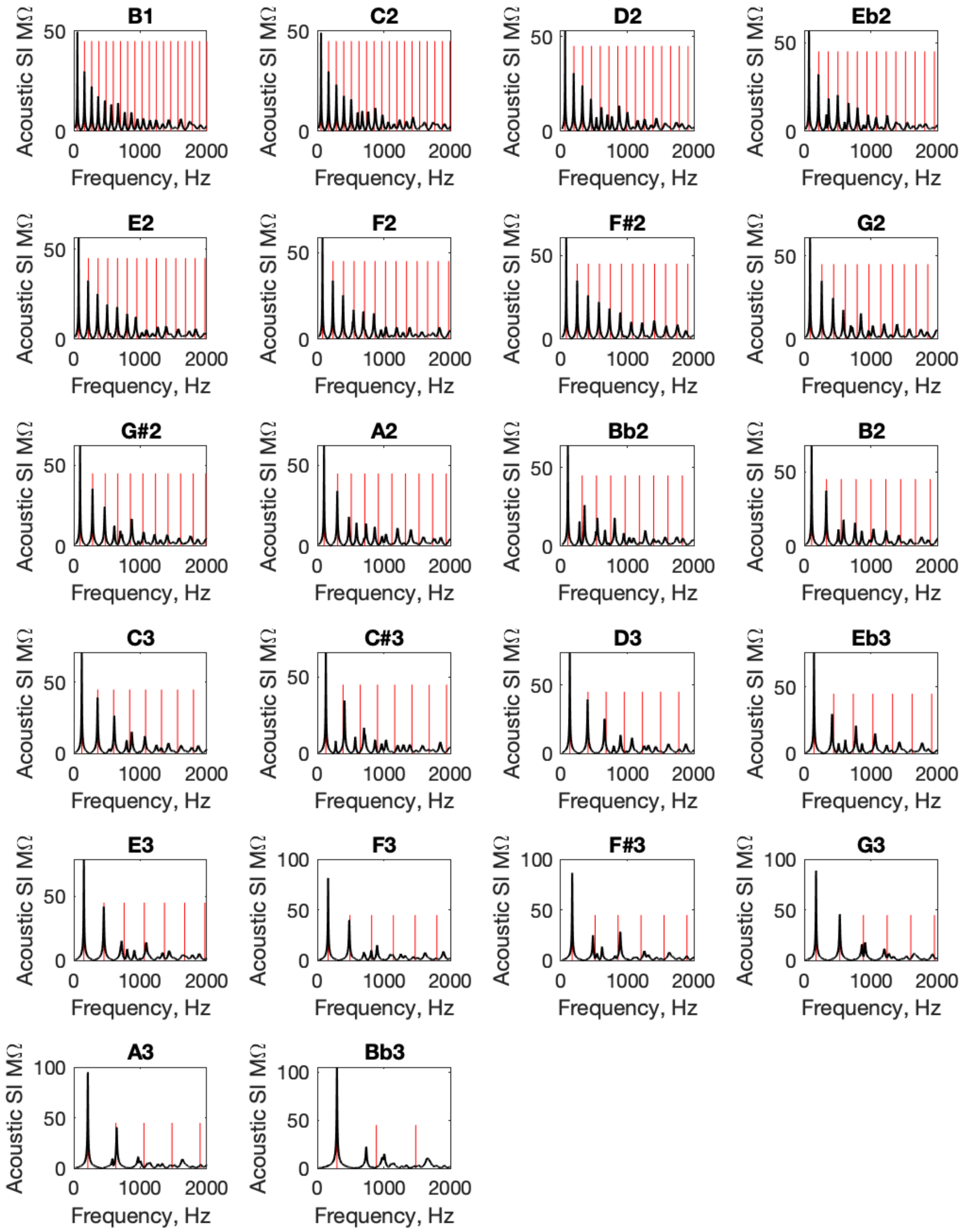

Figure 8.20. Impedance spectra for the Grenser S.S.m.M2653 for the first register, from E2 to B♭3.

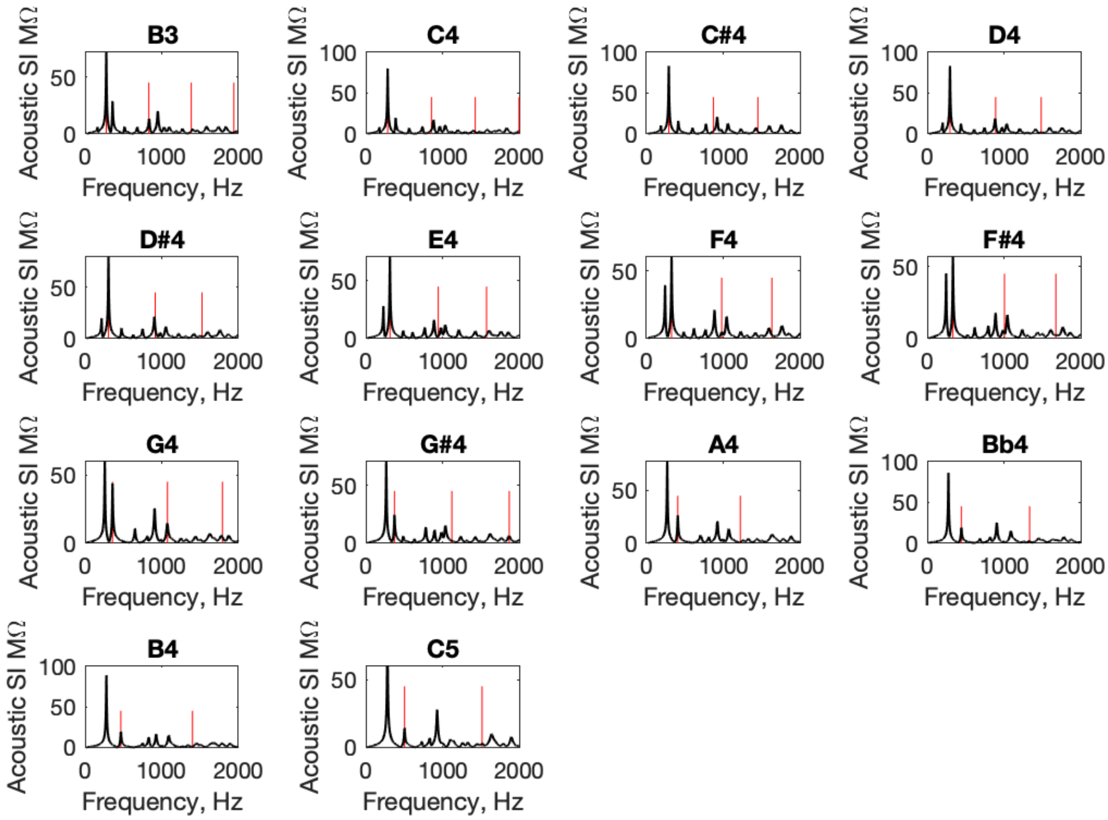

Figure 8.21. Impedance spectra for the Grenser S.S.m.M2653 for the second register, from B3 to C5.

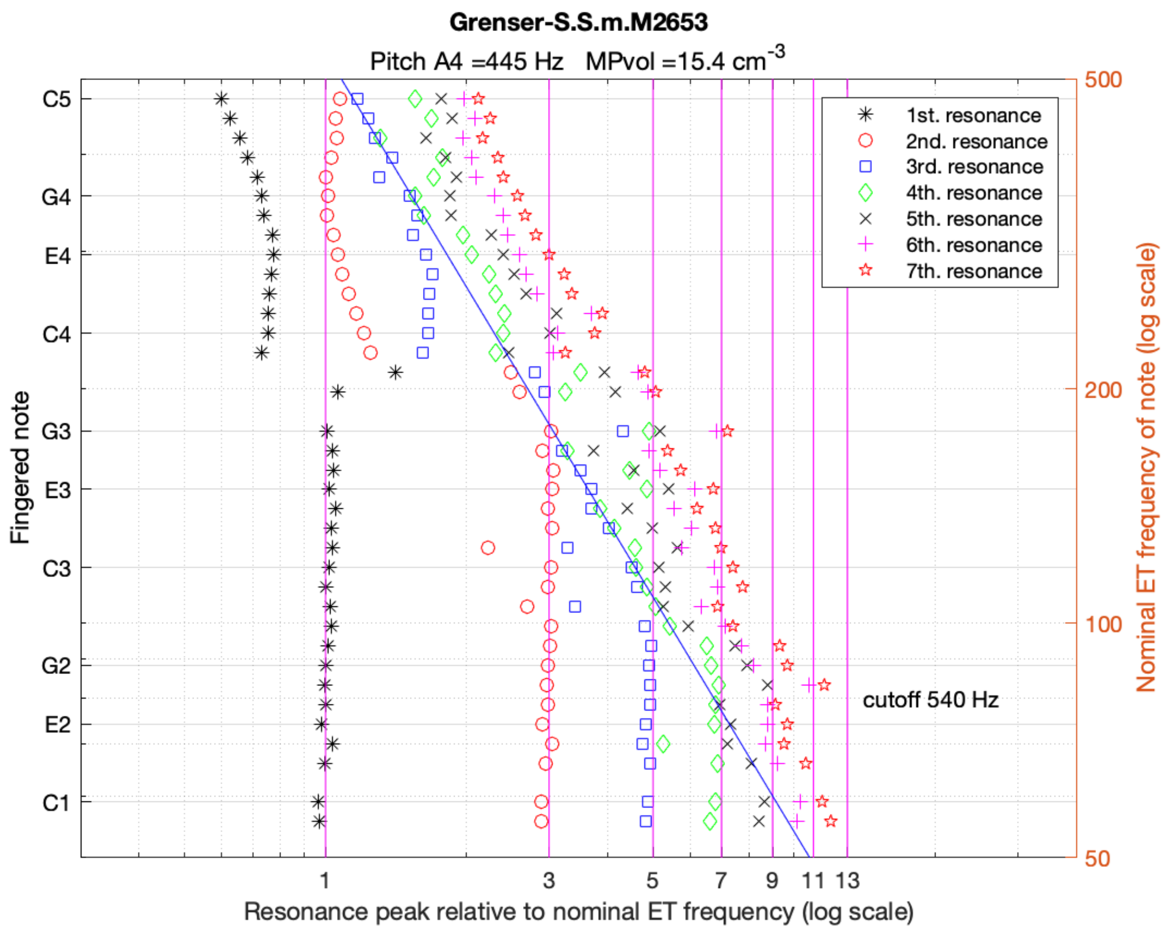

Figure 8.22. Impedance map for the Grenser S.S.m.M2653.

Clearly, the instrument would benefit by having a second register key lower down, to correct the intonation of the lower notes of the upper register (not, as sometimes asserted, to improve the upper notes[17]) and to improve B♭3; it might even act as a functional G#3. It is interesting to note that Heinrich Grenser's uncle and father-in-law Augustin, with whom he had served his apprenticeship, made a very similar instrument the following year, now in Darmstadt. This instrument could not be examined,[18] but the available images show that there is a register key on the crook as on the Heinrich Grenser model. However, there is a second one, lower down, in about the position suggested above. Perhaps the old master was showing that he could still surpass his pupil!

Figure 8.23. Bass clarinet by Augustin Grenser dated 1795. D.DS.hl.Kg 67:133. Image courtesy of the Hessiches Landesmuseum. Photo: Wolfang Fuhrmannek.

The cutoff frequency at the third resonance, ~540 Hz, is now much lower than those of the straight instruments. This severely limits the harmonic makeup of the tone for notes above A2. Nevertheless, the instrument was clearly practical. It is favourably referred to by Gerber in 1812

> Grenser (Heinrich) the student in art and son-in-law [of Augustin Grenser], court instrument maker at Dresden, is currently carrying on all the business of the previous one. He also announced the invention of a new instrument known in 1793, which he called the bass clarinet.

[17] David Kalina, 'The Structural Development of the Bass Clarinet', 1972, 16.
[18] because of museum closure for refurbishment, followed by the Covid lockdown and travel embargo.

> The same goes down to the low B[♮]. There are four octaves plus the low B, which should be of a beautiful and strong tone. Every clarinetist or basset horn player can play this instrument right away.[19]

Hermann Mendel reported in 1870, in a Lexikon entry apparently derivative from Gerber:

> This instrument, invented in 1793, never found further recognition, although it initially caused a sensation … [20]

Mendel also incorrectly reported that the lowest note was B♭. His remark on little recognition appears odd, since by 1870 it is likely that hundreds of bassoon-form bass clarinets were in circulation; more than 70 have survived in museums.

A private letter from Sven Burger, former curator of the Stockholm collection, to David Kalina on June 15 1968 reported that the instrument could be played over three octaves well in tune, and that he produced some good tones in the low register with a beautiful mellow tone. He judged the instrument to be pitched in B♭ but that he could play C5 with 'surprising facility'.[21]

All of these literature reports are consistent with the acoustic calculations except the remark on 'three octaves well in tune'. The calculations show that the lower part of the upper register must be intrinsically very sharp; however, the weakness of the resonances in the second register and the absence of stabilising harmonics because of the low cutoff frequency would make these notes quite flexible and adjustable by the player.

[19] Ernst Ludwig Gerber, *Neues historisch-biographisches Lexikon der Tonkünstler.* Band 2, Leipzig: Kühnel, 1812, 393.

[20] Hermann Mendel and August Reissmann, *Musikalisches Conversations-Lexikon. Eine Encyklopädie der gesammten musikalischen Wissenschaften* Berlin: L. Heimann, 1870, vol 4, 353-4

[21] Kalina, 'The Structural Development of the Bass Clarinet,' 1972, 17.

Streitwolf D.N.gnm.MIR477

The next significant bass clarinet manufacturer was Streitwolf, who announced his new bassoon-form instrument in 1828. Graphs for this 1835 example are shown in Figures 8.24 to 8.26.

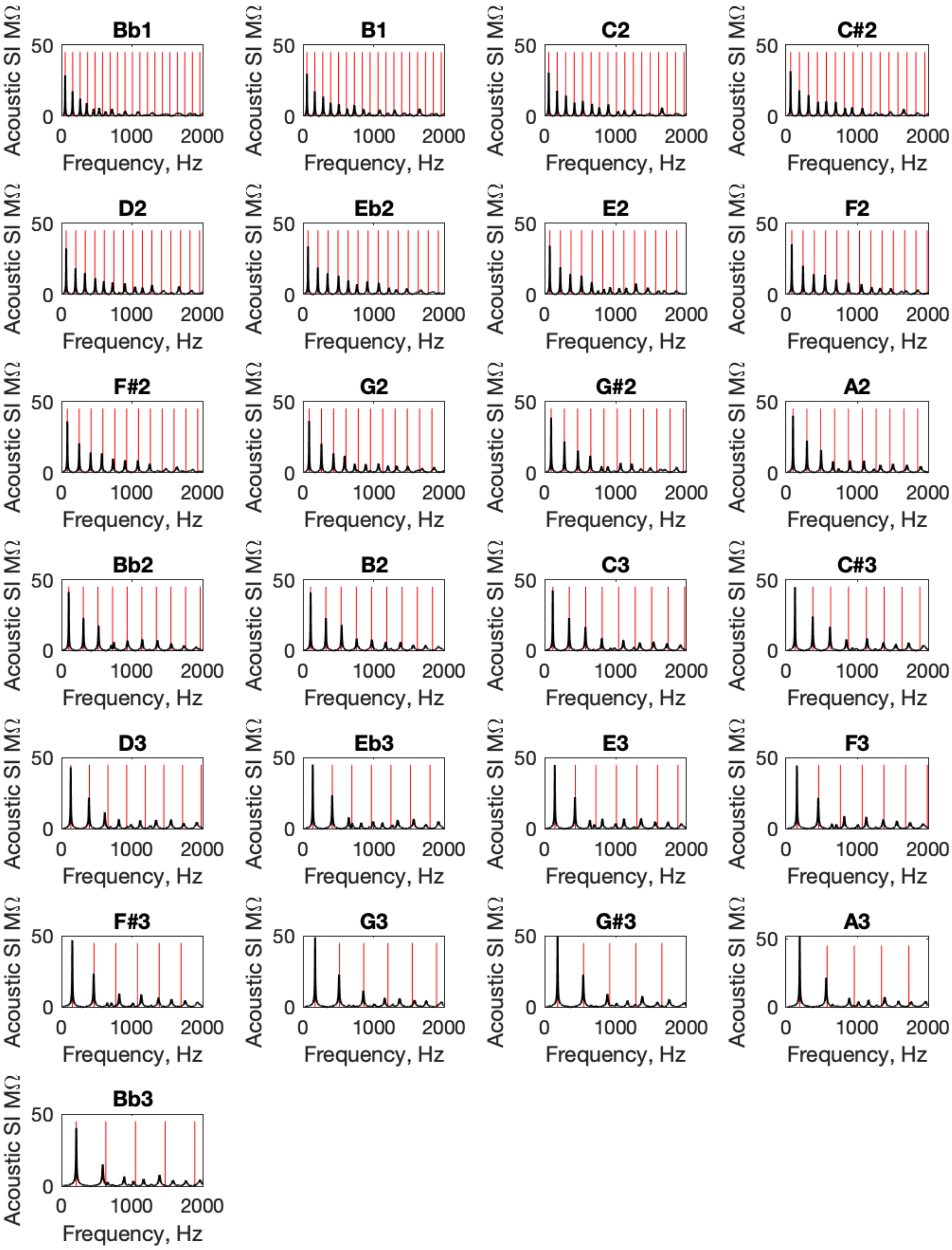

Figure 8.24. Impedance spectra for the Streitwolf D.N.gnm.MIR477 for the first register, from B♭1 to B♭3.

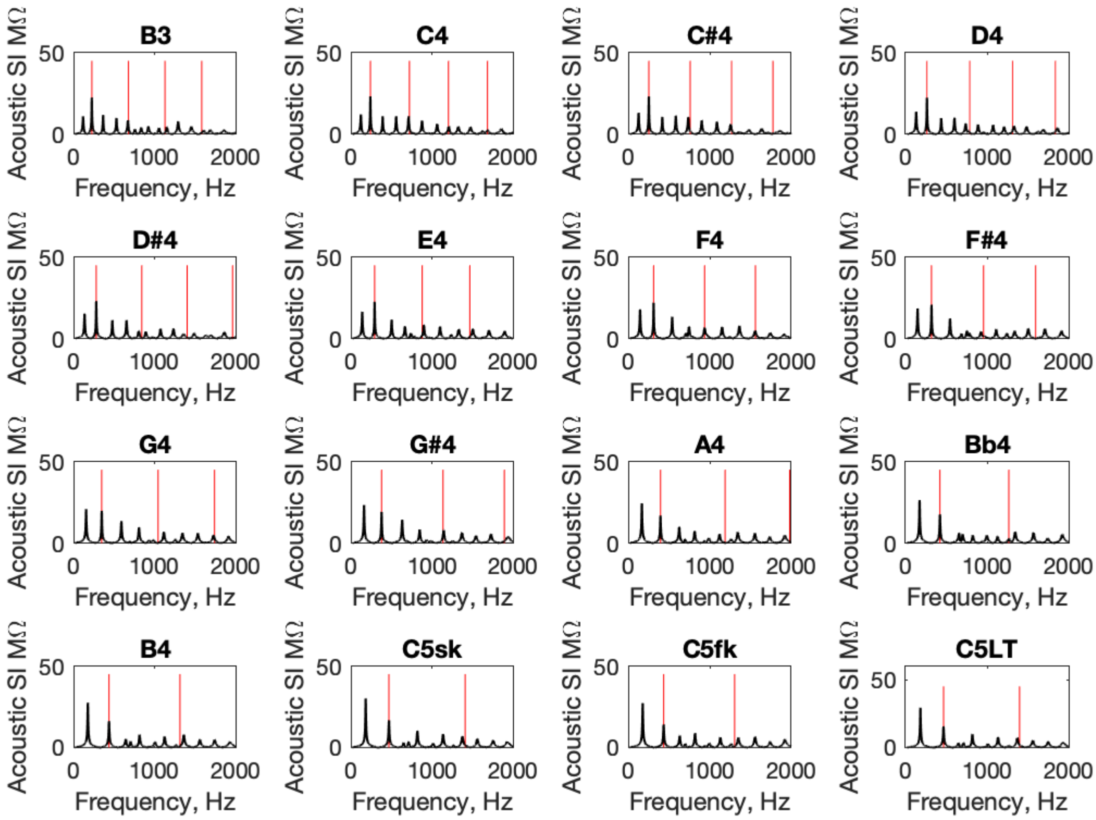

Figure 8.25. Impedance spectra for the Streitwolf D.N.gnm.MIR477 for the second register, from B2 to C5.

This instrument is discussed in Rice.[22] He points out that the bore is considerably greater than that of any of the American bass clarinets from the Catlin school; he gives it as 21 mm, whereas my measurements show that it is even larger, at 24.7 mm diameter (this agrees with Bär's measurements for this instrument[23]). The resonances are well aligned with the harmonics of each note, indicating that the tuning will be stable, and over most of the range several harmonics are well aligned with resonance peaks in both registers. The exception is the range D3 to E3, where the resonances are damped more rapidly (see Figure 8.24) and only two resonance peaks are available to align with harmonics. This is ascribed to the different construction of tone holes I, II and III; these are bored diagonally in the wing joint of the instrument (like those in a bassoon) and have long chimneys: 16.5 – 19.2 mm, cf. 6 – 7 mm in other tone holes in the wing joint. This results in a lower local cutoff frequency for these notes (as discussed below) and implies an alteration of the spectral energy distribution in some way in comparison with adjacent notes. Whilst timbre has not been specifically determined in this project, and involves much more than the presence of various harmonics, it is known that the spectral energy distribution is a major contributor to the perception of timbre.[24] Hence one would expect a different timbre for these notes compared with neighbouring notes. The resonances are also weaker in the low register than they are in the German straight-form

[22] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 272.
[23] Bär, *Verzeichnis Der Europäischen Musikinstrumente in Germanischen Nationalmuseum Nürnberg.* Band 6, 215.
[24] Grey, John M. 'Multidimensional Perceptual Scaling of Musical Timbres'. *The Journal of the Acoustical Society of America* 61 (1977) 1270–77. https://doi.org/10.1121/1.381428.

instruments, though they are comparable in the upper register, and also comparable to the Sax instruments. I would not expect the Streitwolf to have so high a dynamic range as the Sax instruments, because of the smaller bore.

The impedance map shows that the instrument stands in B♭, tunes generally well at A4=440 Hz and descends to B♭1. The twelfths are accurate but the temperament is not quite even, and small embouchure or fingering corrections would be necessary on many notes. It is interesting that the fingering of this Streitwolf, does not conform fully to the Müller-derived keywork followed by most instruments studied. It does not possess the usual F#B key operated by R3 to correct the intonation of B♭2 and F#3. Instead the B♭F key serves this purpose as well as being used for B♭2/F4. The tonehole for this key is not quite large enough and/or not far enough up the instrument to serve this purpose exactly, so B♭2 and F#3 are actually a little flat. Also, F3 is played with LT only; the usual forked fingering (LT, II) is very flat. F#3, usually LT only, is played with LTI and the side key, though it is still flat. These observations, which are paralleled in the second register, exactly conform to and confirm Streitwolf's original fingering chart, and have been used in the computation of Figure 8.26.[25] It is interesting to note that these fingerings for B/F# and F/C are those used on the Boehm system clarinet developed by Hyacinth Klosé between 1839 and 1843.

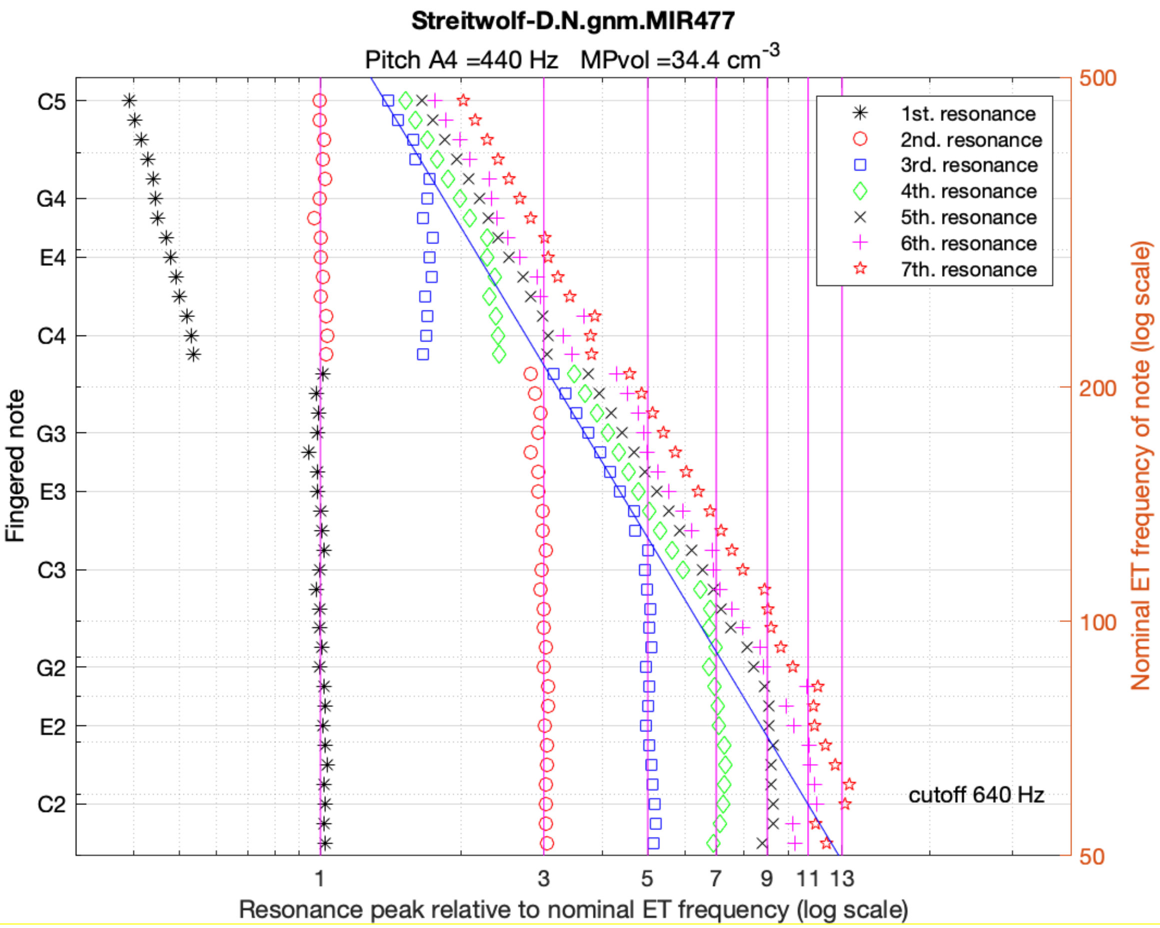

Figure 8.26. Impedance map for the Streitwolf D.N.gnm.MIR477.

[25] Streitwolf, *Anweisung, Die Bass-Clarinette kennen Und Blasen Zu Lernen.*

Streitwolf D.LE.u.1539

The graphs for this bassoon-form instrument in B♭ are shown in Figures 8.27 to 8.29.

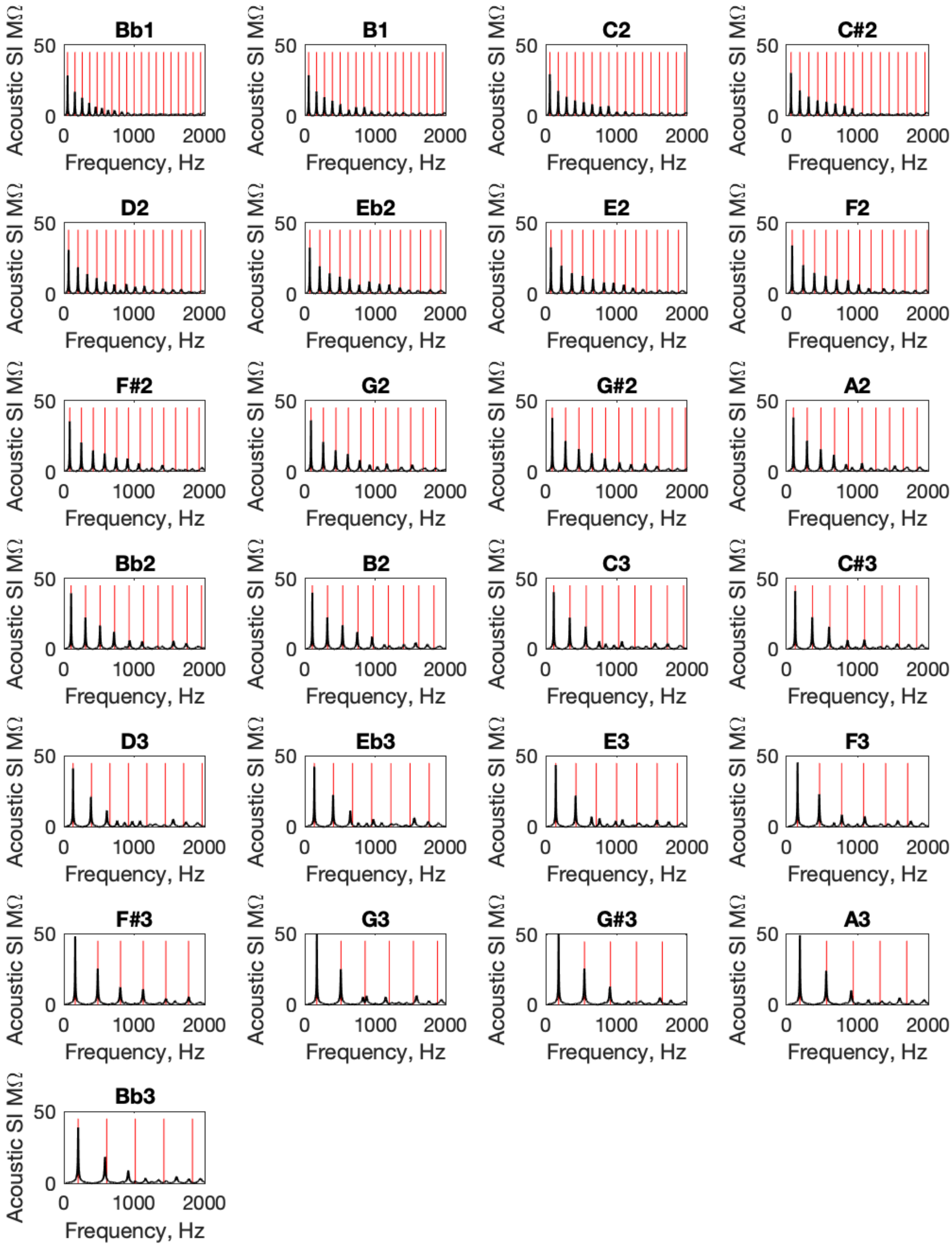

Figure 8.27. Impedance spectra for the Streitwolf D.LE.u.1539 for the first register, from B♭1 to B♭3.

This instrument was measured in order to study the consistency of Streitwolf's manufacture, which was found to be very good. The results for this instrument are very similar to those for D.N.gnm.MIR477, even including the cutoff frequency and some of the small deviations from temperament. Again it descends to B♭1. There are some small fluctuations that are not in common, e.g. F#3 is flatter on the Nuremberg instrument, but nothing that could not be adjusted by undercutting or by embouchure.

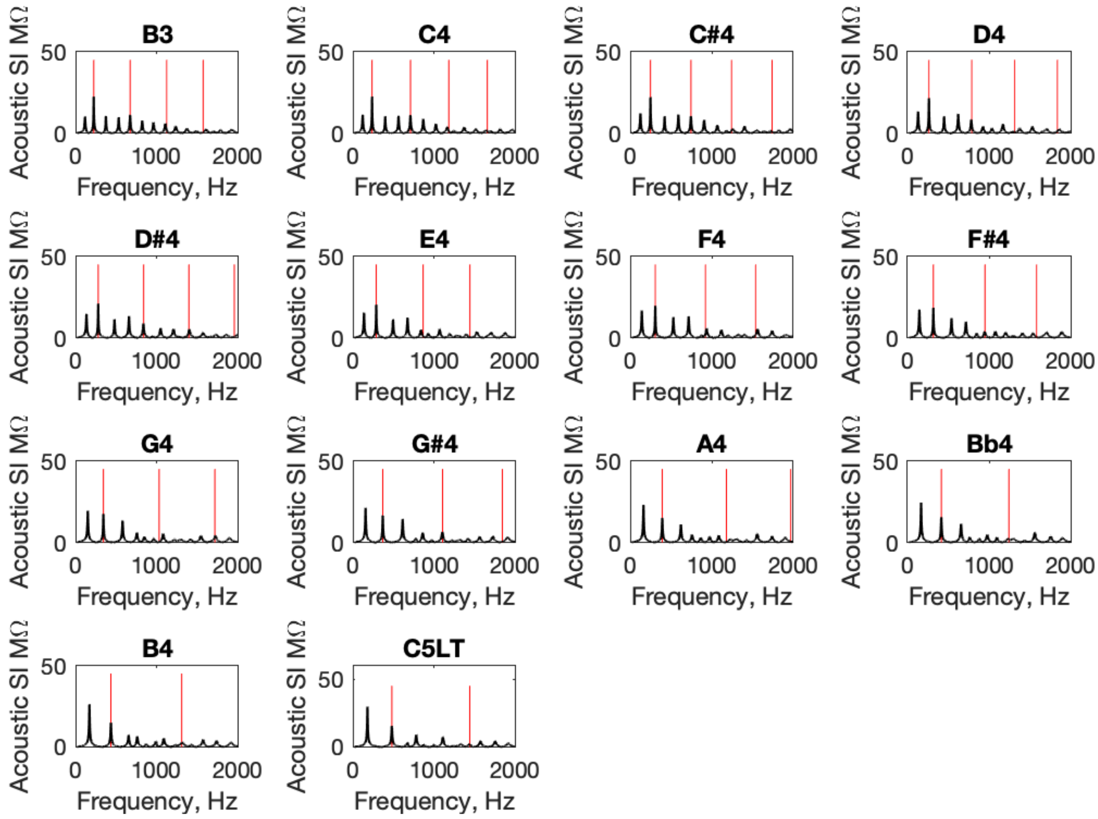

Figure 8.28. Impedance spectra for the Streitwolf D.LE.u.1539 for the second register, from B3 to C5.

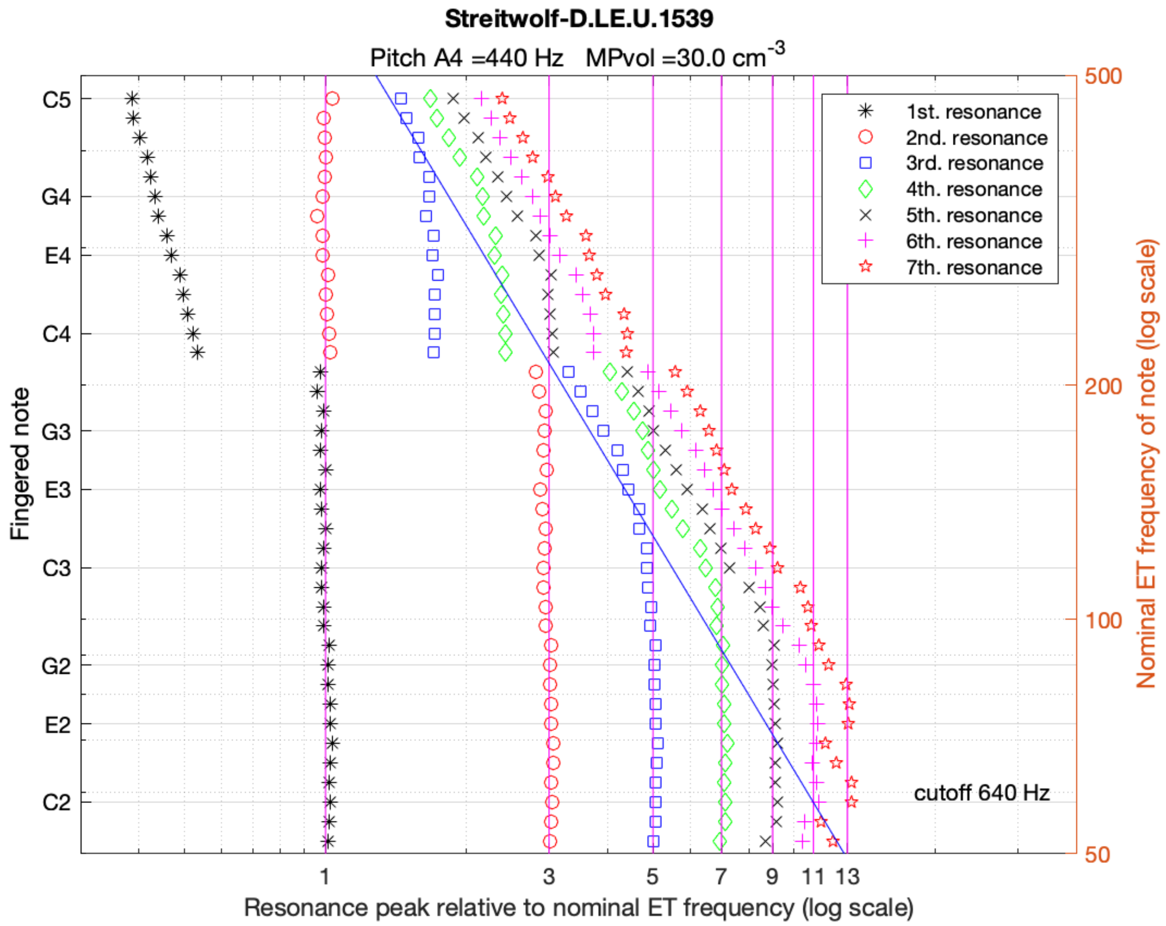

Figure 8.29 Impedance map for the Streitwolf D.LE.u.1539. Fingering as for D.N.gnm.MIR477.

Catterini GB.O.b.496

As seen in Chapter 7, Catterini was also an important innovator, whose instruments show some understanding of the acoustics of the instrument. The graphs for this bassoon-form instrument from 1838 are shown in Figure 8.30 to Figure 8.32.

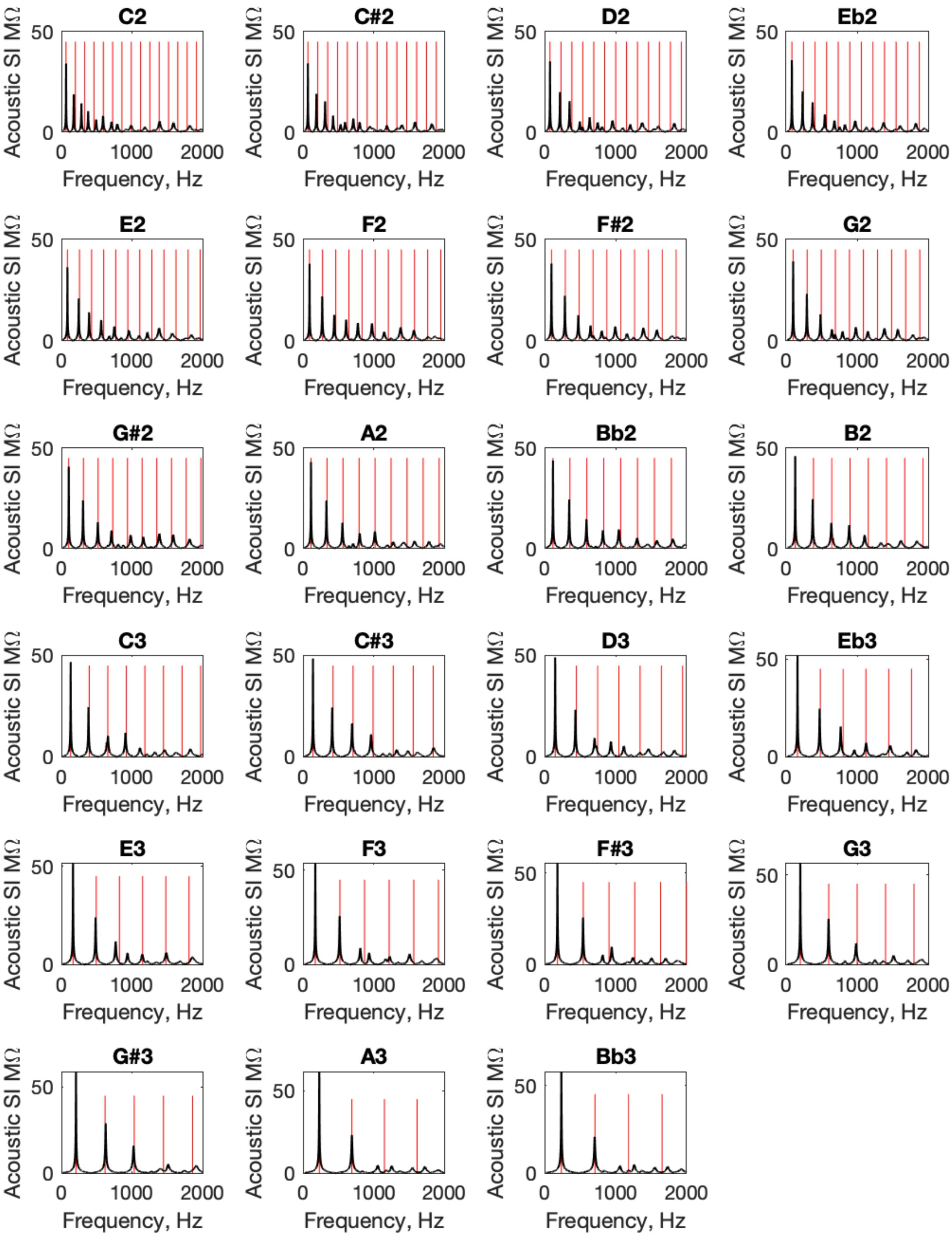

Figure 8.30. Impedance spectra for the Catterini GB.O.ub.496 for the first register, from C1 to B♭3

Alignment of resonances is good after the first two or three notes, and the average intonation is good, with smooth transition to the upper register. However there is a lot of apparently random variance between adjacent notes. This should not be too strongly weighted for the Catterini design, since the X-ray measurements (Chapter 7) showed that the tone hole design is more complex than can be allowed for in the computations. The main tone holes are centrally placed on the body but then make a diagonal, tapered connection to the side of the down tube. They are also lined with narrower diameter inserts at their top ends. In contrast to the very accurate computations of pitch for the Heckel (Chapter 6), the computed spectra for the Catterini indicated a pitch of A4 = 448 whereas the playing tests (Chapter 7) gave a pitch of A4 = 465 (on a non-original mouthpiece). The reason for this is probably the extreme undercutting of the main holes on the Catterini, which are actually slanting and conical rather than cylindrical, as shown by the X-ray data. A large number of holes is affected: I, II, III, IV, V, VI, FC, F#C# and E♭ at least. The computations will not be accurate for this design of tone hole, and the equations to deal with this construction are not yet available. Qualitatively, we can assert that this undercutting will result in lower impedance tone holes, which will result in a higher pitch of the particular note, and of the whole instrument if performed on all or most of the tone holes. The effect will be quite significantly higher with holes that are undercut all their length, not merely at the inside edge. This was confirmed by a trial computation with the tone holes all increased 30% in diameter. This reduces their impedance and indeed raised the calculated pitch of the instrument to about A = 460 Hz. It is not possible to be more specific, but it is certainly plausible that the extreme undercutting would raise the pitch by almost a semitone.

The question arises, whether this kind of error would affect the other instruments discussed in this chapter. Whilst diagonal tone holes are common enough and may give rise to some error from the diagonal, rather than normal, truncation of the holes, the specific Catterini construction with the whole length of a tone hole tapered was, I believe, not normally found even in bassoon-form instruments.

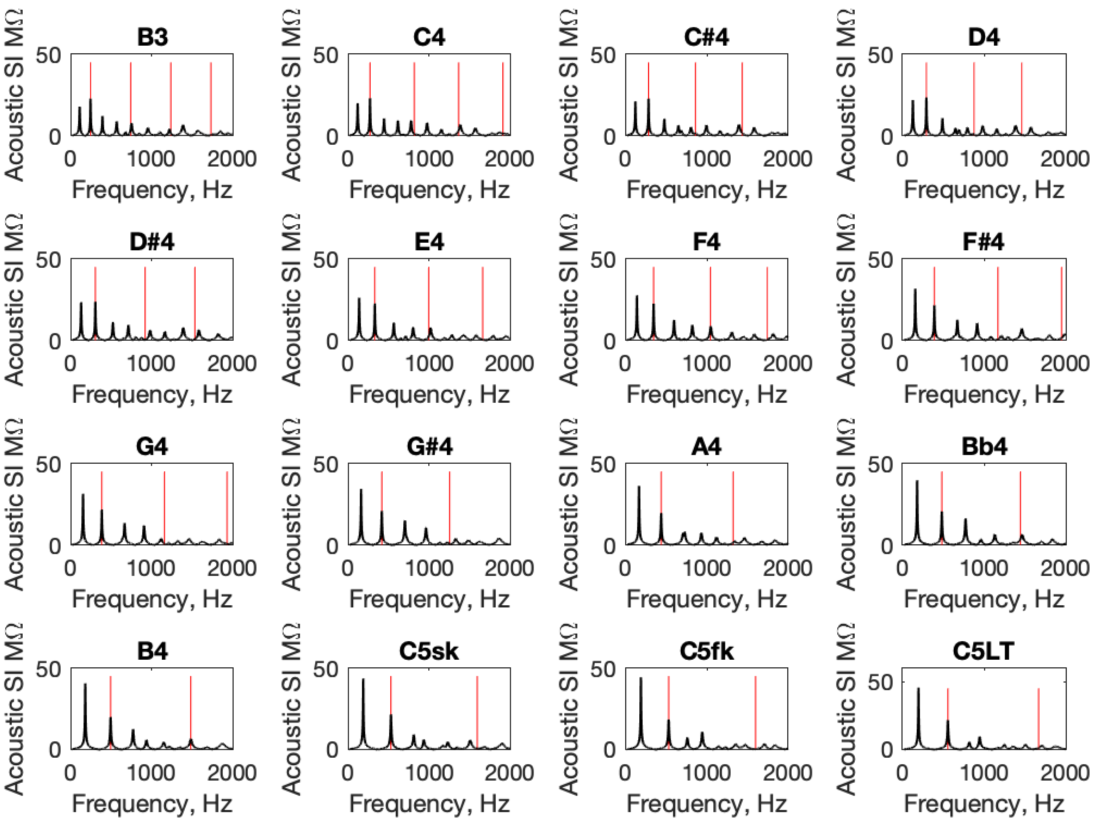

Figure 8.31. Impedance spectra for the Catterini GB.O.ub.496 for the second register, from B3 to C5

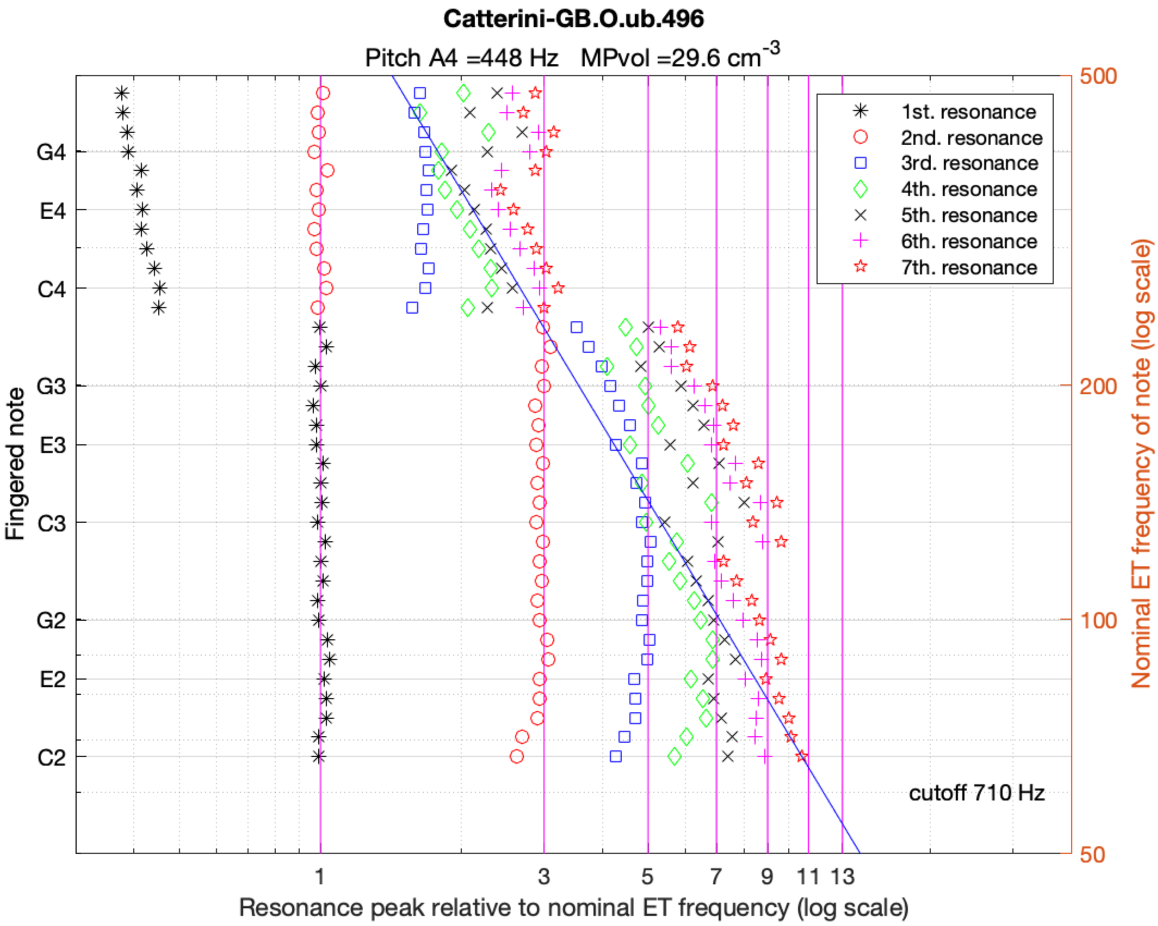

Figure 8.32. Impedance map for the Catterini GB.O.ub.496

Maino B.B.mim.0941

The best fit for this bassoon-form instrument was found for an instrument in C at a tuning pitch of A4 = 435 Hz and a slightly smaller mouthpiece volume of 26.2 cm^3 as shown in Figures 8.33 to 8.35.

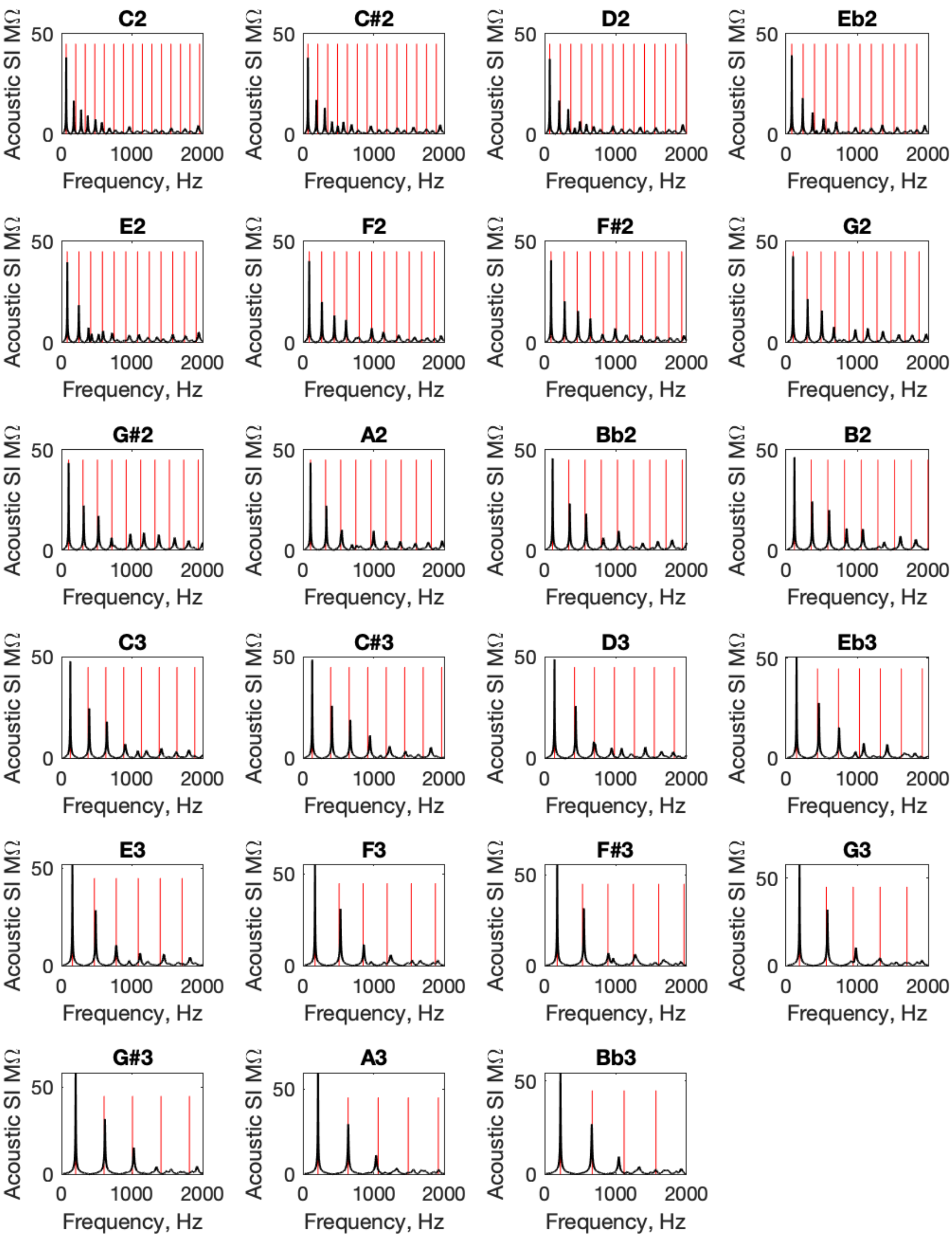

Figure 8.33. Impedance spectra for the Maino B.B.mim.0941 for the first register, from B♭1 to B♭3.

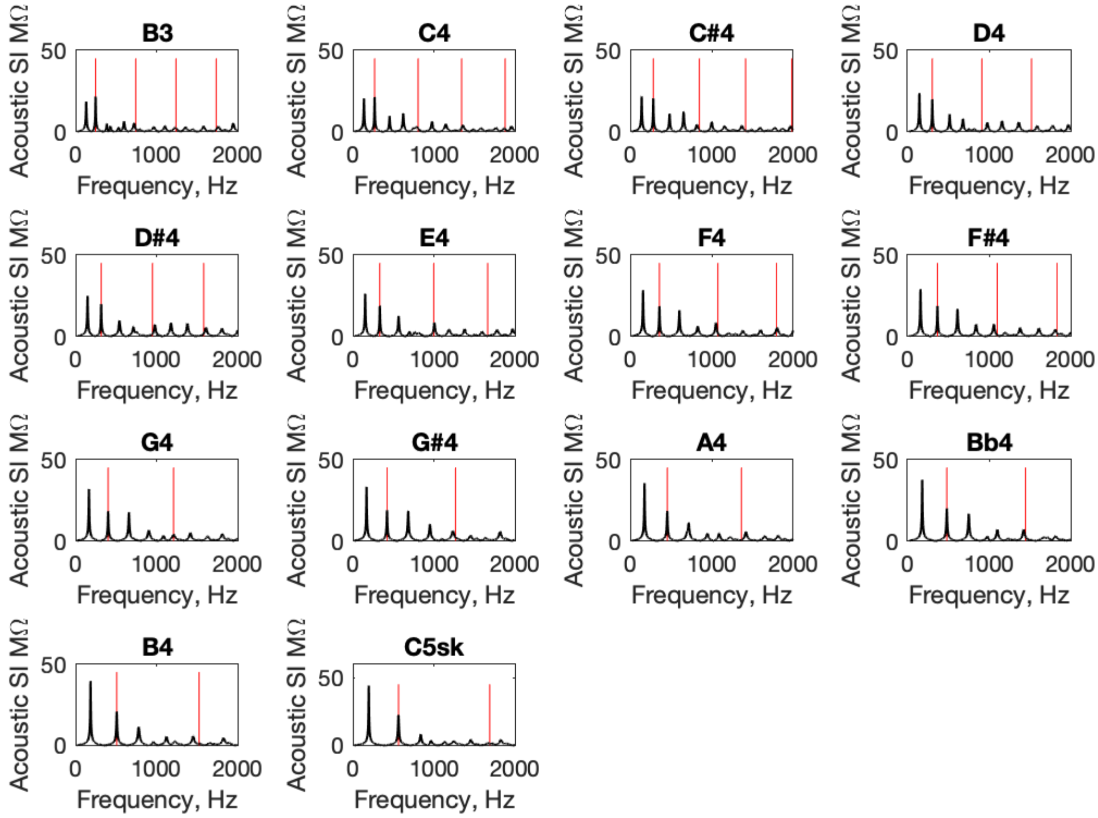

Figure 8.34. Impedance spectra for the Maino B.B.mim.0941 for the second register, from B3 to C5.

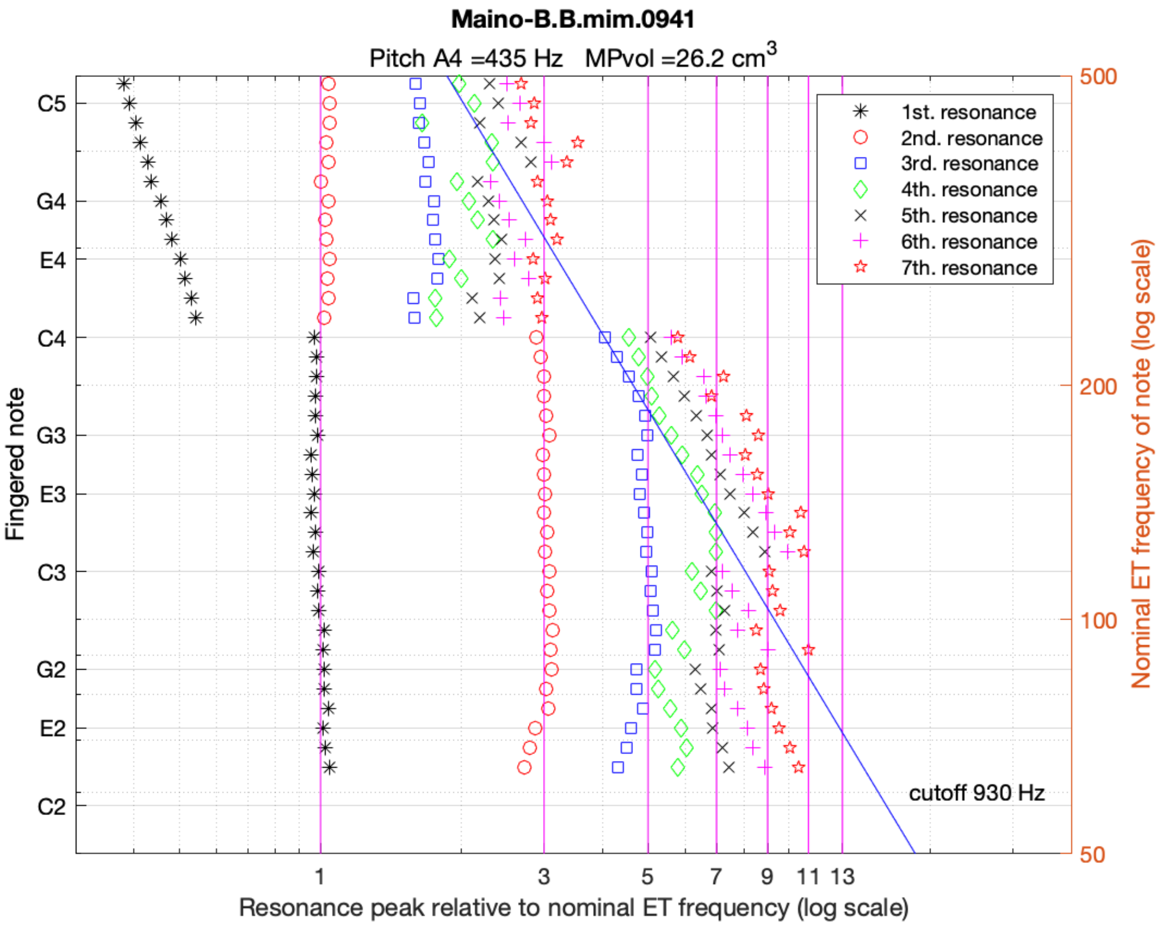

Figure 8.35. Impedance map for the Maino B.B.mim.0941.

Even so, the tuning is rather flat in much of the lower register and sharp in the upper. It is also variable throughout the range and the twelfths are too wide. Tuning at a lower pitch makes the lower register better but the upper register too sharp, and conversely for tuning at a higher pitch. The conclusion is that the holes are not very well positioned in this instrument. There is a significant discontinuity in the tuning over the register break, which could not be avoided by a different choice of tuning pitch. The lowest three notes do not have a good alignment of harmonics with resonance peaks and would likely be difficult to play, tending to leap up a twelfth.

The fifth-resonance cutoff (note fingerings from F3 to B♭3) is quite high at 930 Hz. This would be equivalent to ~ 830 Hz on a B♭ instrument but is still exceptionally high for a bassoon-form instrument.

This instrument is described differently by various authors in the literature. In the original publication by Mahillon it was described as an instrument in C with all-chromatic intervals.[26] Van der Meer however, considered that with an overall length of 170 cm it is more likely to be in B♭.[27] He assigns the basset notes (in SPN) as G2, F#2, C#2 and C2. He seems to have confused the E/B key with a non-existent E♭ key, omits mention of the open hole for RT and does not include the note D2. Rice states that the instrument is in B♭, appearing to follow van der Meer, and that the basset notes (with all holes closed down to E2/B2) are E♭2 (produced by closing the RT hole), D2 and B♭1. Rice also states that there are two speaker keys.

Of the above descriptions, the acoustic calculations show that only Mahillon is correct. This is perhaps unsurprising, since it is known that he played the museum instruments where possible; for example, his remarks on the plank-form instrument B.B.mim.939 which he found to be pitched in A.[28] They were of course 120 years younger at that time and presumably more playable. The calculations show that the lowest possible pitch when all holes are closed would be a little flatter than the lowest impedance peak, which is at 67.5 Hz. For A4=440 Hz the pitch of concert C2 matches well at 65.4 Hz. If the instrument were in B♭ a written C2 would sound 58.3 Hz and a written B♭1 would sound 51.9 Hz. There is no realistic tuning pitch that would make this assignment of notes correspond to the calculations. Furthermore, the gap between the lowest two notes is clearly a semitone, not a tone, as seen on the impedance map. The instrument is definitely in C with a fully chromatic compass to C2. I note also that E♭2 is actually obtained by closing all holes down to E2, plus RT plus opening the normally closed D key. One of the keys labelled as a speaker key by Rice is actually the normally-open LT key corresponding to the LT open hole that emits a G on a soprano or bass clarinet. It is seen that it can be misleading to assign a pitch to a bass clarinet merely on the basis of its length, and proper acoustic calculations are most helpful.

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[26] Victor-Charles Mahillon, *Catalogue descriptif et analytique du Musée Instrumental du Conservatoire Royal de Bruxelles.* Vol 2, 220.
[27] Meer, 'The Typology and History of the Bass Clarinet.'
[28] Victor-Charles Mahillon, *Catalogue descriptif et analytique du Musée instrumental Du Conservatoire Royal de Bruxelles,* 220.

Pictures of both sides of the instrument with the keys annotated correctly are shown in Figure 8.36. This is consistent with Mahillon's publication but more detailed. It is seen that for note fingerings from C2 to E2 the cutoff frequency appears to be as low as 430 Hz and the higher resonances are poorly aligned with the harmonics of the note. For subsequent notes in the lower register the harmonics are well-aligned to the resonances.

Comparison with the Catterini instrument is interesting, since both makers come from North Italy (Kingdom of Lombardy) and both made instruments for the opera houses in the region.[29] It is tempting to look for a connection in the design of the instruments, but there is no evidence for this (unlike the links found between Catterini's design and the anonymous instruments in the MMA discussed in chapter 7). The design of the Maino instrument is more akin to those of Streitwolf. It is 'regular' bassoon form; it has five open tone holes; the pattern of hole spacings and diameters is different, as is discussed later in this chapter; and the cutoff frequency is substantially higher. Maino cannot be ascribed to any 'school of Catterini' on the evidence of these instruments.

[29] Della Seta, ''From The Glicibarifono To The Bass Clarinet'.

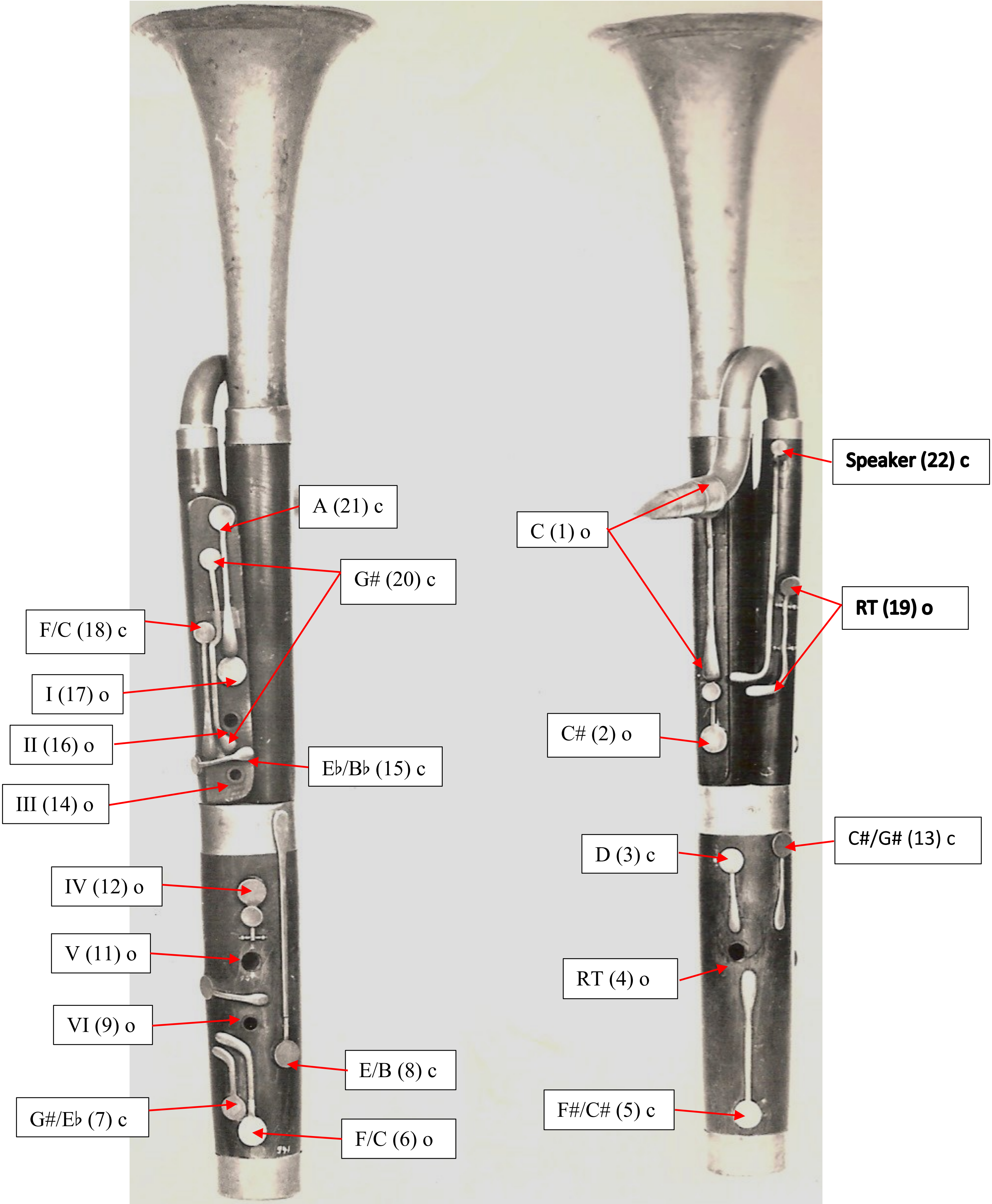


Figure 8.36. Annotated images of the front and dorsal sides of the Maino B.B.mim.0941 bass in C. The numbers correspond to the key numberings in Mahillon, which run from the bell upwards in sequence.

Open and closed keys or holes are indicated by 'o' or 'c'. Image courtesy Muséd des Instruments de Musique, Brussels.

Stengel B.B.mim.0943

This Stengel is dated 1855 and has a 20 mm bore. In appearance and design it is older than the next example (I.F.ga.170 1/2). It is again correctly described by Mahillon as a bass in B♭ with a fully-chromatic range down to C2.[30] It has been described in the literature as in C and also that the bottom range is B♭1, B1, C2, D2, E2, omitting C#2 and E♭2; however, the computations show that it is actually chromatic to C2.[31] Rice also states that it has a water key on the right side of the butt. As shown in Figure 8.37 it has no such key, unlike the instrument in Florence described next (Figure 8.38).[32]

Figure 8.37 (left). Base of butt joint of B.B.mim.0943

Figure 8.38 (right). Base of butt joint of I.F.ga.170 1/2

The graphs for this bassoon-form instrument are shown in Figure 8.39 to Figure 8.41. Pitch was found to be A4=442 Hz. The resonances are strong and generally well-aligned to the harmonics, but the intonation is variable, and tends to sharpness except in the upper part of the lower register. Using the instrument at a pitch of about A4=445 Hz would correct this but then the often-used notes E♭3 to B♭3 would become unacceptably flat.[33]

It is interesting that the notes B♭3 – D3 were computed using the lower speaker key rather than the upper one. This considerably improved the intonation of these notes, which were calculated to be very sharp with the upper speaker key (as with the Grenser). This and the Grenser data show that the function of the second speaker key is primarily to correct the sharpness of the bottom few notes of the second register, when the first speaker key is

[30] Mahillon, *Catalogue Descriptif et Analytique Du Musée Instrumental Du Conservatoire Royal de Bruxelles.*Vol; 2, 223-4

[31] Rice, *From the Clarinet D'amour to the Contra Bass*, 2009, 312.

[32] I assigned the stud on the base of B.B.mim.0943 as a stud for a sling, though it is conceivable that it would unscrew to be a water drain; this was not investigated, because of the risk of damage.

[33] For clarity, the modelling itself and the consequent resonances do not assume any pitch. The pitch must be specified for the impedance maps, which show the relationships between tube resonances and pitches of certain frequencies.

positioned to sound high notes in tune. The cutoff frequency was 760 Hz, well above the Maino and Streitwolf and similar to the Sax instruments.

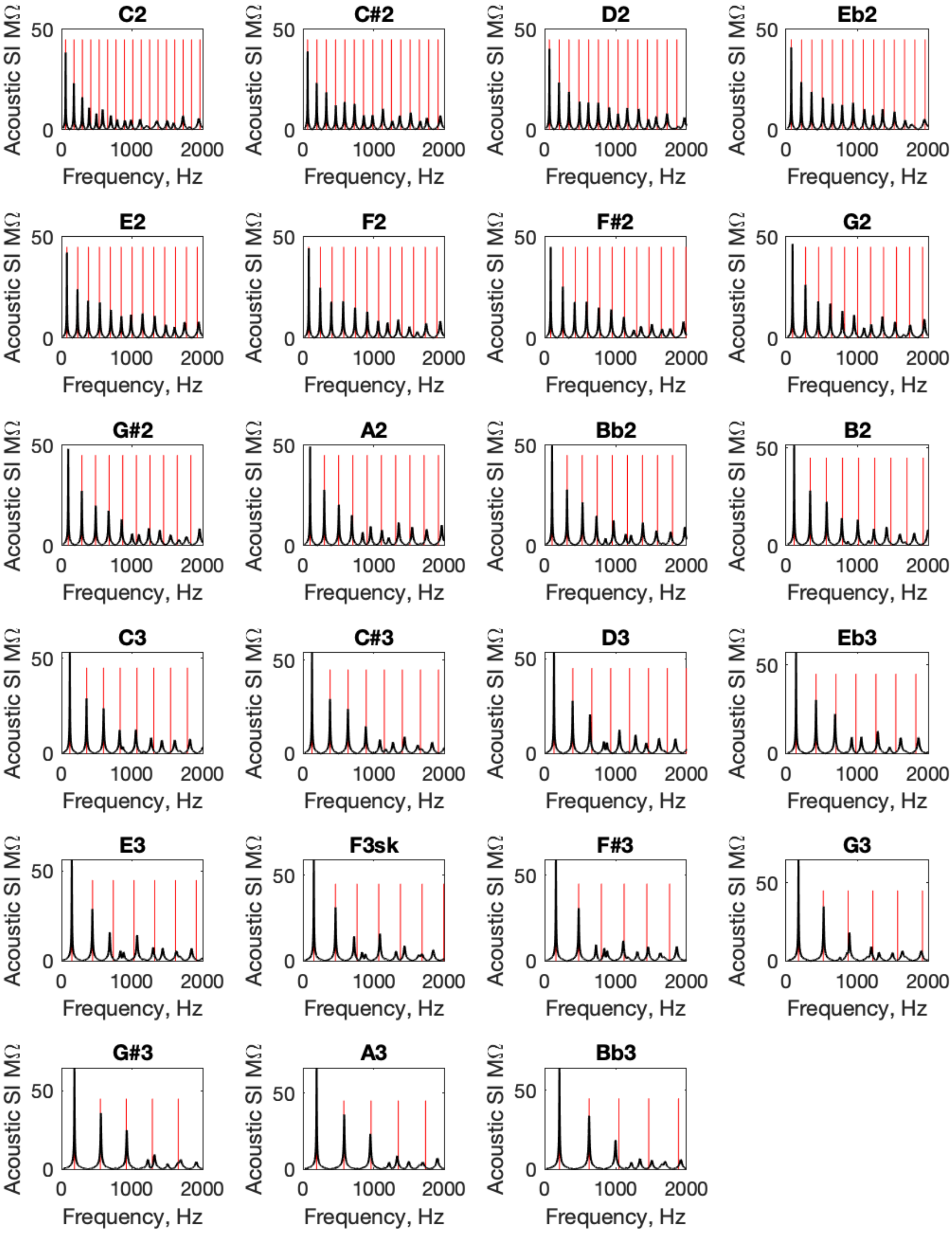


Figure 8.39. Impedance spectra for the Stengel B.B.mim.0943 for the first register, from B♭1 to B♭3.

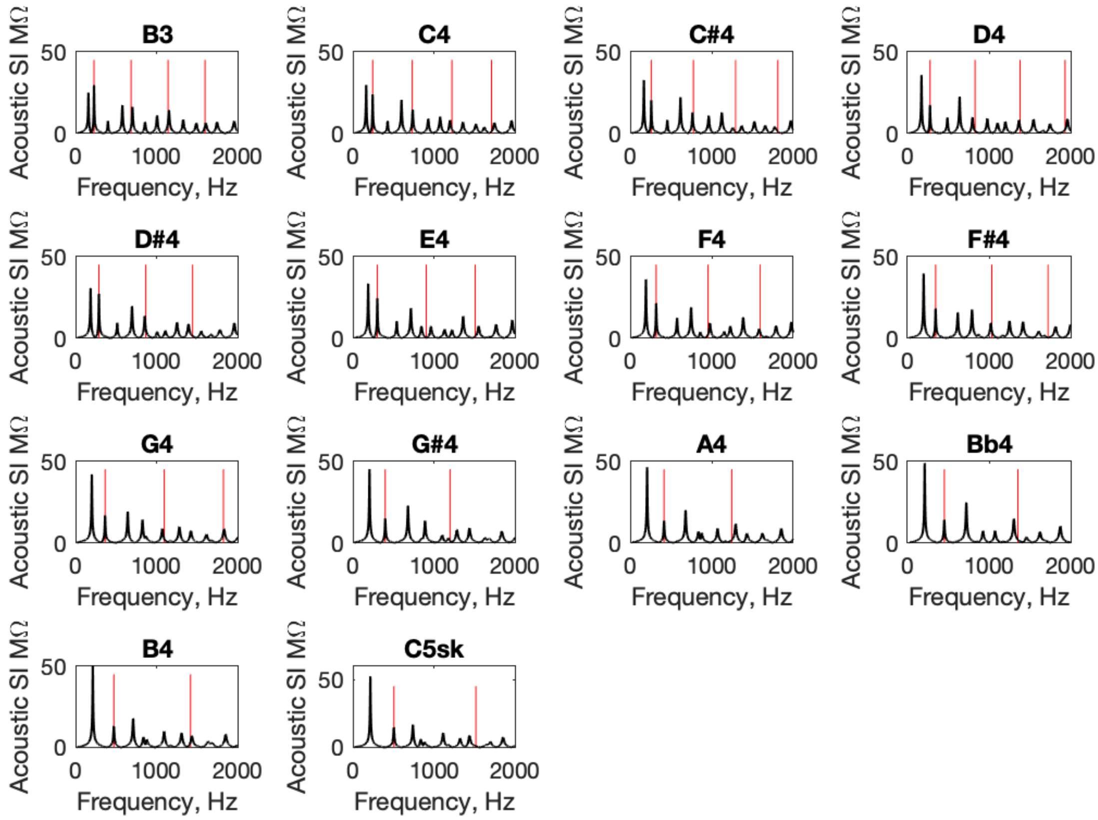


Figure 8.40. Impedance spectra for the Stengel B.B.mim.0943 for the second register, from B3 to C5.

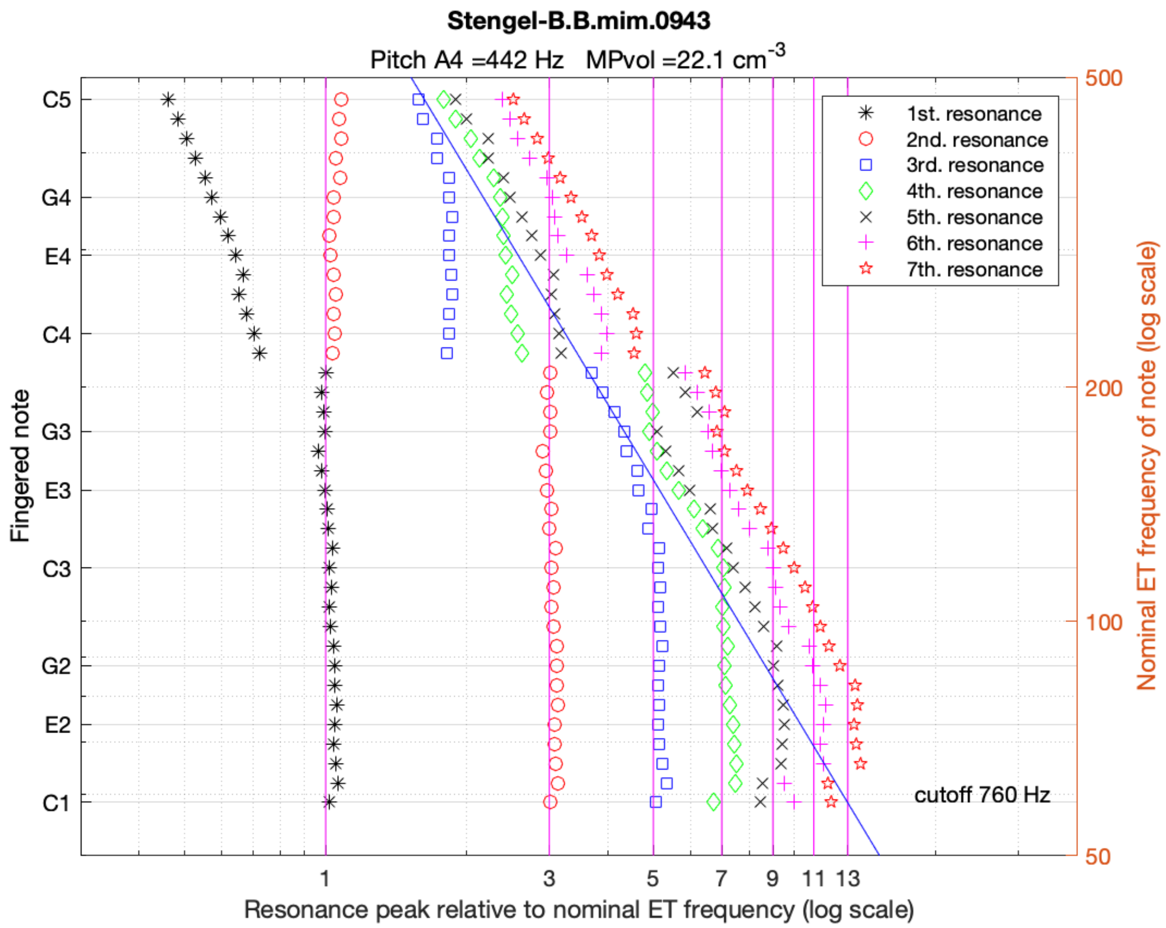


Figure 8.41. Impedance map for Stengel B.B.mim.0943

Stengel I.F.ga.170 1/2

This bassoon-form Stengel in B♭ is dated c.1830 – 1860 and again has a 20 mm bore. The spectra are shown in Figures 8.43 and 8.44 and the impedance map in Figure 8.45. It should be said that this was the first instrument measured in a museum and insufficient time was available in the two half-day visits that were all that were allowed. Although all the bore profile and tone hole positions were measured and a brief playing test was permitted, the pad heights and diameters were not measured. Reasonable assumptions were made for the parameters, with the aid of detailed photographs that were taken.

There is a significant change of keywork layout between B.B.mim.0943 and this instrument, which now appears in the layout that is characteristic of several later Stengel bass clarinets (see Chapter 7). The mechanism is equally effective, but has been simplified. The tone holes have not been changed. The instrument now has a water key, already shown in Figure 8.38. The cutoff onset is 765 Hz, which is not significantly different from the 760 Hz of the Brussels instrument.

With the exception of an unusually flat F#3 the intonation and alignment of harmonics is very good, though there is some scatter in the pitch of notes; that is, the temperament is uneven. There is no tendency for the intonation to drift towards the top of the registers. The decay of the harmonics is quite slow in both registers, resulting in good alignment and reinforcement of notes.

The acoustic effect of the butt joint has been discussed above as inserting 'slugs' of inertance before and after the side hole; these are equivalent to closed tone holes. The joint is shown in Figure 8.42. In this instrument, note A2 emits from the tone hole VI on the down tube;

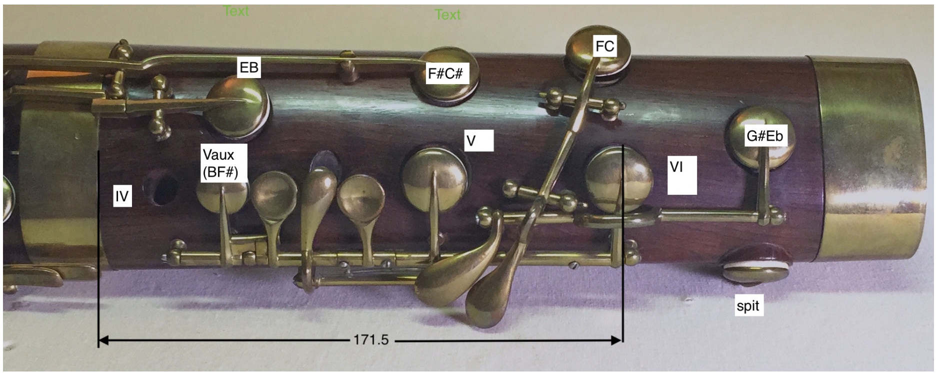


Figure 8.42. Butt joint of Stengel I.F.ga.170 1/2 with tone holes labelled.

G#/E♭ is almost exactly on the side hole between the tubes; G2 and lower notes are emitted from holes on the up tube. Examination of the impedance spectra of these notes in Figure 8.43 shows little difference in the overall shape or amplitude of the resonances in these notes. If anything it is the note A2 that shows some differences (around the fifth resonance) from its neighbours, rather than the notes emitting from the up tube. The maker has clearly succeeded in adjusting the corks to compensate for the inertance decrease of the bend. This confirms the playing test on the Schediwa bass clarinet discussed in Chapter 7.

In this instrument, unlike the Brussels example, there is a water key on the back side of the instrument. It is not reachable when the hands are in the playing position, so it is clearly not a tone hole.

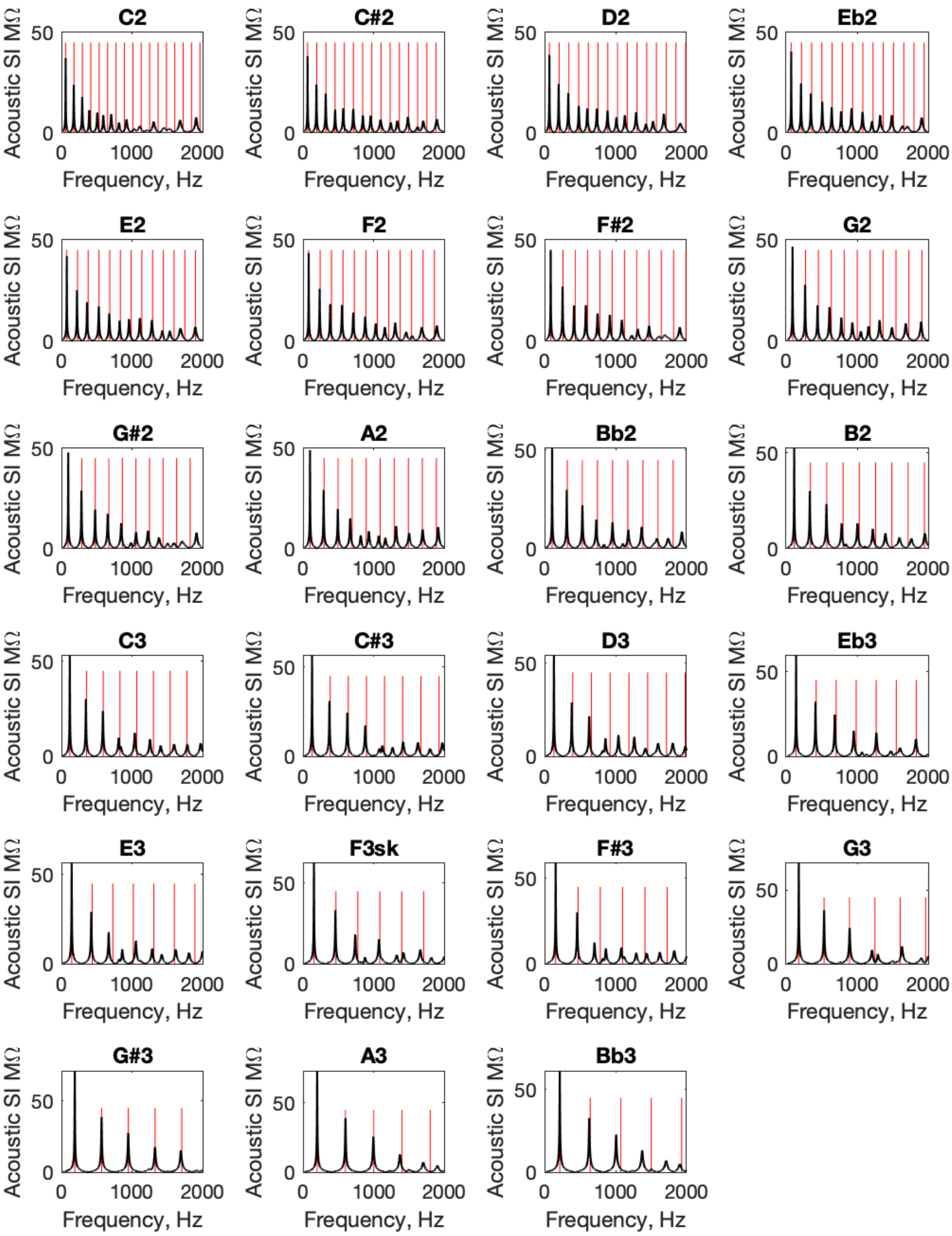


Figure 8.43. Impedance spectra for the Stengel (bassoon form) I.F.ga.170 1/2 for the first register, from C2 to B♭3.

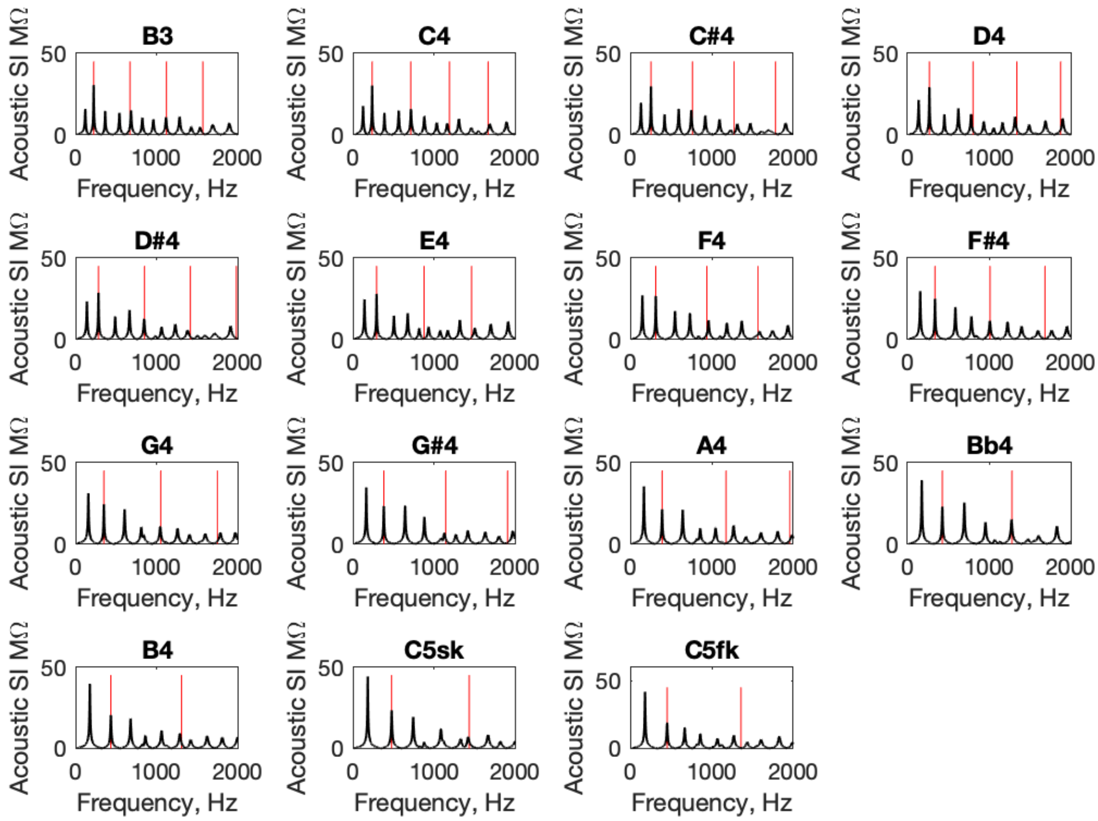


Figure 8.44. Impedance spectra for the Stengel (bassoon form) I.F.ga.170 1/2 for the second register, from B3 to C5.

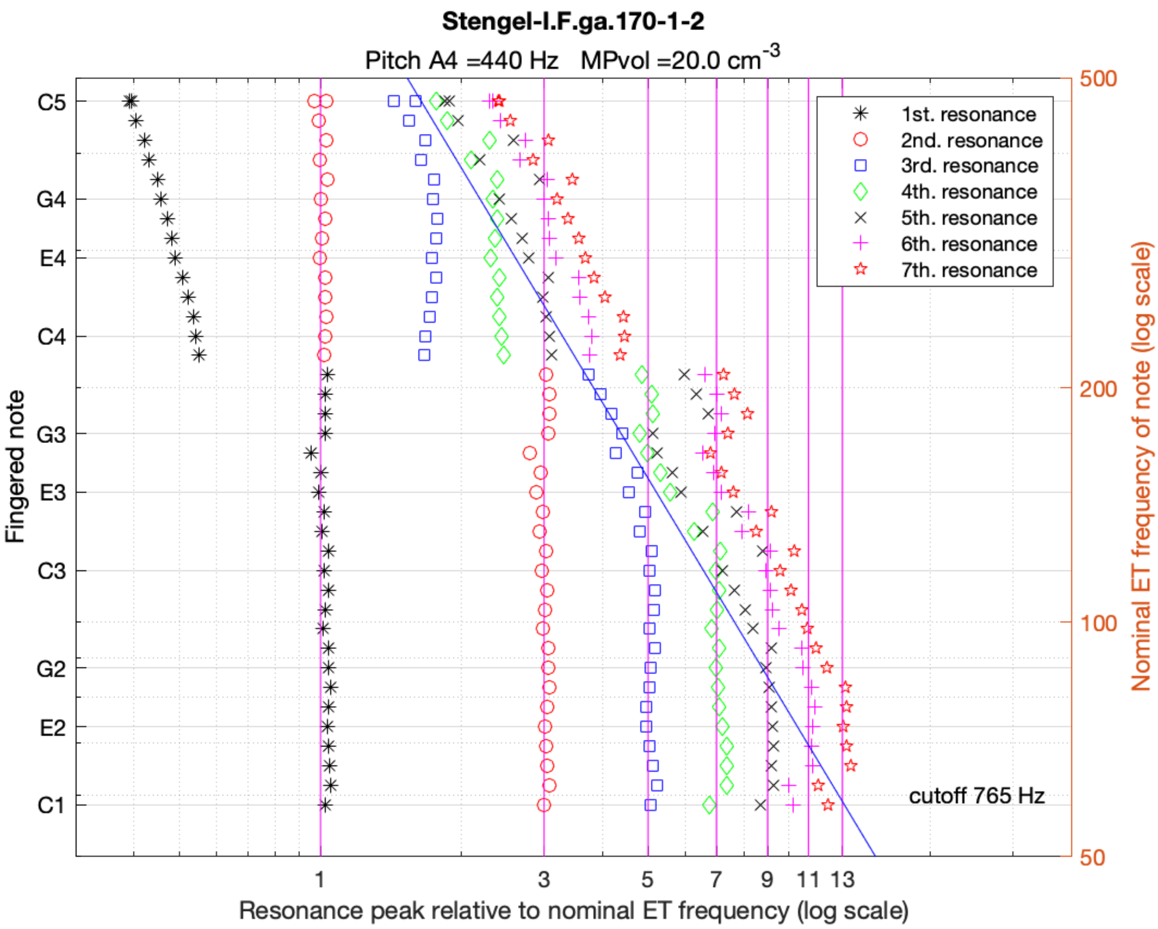


Figure 8.45. Impedance map of Stengel (bassoon form) I.F.ga.170 1/2

Kruspe CH.B.hm.1999.136

The graphs for this B♭ instrument tuning at A4 = 440 are shown in Figures 8.46 to 8.48. The range is chromatic down to D2 plus the notes C2 and B♭1, omitting C#2 and B2. The lower register is seen to be well in tune with well-aligned resonances up to D3 after which the alignment remains good but the notes get progressively flatter. These could possibly have been corrected by undercutting but this was not discernible without X-ray inspection. The second register is quite well in tune. The cutoff at 945 Hz is the highest of the bassoon-form instruments. This instrument is discussed further below.

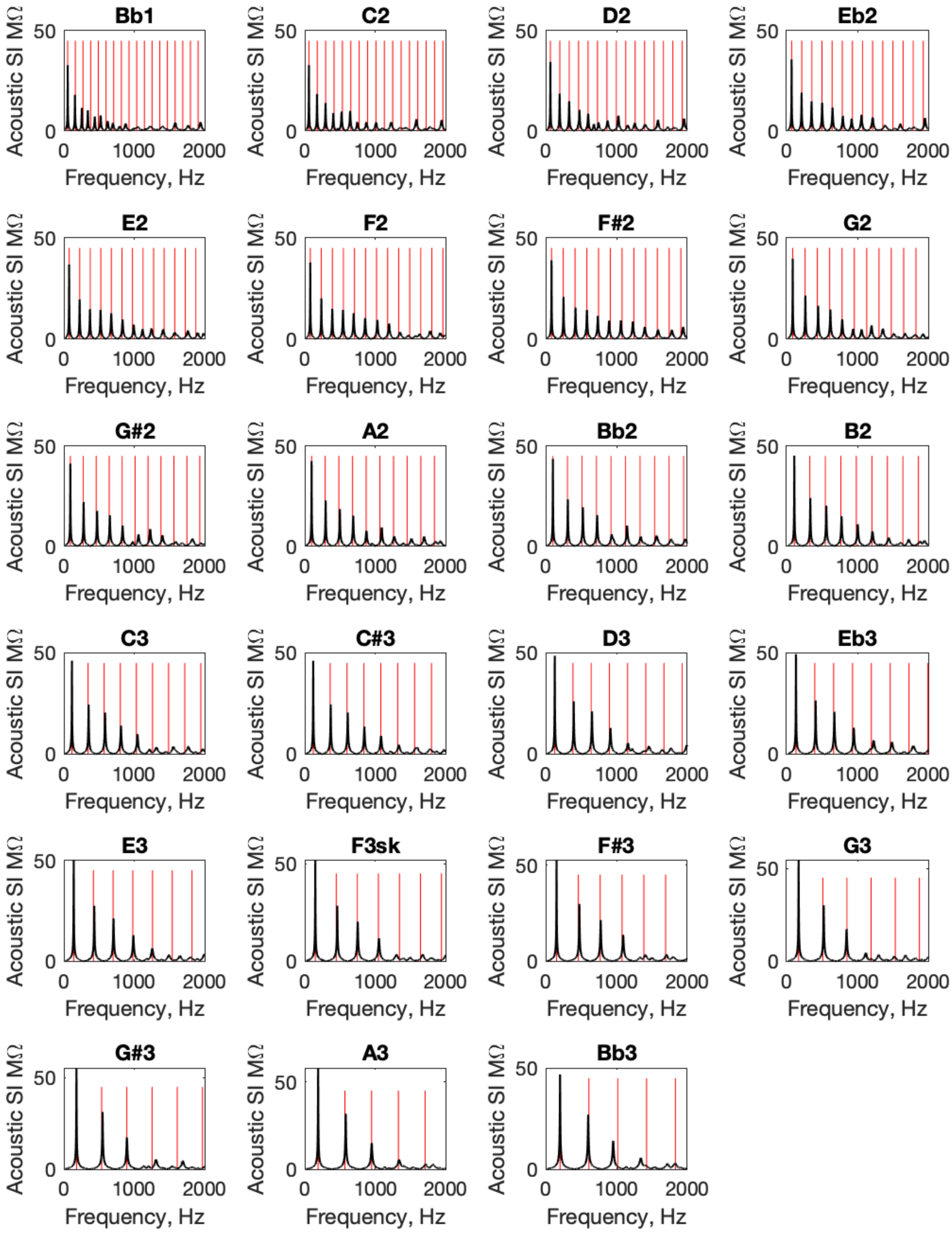


Figure 8.46. Impedance spectra for the Kruspe (bassoon form) CH.B.hm.1999.136 for the first register, from B♭1 to B♭3.

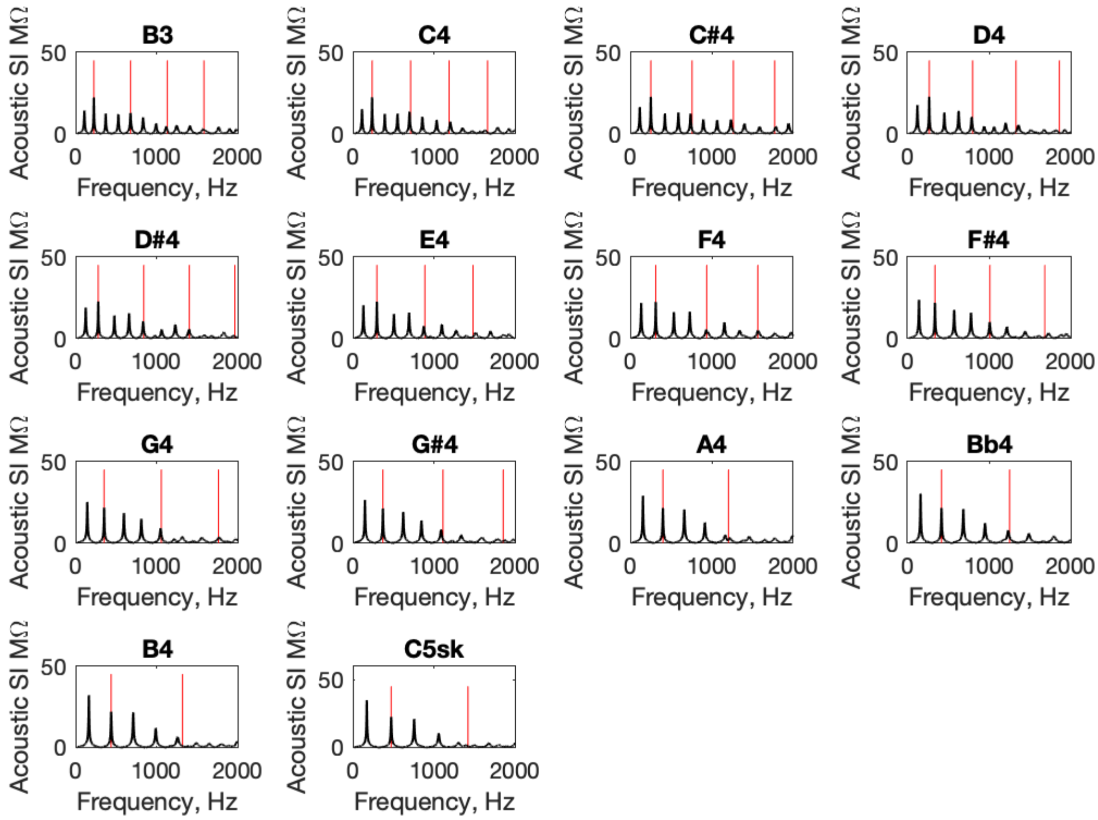


Figure 8.47. Impedance spectra for the Kruspe (bassoon form) CH.B.hm.1999.136 second register, from B3 to C5.

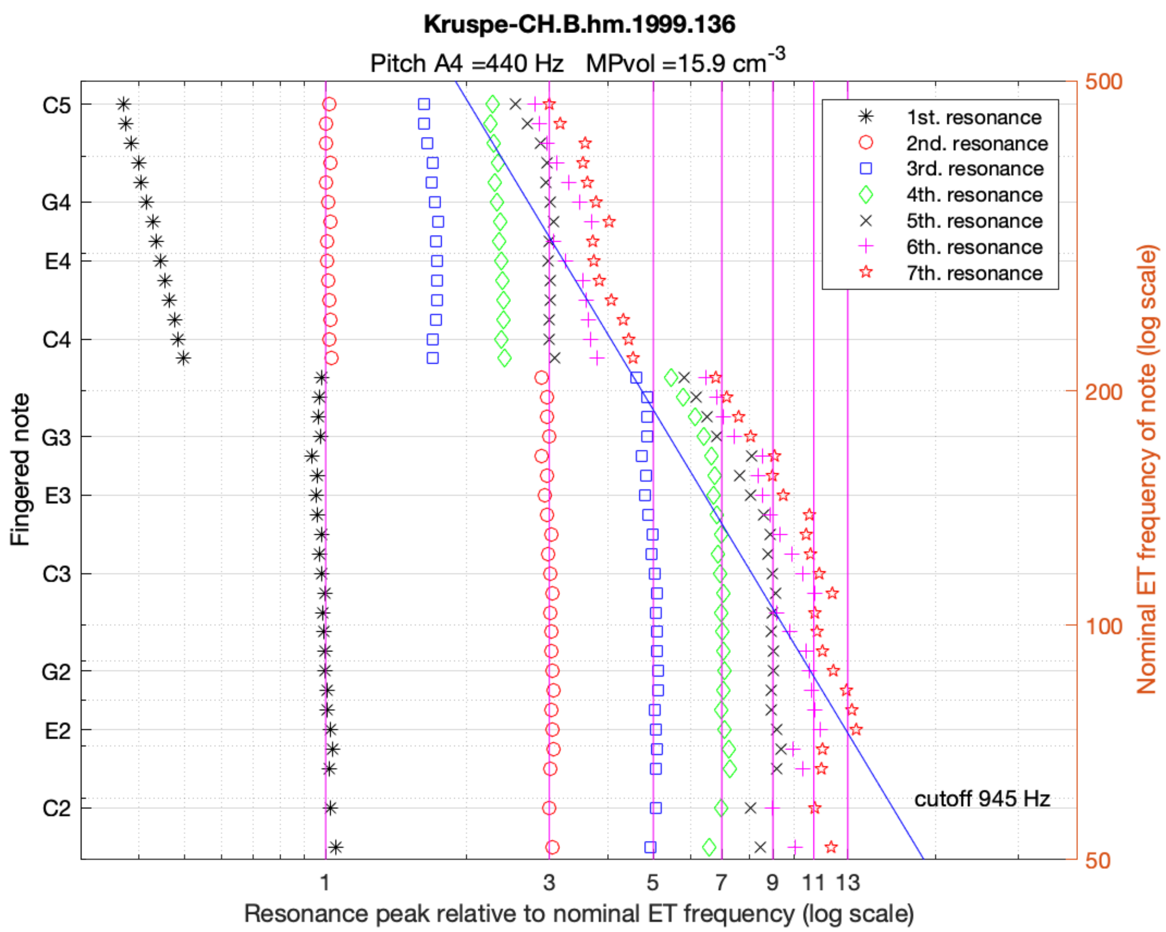


Figure 8.48. Impedance map for the Kruspe (bassoon form) CH.B.hm.1999.136.

Comparisons and analyses of the data

We must first enquire into the robustness of the computed results. The overall accuracy was determined experimentally with the Heckel instrument, as discussed in detail in Chapter 6. All instruments were measured with the same set of measuring instruments, so comparative results should be valid; the instruments were certified in accuracy and were also calibrated against certified slip gauges and a calibrated vernier gauge. Any errors in the measuring instruments themselves are likely to be below the 0.1 mm level (in either lengths or bore diameters), which will lead to negligible variation in the computed results.

The largest source of measurement error is likely to be in the measurements of hole positions. The Heckel is in my possession, and so could be measured very carefully, removing keys that were obstructing the measurement. This was rarely possible with museum instruments (except for the Catterini, for which it was allowed) and access to some holes could be difficult. It is possible that there could be errors of about ±1 mm in some hole positions. However, each measurement was independent from a fixed reference, such as the end of a tenon, so the errors will not accumulate. A trial computation was run on the Heckel with each of the main fingerholes (I – VI) displaced alternately by 1 mm. The resulting impedance map showed a barely detectable change in the resulting frequencies, hence it was concluded that the measurement accuracy was sufficent for valid conclusions to be drawn.

The mouthpiece volume and playing pitch were estimated by finding the values for which the most accurate and consistent intonation was seen on the impedance maps. This neglects the finer details of the mouthpiece shape but can be thought of as an ideal mouthpiece volume for that instrument. Scaling the mouthpiece volume to that of the Heckel instrument (which had been studied in detail, see Chapter 6) by means of the bore area worked very well, and only minor adjustments were made to this rule. However, we cannot say whether this volume was actually used in practice.

The largest question concerning the accuracy of the computations themselves is whether the geometric model used is accurate enough to be described by the equations used. The detailed study of the Heckel (Chapter 6) showed that in that instrument the accuracy was quite sufficient. However, one factor is missing from the computational model: the effect of undercutting of the tone holes. This is particularly difficult to measure in practice unless X-ray images are available. Where very strong tapers running almost the whole depth of the hole were present, it was empirically found (on the Catterini GB.O.ub.496) that the pitch could be increased by about a semitone. I believe, however, that the construction of this instrument is unique among those examined.

It is seen from the impedance maps that the accuracy of temperament varies considerably between the instruments. This may be quantified by calculating the closeness of the points for each note to the ideal value of 1 for the fundamental resonance of each note. This is simply achieved by taking the standard deviation of the set of frequencies of the notes, divided by the nominal equal temperament frequency for each note. This is tabulated in Table 8.2. The standard deviation gives equal weight to positive and negative errors, and also emphasizes outliers. As previously noted, this may not be the tuning that a maker will aim for, since sharp notes are easier for the player to correct than flat notes, and the odd outlier might be correctable by a fingering adjustment (e.g. on the throat A and B♭). Nevertheless it is a guide to the accuracy of intonation of the instrument. There is a general tendency for the intonation, relative to equal temperament, to improve with date of manufacture. The instruments with the best intonation are the straight-form Stengel, Kruspe and the later Heckel instruments with the bassoon-form Kruspe fairly close. Note again that the later Sax instruments were not studied. The best bassoon-form instruments are the Streitwolfs, but after the initial improvement from the Grenser (which would probably include the second, Augustin Grenser, with the extra speaker hole) there is not very much difference. Looking at the impedance curves of the best straight-form instruments, it does appear that the makers were aiming for equal temperament. There is no evidence of systematic oscillations over an octave in the values for the fundamental resonance as should occur for any of the other tuning methods. It appears that tuning for 'perfect' (beat-free) harmony with other instruments was, then as now, left to the adjustments of the player. However, such variations in temperament, which can only amount to less than 12 cents deviation from equal temperament in any note,[34] are really at the limit of the accuracy of the computational methodology at present.

Table 8.2. Comparison of main features of impedance maps. B-F = bassoon form; H-B = half-bassoon form; S-F = straight form. M/K = calculated from Moers-Kegomard theory.

Maker	Instrument	Form	Date	Pitch A4, Hz	Reg. 1 tuning Variation %	Reg. 2 tuning Variation %	Cutoff at Resonance 3 Hz	Cutoff (M/K) Hz
Grenser (B♭)	S.S.M.2653	B-F	1793	445	8.8	7.6	540	429 - 807
Streitwolf (B♭)	D.N.gnm.MIR477	B-F	1835	440	2.0	1.7	640	474 - 734
Streitwolf (B♭)	D.LE.u.1539	B-F	1835	440	2.0	1.8	640	469 – 803
Catterini (C)	GB.O.ub.496	B-F	1838	448	2.2	2.1	710	627 - 1187
Maino (C)	B.B.mim.0941	B-F	1840	435	2.7	1.9	930	621 – 935
Sax (B♭)	B.B.mim.2601	S-F	1840	440	2.3	1.5	780	664 – 745
Sax (B♭)	B.B.mim.0175	S-F	1840	440	2.1	2.7	810	700 – 779
Stengel (B♭)	B.B.mim.0943	B-F	1855	442	2.6	2.0	760	514 – 1108
Stengel (B♭)	I.F.ga.1988/170	B-F	1860-80	440	2.2	1.7	765	506 – 1129
Stengel (B♭)	GB.E.U.4932	S-F	1880	440	1.4	1.1	980	788 – 1098
Kruspe (B♭)	CH.B.hm.1999-136	H-B	1865-75	440	2.7	0.9	945	849 – 1142
Kruspe (B♭)	D.LE.u.4479	S-F	1865-75	440	1.1	0.8	970	784 – 1036
Heckel (A)	GB.Warwick.bowen	S-F	1910	440	0.7	0.8	940	640 – 937

The tonehole cutoff frequency variation is striking. This was obtained consistently from the calculated impedance maps, by noting the frequency at which the values of the third resonance (which should align with the fifth harmonic) stop increasing and become a constant frequency. This is useful since the cutoff is a band rather than a single frequency and

[34] Randel, Don Michael. 'Temperament', *The Harvard Dictionary of Music*, 837.

does vary with the resonance number and hence with the fingering. This is strongly demonstrated for the Maino B.B.mim.0941, where the cutoff seen for the seventh harmonic (fourth resonance) is only 430 Hz, but the third and fifth harmonics align quite well with resonances up to about 900 Hz. Nevertheless it is clear that the onset of cutoff is systematically lower for the bassoon-form bass clarinets than for the straight form instruments, and this is the largest single difference between the forms.

It is interesting to compare these values with those that are calculated theoretically. Benade's approximate formula[35,36] for an open tone-hole lattice is

$$f_c = 0.11c\left(\frac{b}{a}\right)\left(\frac{1}{sl}\right)^{1/2}$$

where f_c is the cutoff frequency, c the speed of sound, a the pipe radius, b the hole radius, s the hole spacing and l the acoustic length of the holes. We see that a high value of cutoff is obtained by decreasing the bore a, increasing the size of the holes b, and decreasing the length of the holes (the chimneys), l. The hole spacing s will be largely similar in instruments of the same tonality. It is certainly the case that bassoon-form instruments are physically bulkier in both butt and wing joints. This leads to higher values of the chimney length, l, especially in the wing joint where diagonal holes are drilled through the wing to reach the correct positions for the tone holes yet keep them within reach of the fingers. Bassoon-form instruments often also have more fingerholes that are open (not covered by keys), leading to small values of b, since fingers cannot cover large holes. Either type of instrument can have large or small bore radii, a. However, we cannot see the variations along the instrument very easily from Benade's formula, which is explicitly derived from a consideration of a uniform tone-hole lattice. Real clarinets usually have both hole sizes and spaces increasing as one moves further away from the mouthpiece. The simple formula cannot properly be applied in such cases.

It is likely that the first two open holes are the most important in considering the frequency cutoff, since intensity will be lost by radiation through tone holes and by wall losses as the waves progress down the instrument. Moers and Kergomard[37] have addressed this problem and proposed that one may consider a local cutoff; this is equal to the resonant frequency of a cylinder of length 2d enclosing two open tone holes spaced d apart, with the two tone holes acting as necks: essentially a Helmholz resonator with two necks. Their expression for the local cutoff frequency of a pair of holes (their equation 16) can be rewritten as

$$f_c = \frac{c}{2\pi a}\sqrt{\frac{1}{2d}\left(\frac{{b_1}^2}{h_1} + \frac{{b_2}^2}{h_2}\right)}$$

where c is the speed of sound in air, a is the (constant) bore radius, b_1 and b_2 are the radii of the two holes and h_1 and h_2 are their corrected chimney lengths. The lengths are corrected by adding 1.6× the tone hole radius to its length, following Moers and Kergomard; the factor

35 Benade, *Fundamentals of Musical Acoustics*, 449
36 Wolfe and Smith, 'Cutoff Frequencies and Cross Fingerings in Baroque, Classical, and Modern Flutes.'
37 Moers and Kergomard, 'On the Cutoff Frequency of Clarinet-like Instruments.'

1.5 is used by Benade. Wall losses and the influence of pads are not taken into account in any of these models, so they must be regarded as approximate.

Figure 8.49 shows the results of the Moers-Kergomard equation for the bassoon-form and straight-form instruments, respectively. For ease of comparison, only the 'main' holes, I, II, III, IV, V, VI and F/C are used for this calculation. A sense of how the cutoff varies down the instrument is obtained. The bassoon-form instruments are generally lower in cutoff than the straight-form basses, and also show a significant dip at the hole pair III-IV. This is at the join between wing joint and butt, at which the instruments often show a small hole IV with a thick wall, and usually a greater hole separation than elsewhere because of the large tenon into the butt. These are absent or much less prominent on the straight form instruments. Thus the minimum at hole III is a consequence of the bassoon-form construction, both from its narrow diagonal hole and also its larger than average spacing to hole IV, the other side of the heavily-constructed butt-to-wing joint.

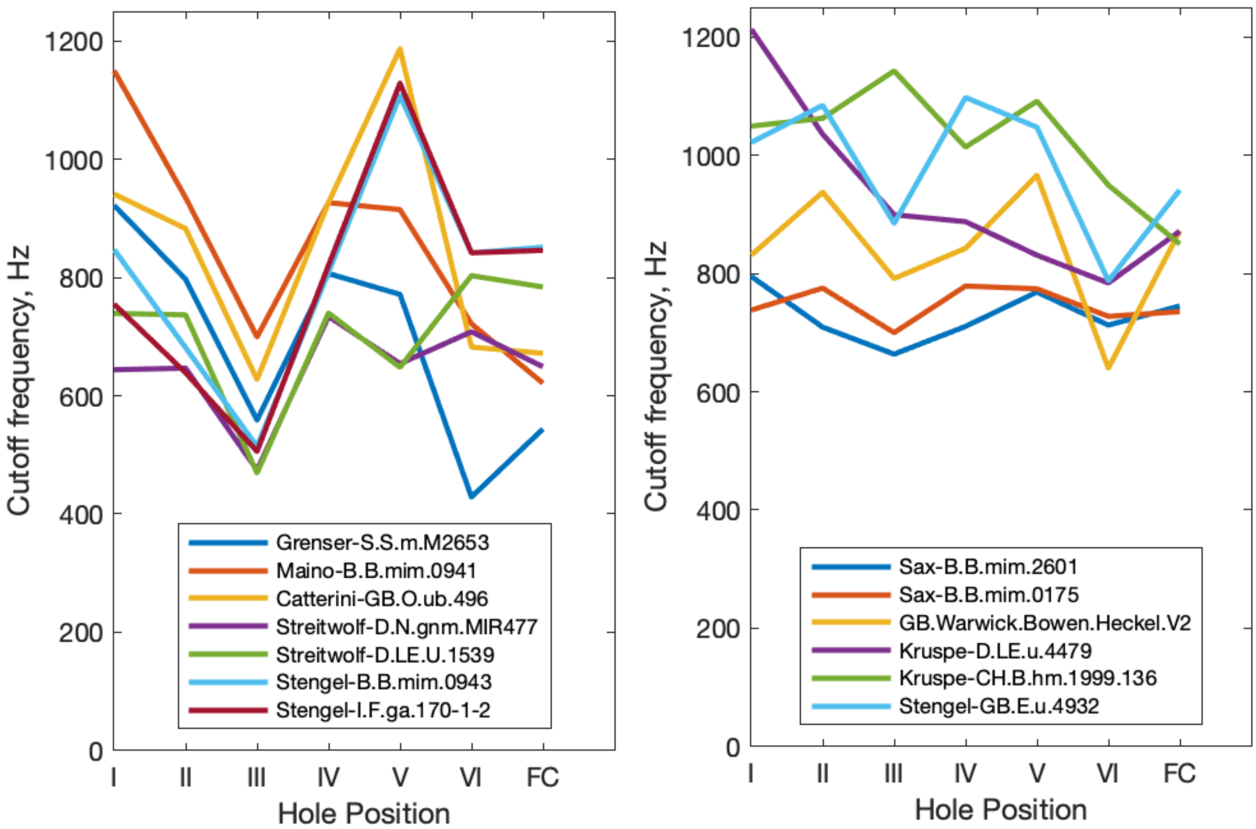


Figure 8.49. Calculated cutoff frequencies for (a) bassoon-form bass clarinet; note that the Maino and Catterini are in C, (b) Straight form bass clarinets (including Kruspe CH.B.hm.1999.136); note that the Heckel is in A. The frequencies are calculated for the pair of holes beginning with the hole labelled on the x axis.

Table 8.2 shows, in addition to the cutoff frequency at the third resonance, the range of cutoff values derived from the Moers-Kergomard equation (excluding the values for hole I). The ranges are quite wide and the best that can be said is that they are approximately consistent with the values derived from the impedance maps. We do know from the analysis in Chapter

6 that the computed and experimental impedance maps agree very well, provided that the tone holes are not heavily undercut.

It therefore cannot be said that there is a single cutoff frequency for each instrument. Benade found from direct measurements of impedance spectra that the trend in woodwind design over about 200 years was that makers modified their designs so that cutoff frequencies generally became approximately constant from top to bottom of the instrument.[38] He described this process as an 'evolution'.[39] What we are seeing in these bassoon-form instruments is the beginning and intermediate stages of this process. Moreover, it can be said that the single largest step in the process in bass clarinets as a whole was the straight-form design of Adolphe Sax. Not only did Sax's instruments have better intonation and temperament than their bassoon-form contemporaries, but they had much more even and higher cutoff frequencies. The development after Sax, especially in German-bore instruments,[40] was primarily in making the intonation still more accurate and the cutoff frequency still higher. I next examine how this was achieved.

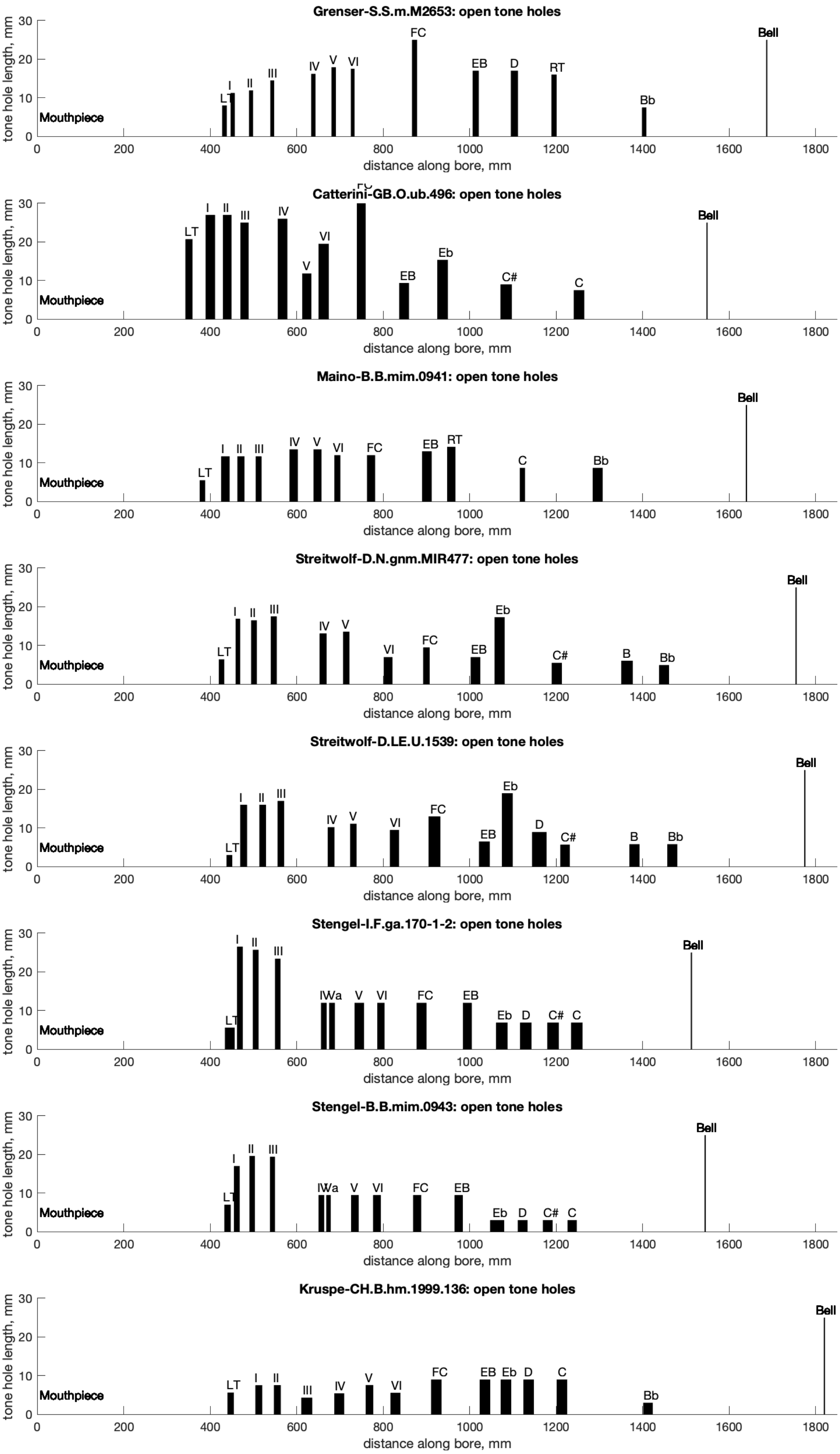
The hole distributions, lengths and diameters for bassoon-form and straight-form instruments are shown in Figures 8.50 and 8.51. In these diagrams, the open tone hole positions are plotted along the instrument. The height of the lines is equal to the actual length of the tone holes, and their thickness is proportional to the diameter of the holes (at a magnified scale compared to the positions). These plots were also found useful in determining the notes emitted by each hole when studying the instrument. Note the different layout of the Kruspe bassoon-form instrument from the others of this form.

Figure 8.50 (next page). Map of tone hole positions, chimney lengths and hole diameters for bassoon-form bass clarinets. Note that the Kruspe is also plotted in the next figure, and also that the Maino and Catterini instruments are in C but the others are all in B♭.

[38] Benade, *Fundamentals of Musical Acoustics*, 435, 465 ff.

[39] A.H. Benade and S. N. Kouzoupis, 'The Clarinet Spectrum: Theory and Experiment'.

[40] I have not examined or computed the spectra of later French–bore bass clarinets.


Grenser-S.S.m.M2653: open tone holes
Catterini-GB.O.ub.496: open tone holes
Maino-B.B.mim.0941: open tone holes
Streitwolf-D.N.gnm.MIR477: open tone holes
Streitwolf-D.LE.U.1539: open tone holes
Stengel-I.F.ga.170-1-2: open tone holes
Stengel-B.B.mim.0943: open tone holes
Kruspe-CH.B.hm.1999.136: open tone holes
tone hole length, mm
distance along bore, mm
Mouthpiece
Bell

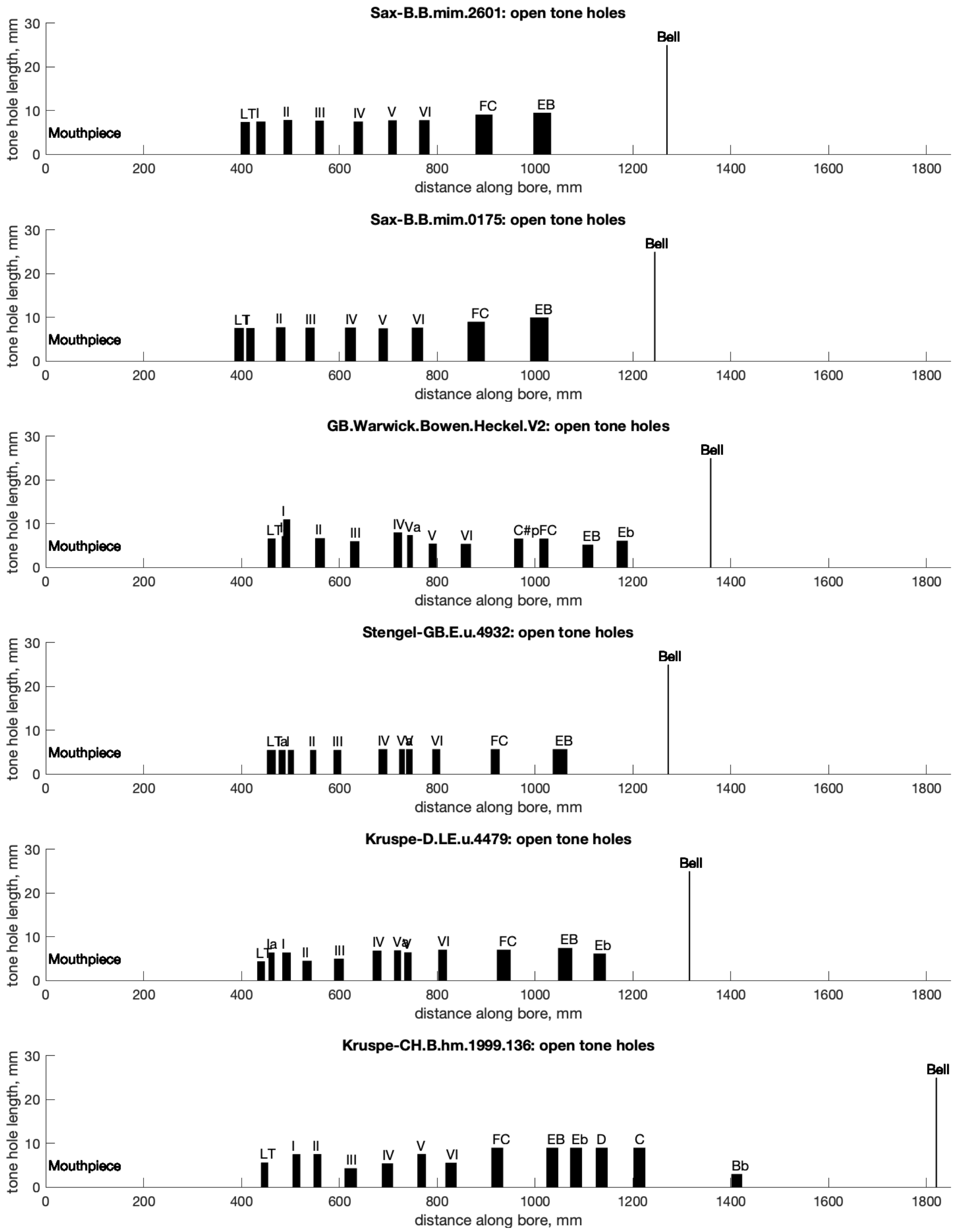


Figure 8.51. Map of tone hole positions, chimney lengths and hole diameters for straight-form bass clarinets. The Kruspe CH.B.hm.1999.136 has been included in this set of data and is seen to be quite similar to the same maker's straight model. Note that the Heckel model is in A, hence proportionately longer than the others, which are all in B♭.

It is clear at a glance that, with the exception of the Kruspe bassoon-form,

- The bassoon-form instruments as a group have longer tone holes;
- The bassoon-form instruments have narrower tone holes;
- The bassoon-form instruments all have atypically large spacings between holes III and IV, but none of the straight-form instruments does;
- Straight form instruments have relatively evenly-spaced, shorter and wider tone holes;
- There is a trend with date in the bassoon-form instruments to make the tone holes shorter, wider and more evenly spaced, thus approaching the design of the straight form.

All of these features have similar effects: to make the straight-form instruments higher and more regular in their cutoff frequencies. There is therefore a significant acoustic difference between these two forms. It is also evident that the sounding length of an instrument on its own is not adequate to infer the tonality. One also needs to know the lowest note and, more subtly, the width of the bore and its profile near the bell. Although the primary influence on the pitch of a note is the length of the air column, the *sounding* length is subject to an end correction which depends also upon the bore width; the correction is larger as the bore size increases.[41] There is also a much larger correction that depends on the shape of the bell, for which there is no simple formula; qualitatively, the effect of the bell is to make the instrument acoustically significantly longer than its physical length. This is accounted for numerically in the computer program used. Nevertheless, in the absence of detailed computer modelling, the tone hole maps in comparison with those shown below are a useful start for discovering the notes available on a certain instrument. It is noteworthy that there are mistakes in reputable sources in the literature in the assignment of notes and intervals for the so-called basset notes of a bass clarinet. Indeed, my own assignments before calculating the impedance spectra were not always correct.

The hole positions and sizes were developed empirically, at least up until the time that Sax developed his Law of Proportions, discussed in Chapter 2. Even he did not know, or reveal that he knew, about the full influence of tone hole sizes. Part of the empirical knowledge was that if a tone hole is drilled in a position that makes the pitch too flat, it can be corrected either by drilling or scraping it out to a larger diameter or undercutting the inner end of the hole; and conversely for a note that is too sharp. This is what the makers have done on the bassoon-form instruments. What has not been previously pointed out is that this practice will also affect the local cutoff frequency. From either the Benade or the Moers-Kergomard equation we see that the cutoff frequency is linear in the tone hole diameter b, but depends on the inverse square root of the interhole spacing, $2s$. Thus the tone hole diameter has a larger influence on the cutoff frequency than does the interhole spacing. Using the freedom to vary the position and the diameter of tone holes to correct intonation has concomitant effects on the cutoff frequency. It may therefore make notes blaring or muffled. In contrast, a design in which cutoff is designed and controlled (theoretically or empirically) in addition to intonation leads to instruments with the most uniform sound throughout the range.

We also see that the straight forms are more equal in cutoff across the range of holes. The comparison between the Stengel bassoon form and the same maker's straight form is quite marked, with the straight-form instrument having a higher cutoff almost everywhere. The exception is the Kruspe bassoon form, which has similar or higher cutoff frequency than the Kruspe straight form, and its hole length and distribution is similar to the latter. Examination of the Kruspe, however, shows that its construction is actually that of a straight form in most respects (see Chapter 7). It does not have the broad wing joint or the bulky butt joint typical of the bassoon form. Instead it has two cylindrical tubes, which plug in to a very short butt

[41] Fletcher and Rossing, *The Physics of Musical Instruments*, 200. The correction is approximately 0.3 times the bore diameter.

that simply suffices to fold the instrument for a more compact form; the butt only contains one keyhole, F/C, which is constructed so that it has very similar chimney length to those in the main tubes. The only real acoustic difference between this and a regular straight instrument is the presence of the two end-volumes between the transverse hole between the bores and the cork bungs at the end of the butt. These have been treated in the computations as permanently closed holes. The effect of closed holes has been discussed and modelled quite extensively in the acoustic literature.[42] Their effect is to increase the effective volume of the segment in between holes. It is simple to correct their effect on intonation by the placement of the tone hole on the downstream side of the butt, and to adjust this correction by the depth of insertion of the cork bungs. This provides an acoustic rationale for the practicality of the traditional butt joint. The Schediwa instrument with this construction was found to play equally well for notes emitted on both sides of the butt joint (Chapter 7); and this was the normal construction for the very successful baroque bassoon.[43]

The discussion and images in Chapter 7 showed that it is the kinks in the crook and bell of the Kruspe that enable the use of plain tubes to be used instead of the bulky joints with long tone holes seen in most of the other bassoon-form bass clarinets. This design is quite extraordinary, and in a sense is the pinnacle of the bassoon-form designs. We see that it is very likely that the maker was aware of the acoustic properties of straight-form designs and short tone holes and succeeded in making an instrument that was folded and compact, yet incorporated this advance. The intonation drifts flat in the upper part of the lower register; the only explanation for this is that the holes for the left hand are not quite in the correct places. Conceivably this might have been modified by the kinks and bends in the crook and bell, since these will have a frequency-dependent and (usually) flattening effect, or by undercutting some tone holes, but such effects have not been taken into account in the present calculations.[44] The straight-form Kruspe discussed earlier is, however, a very well-tuned and well-aligned instrument with a high cutoff frequency.

It should be noted that the Kruspe folded instrument is very close to the ophicleide design; indeed an ophicleide-form instrument attributed to Kruspe is illustrated in Chapter 7. The short butt joint is simply replaced by a U-tube; see also the discussion of the Losschmidt instruments in Chapter 7. Catterini, De Azzi, Losschmidt and other makers avoided the complexity of the Kruspe design by keeping the two tubes side by side but providing key linkages or extensions to allow the fingers to operate the pads covering the tone holes on the down tube. These holes are correctly placed and sized and have fairly short chimneys. As confirmed in a short playing test, discussed in Chapter 7, the ophicleide form is a very good acoustic design. It is also compact, and would have satisfied both band and orchestral playing. The reminiscences of J.H. Maycock, quoted and discussed in chapter 3, show that both he and

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[42] e.g. A. H. Benade, 'On the Mathematical Theory of Woodwind Finger Holes,' *J. Acoust. Soc. Am.* 32 (1960) 1591–1608. https://doi.org/10.1121/1.1907968; Keefe, 'Theory of the Single Woodwind Tonehole.'; Nederveen, *Acoustical Aspects of Woodwind Instruments (Revised Edition)*, 54.

[43] Mathew Dart, "The Baroque Bassoon: Form, Construction, Acoustics, and Playing Qualities" Vol. 1, viii

[44] Nederveen, *Acoustical Aspects of Woodwind Instruments (Revised Edition)*, 118; Félix, Dalmont, and Nederveen, 'Effects of Bending Portions of the Air Column on the Acoustical Resonances of a Wind Instrument.'

Lazarus were happy to use what was possibly an ophicleide instrument in operatic performances till late in the nineteenth century. The form did not appear to become popular for general use, and disappeared in the early twentieth century. It would probably have been significantly more expensive to build than the straight form, and little orchestral or operatic music then required notes below E♭2.[45] It does survive to this day in the contralto and contrabass forms, for which straight forms are impractically long.

One final reminder must be made regarding the impedance computations: they all use equations that were derived and confirmed under small-signal conditions, that is, *pianissimo* playing levels, or, put another way, linear acoustics. These are certainly accurate enough to calculate impedance spectra with considerable accuracy, and the consensus in the literature is that it is adequate to use linear acoustics for this purpose. However, the linear instrument body is coupled to a highly non-linear oscillator in the system comprising the reed and mouthpiece. The mathematics of this system become extremely complicated and are beyond the scope of this thesis. However, some generalisations and qualitative conclusions may be drawn, and have already been reviewed in Chapter 6.[46]

- At very low blowing pressures the reed vibration is small and the sound is close to a pure sine wave with frequency close to that of the lowest impedance peak.
- At higher blowing pressures, the reed oscillates at multiple frequencies; these must be harmonically related once the initial transient is passed and a steady tone is produced.
- The oscillations ‘cooperate’ with the resonances in the instrument. If the harmonic components are aligned with the frequency of the first resonance then there is strong feedback to the reed and the oscillation is stabilised at this ‘set of fundamental-and-harmonic’ frequencies.[47] This phenomenon is known as *mode locking* or *phase locking* and has a major effect on the intonation of the instrument and its stability.
- If, the resonances are not quite aligned, then the feedback may be strengthened by shifting the fundamental frequency slightly to maximise the contribution from higher resonances. Since harmonics will increase in amplitude with air pressure (a principle of non-linear systems) the intonation may change either way as the volume is increased.[48]

To get a more accurate model of the sound produced by an instrument, the non-linear mathematical problems and the dynamics of the mouthpiece must be solved. This has not been attempted in the present project, though it should be noted that substantial progress has been made in this field by Pierre-André Taillard and his colleagues.[49] Nevertheless, the

[45] Bowen, *The Rise and Fall of the Bass Clarinet in A*, 2011.
[46] Benade and Kouzoupis, ‘The Clarinet Spectrum.’; Benade and Gans, ‘Sound Production in Wind Instruments.’; Nederveen and Dalmont, ‘Mode Locking Effects on the Playing Frequency for Fork Fingerings on the Clarinet’; Worman, ‘Self-Sustained Nonlinear Oscillations in Clarinet-Like Systems’.
[47] Called by Benade a ‘regime of oscillation’.
[48] Note however, that the increased opening of the reed used for louder playing will give an additional impedance change that tends to flatten the pitch in a clarinet as blowing pressure increases.
[49] Pierre-André Taillard, Fabrice Silva, and Philippe Guillemain, ‘Simulation En Temps Réel de l’impédance d’entrée Mesurée Ou Calculée Des Instruments à Vent’; Taillard and Kergomard, ‘An Analytical Prediction of the Bifurcation Scheme of a Clarinet-Like Instrument.’; Pierre-André Taillard, Thomas Hélie, and Joël Bensoam, ‘Numerical Computation of the Transfer Functions of an Axisymmetric Duct with the Extended Discrete Singular Convolution Method,’ in Proc.ISMA 2014. Leuven: Katholieke Universiteit Leuven - Departement Werktuigkunde, 2014.

starting point for those calculations and models is the input impedance spectrum, either measured or calculated as in this chapter. Not only does the impedance spectrum provide the fundamental data for further research, but, as shown in this chapter, it allows both quantitative and qualitative information to be deduced on the acoustical and musical behaviour of instruments and their development; in this case we have seen development over more than a century of progress in instrument design and manufacture.

Concluding remarks

In the analysis of impedance spectra we indeed see the 'evolution' of the acoustical properties of the bass clarinet over the long nineteenth century (1793 – 1914). The bassoon-form instrument proved remarkably useful and was widely adopted, maintaining its presence in military and civil bands long after it had been discarded for Art music. Over the century, improvements in design allowed improvements in intonation and in cutoff frequency in both forms. The greatest single step was the introduction and adoption of the straight-form, due to the technical innovations of Adolphe Sax. However, the bassoon-form kept its place in military and civil bands despite its likely higher cost. The sound would have been less distinctive but may well have blended better with brasswind basses, a clear objective for the sound of a band. On the other hand, the ability to keep an optimum spacing of toneholes, uniformly short tonehole chimneys and large diameter toneholes is the characteristic of straight-form instruments that I believe made them acoustically preferable for Art music, displacing bassoon-form inctruments for this purpose and ensuring their survival to the modern day.

Chapter 9

Conclusions

The story of the bassoon-form instrument unfolded in Central Europe: German, Italian, Austrian and Czech lands, mainly under the Kingdoms of Saxony and Bavaria, the Austrian Empire Kingdoms of Austria itself, Lombardy, Bohemia and Moravia and in small contiguous states also belonging to the German Confederation. There are very few makers known outside these regions in Europe. There was a significant and productive independent grouping of makers in New England, USA, but unfortunately, this did not give rise to a continuing American tradition.

The history of the bass clarinet has been characterised and illustrated in this thesis, from the earliest attempts to modern times. The two forms that have been outstandingly successful and made in large numbers have been the bassoon form and the straight form. The straight form has now displaced all rivals. The bassoon form and its variants, however, was made in significant quantities from the late eighteenth to the early twentieth centuries, and extant examples are collected and classified in a new database. An improved sub-classification has been proposed for the structural variants of the bassoon-form bass clarinets based upon the understanding of their acoustical properties developed during these studies.

Contemporary literature shows that from early in the nineteenth century there was competition between the bassoon form and the slightly later straight form, reinvented and championed by Adolphe Sax, whose design eventually dominated the Art music scene.[1] The folded rivals disappeared completely by early in the twentieth century, except for the very large contraalto and contrabass instruments, which are still made only in folded (ophicleide) form. But the two forms of the bass clarinet coexisted for more than 70 years, so it is clear that each design found a substantial niche for which it was deemed preferable. It has been shown that, with few exceptions, the straight form dominated in Art music from the middle of the nineteenth century but that the bassoon form at least maintained its popularity in wind and military bands, despite the higher cost that the more complex form must have incurred.

In surveying the repertoire, I am confident that at least the great majority of compositions for bass clarinets in operatic and orchestral music in the nineteenth century have been found and evaluated.[2] In the period from about 1830 to 1850 there was a flowering of remarkable virtuoso obbligati for the bass clarinet in both operatic and chamber music from Neukomm, Mercadante, Viviani, Meyerbeer and Verdi. All of these composers except Meyerbeer clearly wrote for the bassoon-form instrument with its greater low range, and made good use of it to set the dramatic and emotional context. At the same time there was rapid initial adoption by military bands, using mainly the bassoon-form instruments of Streitwolf, Catterini and their followers in German and Italian lands respectively. The adoption of the bass clarinet in Art music was a case of gradual, but inexorable penetration. The utilisation of the bass clarinet by

[1] e.g. François-Joseph Fétis, *Revue Musicale* 8 (June 5, 1834) 329.
[2] e.g. Jensen and Piperno, *The Opera Orchestra in 18th and 19th Century Europe*.

Richard Wagner in all of his operas from 1845 onwards established this trend but also changed its mode of use. He did not write the spectacular solo *obbligati* seen in earlier works, even though the bass clarinet by then was much more capable of playing them. Indeed, such *obbligati* seem to have largely disappeared from the operatic literature around that time. Instead, Wagner's solo writing for the bass clarinet focussed on the instrument's tonal quality and its ability to set atmosphere, This may be melancholy or sinister, as in the scene where King Mark realises Tristan's betrayal in *Tristan und Isolde*; or hopeful, as in the scene in *Siegfried* in which the hero awakens Brunnhilde. But also, the trends in the nineteenth century, beginning with Parisian Grand Opera, for larger and louder orchestras with extended tonal colouration, and for larger opera houses and concert halls, suited the bass clarinet perfectly. It is easily the strongest orchestral bass woodwind instrument and also the one with the greatest dynamic range. Its use was a natural consequence of the development in size, volume and diversity of instrumentation of the whole orchestra. The works of Ferenc Liszt, Richard Strauss and Gustav Mahler, all of whom used the bass clarinet extensively and thoughtfully towards the end of the century, spring to mind.

There is not the same degree of confidence in the preservation of chamber, recital and small ensemble works despite the impressive early work by Neukomm. Very few have been preserved, which contrasts with quite frequent local press reports about chamber concerts and recitals that included bass clarinet players. The likely explanation appears to be that, with a few exceptions, these were not original works but arrangements made by the players, which would not normally have been published. This remained the case until the twentieth century, when chamber works using the bass clarinet began to appear.

The evidence of repertoire is also limited in the case of bands, both civic and military. It has been seen that it was the norm for bands to perform arrangements and not original works except for the case of marches. Since there was *no* standard instrumentation for either the military or civic bands in the nineteenth century, it was not even possible for a significant market in arrangements to exist.[3] It was the norm, and comprised part of their training, for bandmasters to arrange works for their own band, and there was very little incentive to publish these arrangements.[4] There is a small number of published works but it is certain that our knowledge of the use of the bass clarinet in military and especially in civic bands is seriously lacking. However, there is much scope for further research in local town archives (such as the one for Persiceto, Italy),[5] which will be widely distributed around Europe. Mandel's informative writing about band orchestration, however, points to the value of the bass clarinet as being to improve the blend of the bass instruments such as the bombardons and to form a more powerful bass instrument than the bassoon. His complaint about the German (bassoon-form) bass clarinet is that it is not still more powerful. It is clear that he did not think of the bass clarinet as a solo instrument, but as a valuable ensemble instrument in

[3] Whitwell, *The History and Literature of the Wind Band and Wind Ensemble: 5. The Nineteenth-Century Wind Band and Wind Ensemble*; Herbert and Barlow, *Music and the British Military in the Long Nineteenth Century*.
[4] Herbert and Barlow, 190.
[5] Valentini, "L'Orchestra a San Giovanni in Persiceto e Le Istituzioni Musicali Dell '800."

the band. For this purpose the lower cutoff frequencies of bassoon-form instruments, which result in what clarinettists term a 'dark' or 'less bright' sound,[6] would be important.

Since bassoon-form instruments are found in museums across Europe in significant numbers, totalling over 80, with dates of manufacture throughout the century, I conclude that the bassoon-form instrument was indeed in considerable use in both military, civic and church bands throughout the century. The direct evidence of band use must be a considerable underestimate. Since the cost of a bassoon-form instrument must have been significantly higher than that of a straight form, this choice must have been based upon its higher suitability for the band role. I have suggested that this was due to

- the greater lower range, providing better musical support for the other bass instruments;
- the tonal properties that blended with and supported the lower brass;
- the compact form of the instrument for marching;
- the appearance with a polished upright bell that matched the smart appearance of the brass in a formal band display.

A main aim of this research has been to understand and to evaluate the evidence of the large number of these surviving instruments, and to map their acoustic characteristics over the nineteenth century. Only a few of them were in a good enough condition to be played; whilst valuable insights were obtained from playing or listening to performers on restored original period instruments, these insights had to be examined and assessed.

The terms 'evolution' and 'development' have been used in this thesis, despite the concepts that they embody, and the Victorian ideas of linear progress from simple-to-complex and from imperfect-to-perfect, being generally unfashionable or even discredited in current humanities scholarship.[7] It is also evident that no single factor was responsible for the developments, which were the result of a 'network' that included makers and their agents, players, composers, concert halls, critics and audiences. However, the case of the bass clarinet is very specific. There was no change in the essential acoustic 'Simple' pattern of tone holes in either form of the instrument; some small holes and mechanisms were added to improve the intonation and player convenience. All of the musical and technological drivers are common to both forms of the instrument current in the nineteenth century. I suggest that these drivers were:

- The competition between makers for the custom of players;
- the demands of the market, especially
  - the large military band market
  - the professional public and court opera and orchestra market;
- the demands of composers, especially when there was personal contact between composers and makers (e.g. Berlioz and Sax);

[6] Benade, Fundamentals of Musical Acoustics, 486

[7] Bennet Zon, *Representing non-Western Music in Nineteenth-Century Britain*. Rochester, NY: University of Rochester Press, 2007. ———. *Evolution and Victorian Musical Culture*. Cambridge: Cambridge University Press, 2017. But note that the Imperial Victorian outlook was not necessarily relevant to the bass clarinet, since none of the innovations in the bass clarinet originated from the UK during this period.

- The demands of players, again especially where there was a specific collaboration with a maker.

One may also identify the musical aims of the process, partly from musical principles and partly from the analysis of what actually happened as judged from the acoustic analysis:

- Better and more even intonation over the range of the instrument;
- Better uniformity of sound across the range, judged from a more uniform cutoff frequency across the range;
- Better stability and quality of the tone, judged by the number of harmonics contributing to the cooperative regime of oscillation of the reed;
- Greater volume, to suit military displays, and larger concert halls.

In this context the use of the word 'development' is quite justified. It is similar to the use of the term in the 'Research and Development' department of a science-based industry, which itself has some analogues with musical instrument development.[8] 'Evolution' is more problematic, since it has associations with Darwinism and natural selection, which were not relevant. However, it is frequently used, for example by Benade, as a summary of the results of the process that occurred in woodwind instruments in general over approximately two centuries.[9]

The first task in the research was to catalogue and to classify the extant instruments in museums, from museum catalogues and personal visits. The instrumental characteristics such as pitch, range of notes, and number of keys, where these data are reported, are included in the database and form a ready reference. Where possible, bore diameters are also included, since the acoustic work showed that this parameter has greater importance than has normally been appreciated. The examination of a large number of instruments also allowed the geographical distributions to be observed and assessed.

Approximately one-third of extant folded clarinet instruments in museums were examined in detail during the course of this thesis. The small numbers of folded alto clarinets, basset horns and soprano clarinets provide interest and context to the main theme of bassoon-form bass clarinets. The playing tests and analysis of performances gave valuable information about the pitch, accuracy of intonation and temperament, sound quality and in particular the dynamic capabilities of a selection of instruments, and have indicated qualitatively how these correlate with the bore and flare dimensions. A critical examination of tone hole positions has suggested alterations to the fingering assignments made in the literature in some cases, which were subsequently confirmed by quantitative acoustic modelling. Inspection of the geometric design of the keywork has indicated a new assignment of one instrument: D.N.dm.46262, proposed as a prototype model by Johann Simon Stengel or his workshop.

Two general trends are evident:

- Makers were slow to apply the Boehm system of keywork (first fully released by Buffet in 1850 for the soprano and 1855 for the straight-form bass clarinet) to the bass clarinet. It

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[8] Emily N. Dolan, 'Seeing Instruments'. *Journal of the American Musical Instrument Society* XLIV (2018) 33–40; Karin Bijsterveld and Peter Frank Peters (2010) Composing Claims on Musical Instrument Development: A Science and Technology Studies' Contribution, Interdisciplinary Science Reviews, 35 (2010) 106-121. https://doi.org/10.1179/030801810X12723585301039

[9] A. H. Benade and S. N. Kouzoupis, 'The Clarinet Spectrum: Theory and Experiment'.

was never applied to the bassoon-form instrument and was not applied to any of the straight forms considered in this thesis.
- Art music for operas and orchestras appeared to use almost exclusively the straight form instrument down to E2, in C, B♭ and A tonalities from about 1850. But the bassoon-form instrument was made in significant quantities in the period 1850 – 1900 and even beyond and enjoyed significant developments in this period, notably by Kruspe. This reinforces the conclusion that they were used primarily in bands and outdoor music, for which they are well suited, and even arguably preferable.

After the descriptive observations included in the database or in the observations in Chapter 7, the method chosen for the assessment was the modelling of the acoustic properties of the instrument by careful geometric measurement and computer modelling of their impedance spectra. A new computer program was written to implement the known acoustic equations and to extend the means of analysis and interpretation. The computational model is based on small-signal, linear, plane- and spherical-wave acoustics with viscous and thermal losses at smooth walls. It does not take account of some loss mechanisms such as wall porosity, internal tone-hole edge turbulence and finger and pad resilience, nor of undercutting of tone holes. The results of the computations are a series of impedance or resonance spectra for each note of the instrument. These inform us about the intonation, pitch, temperament, tuning and the fingering of each note, and give some indications of timbre.

In order to be able to rely on these results, despite the known drawbacks, a detailed verification study was made on a high-quality straight-form instrument by Heckel from 1910, which had been kept continuously in playing condition since manufacture. The outcomes of the computer modelling were quantitatively compared with two sets of experimental measurements:

- the measured impedance spectra for each note using calibrated acoustical equipment.
- audio recordings of sustained *mf* notes played on each note of the instrument.

The results showed an accuracy before any correction of *c*.50 cents in the predictions of the pitches of the notes, which is reduced to less than 10 cents by some calibration and embouchure corrections. Alternative fingerings can easily be examined and were verified by playing tests. I therefore demonstrated that this method was sufficiently accurate to be used for assessment of historical instruments that could not be played, but were complete and in good enough condition for their dimensions to be measured accurately. The method is certainly accurate enough for the purpose of reconstructing and comparing the acoustic impedance (resonance) spectra of a set of instruments of this type. This has not been done before for any type of clarinet and has only once been attempted for a large set of historical instruments: the case of baroque bassoons.[10] However the detailed experimental confirmation of the acoustical modelling is novel. The work was peer-reviewed and published in an acoustics journal.[11]

[10] Dart, 'The Baroque Bassoon: Form, Construction, Acoustics, and Playing Qualities.'; Bryant Hichwa and David Rachor, 'In-Depth Acoustic Modeling and Temperament Studies of 18th and Early 19th Century Baroque Bassoons'.

[11] Bowen et al. 'Assessing the Sound of a Woodwind Instrument That Cannot Be Played.'

The calculation of resonance peaks has utility in instrument design, restoration and modification as well as in historical research. Playing problems with a particular instrument may also be diagnosed. The calculated impedances could also indicate how to alter a tone hole to improve the tuning, and what effect this would have on other notes. The method of acoustic impedance modelling has therefore been quantitatively validated as a research tool for investigating and restoring both historical and modern bass clarinets.

The measurement detail required is, not implausibly, similar to the detail one would need in order to make a reproduction of the instrument and is quite time consuming. Thus it could not be performed on all instruments (which were widely distributed across Europe and the USA) but a set of thirteen instruments was chosen to answer critical questions about instruments that were key to the development of the bass clarinet, from the earliest example of 1793 to the mature orchestral instrument of 1910. In the analysis of impedance spectra we see the history of the acoustical properties of the bass clarinet over more than a century.

Such analysis was greatly facilitated by the development of the impedance map as a means of showing the information contained in tens of thousands of individual calculations in one single diagram. From an impedance map one may see at a glance the consistency and accuracy of intonation of both registers of the instrument, the number of harmonics that are aligned with the resonances (impedance peaks), notes that have rogue intonation or timbre and the cutoff behaviour for all notes.

The earliest instruments showed functionality, a wide range and a reasonable alignment of harmonics (the feature that gives stability and fullness to the tone) but clearly were limited prototypes with some notes missing, variable intonation across the registers and in some instruments a poor alignment of the registers (often showing wide twelfths). These defects were gradually ironed out over the century but more rapid progress was made once the straight form was introduced by Sax. The original Sax Brussels instruments were very good in the first register, but went progressively sharper in the upper register indicating that much correction would be needed by the player. The additional register key proved vital for improving the intonation at the lower end of the second register, and it was shown that it is the lower register key that is significant in this respect. It would be interesting to examine a later example of the Sax bass clarinet in similar detail. However, the straight-form examples by Kruspe and Stengel from 1870 – 1880, as well as the Heckel instrument of 1910, showed excellent intonation and harmonic alignment, which were superior to the contemporary bassoon-form instruments by each maker.

It is probable that the bassoon-form instrument could have been developed further in respect of its intonation over the whole range, and this might even have been achieved in instruments yet unexamined. However, it is unlikely that the harmonic alignment could have been much improved. A significant and systematic difference was found between the two classes of instrument, namely, the cutoff frequency, the frequency at which vibrations are not reflected at the first open tone hole but pass through to the bell. They then do not contribute to the standing waves that form the note that is sounded, and instruments with a lower cutoff frequency will necessarily have a more limited number of harmonics that contribute to the timbre and stability of the note.

The cutoff frequency is known to be controlled by the bore diameter and the geometry of the open holes below the fingered holes. It increases with increasing tone hole diameter, decreasing bore diameter, decreasing chimney length of the tone holes and decreasing tone hole spacing. To some extent the maker has freedom to adjust the tone hole diameter to compensate for a designed or accidental variation in spacing. If a note is sharp, it can be lowered in pitch by lining the inside of the first open hole, as is well known to makers and repairers. What has apparently not previously been noticed is that this operation also lowers the cutoff frequency; one cannot adjust intonation without also adjusting the timbre, and vice-versa.[12] Nor has it been previously observed that the bassoon-form bass clarinet has two structural features that each depress the cutoff frequency:

- The conventional bassoon-type wing joint with open holes necessitates the use of relatively long holes in order to fit the player's hand on the outside and the required tone hole positions on the inside of the bore.
- These holes must also be narrow enough to be covered properly by the players' fingers.
- The massive construction of the butt joint forces an inappropriately large spacing between tone holes III and IV on each side of the tenon.
- This construction also necessitates a somewhat longer tone hole IV.

These structural arguments are backed up by maps of the tone hole placements and dimensions in the thirteen instruments measured. Calculation of the cutoff frequency from acoustic theory and by observation of the impedance spectra showed

- a general trend for increase in cutoff frequency with the date of manufacture;
- a jump in the average cutoff frequency for straight form instruments compared to those for bassoon forms;
- a general tendency for cutoff frequencies to be evened out from top to bottom of the instrument as time progressed, especially for the straight instruments.

These observations also imply that there would have been a difference in sound between the bassoon-form and straight-form instruments. Instruments with higher cutoff frequency have more harmonics contributing to the timbre, which plausibly leads to a more characteristic and more interesting sound, more recognisable and more suitable for solo passages. The means by which this was obtained was principally by increasing the tone hole diameters relative to that of the bore. This has the unavoidable concomitant effect of increasing the radiation from the tone holes, that is, making the instrument capable of being played louder. In view of the demands for higher dynamic ranges for military bands and large concert halls, this may have been a major driver in the development and acceptance of the straight form instrument. Conversely, the change in tonal quality may even have been perceived as undesirable for the wind band environment, leading to the extended retention of the bassoon form in that genre.

[12] A possible exception is the Schmidt Reform Boehm design by Ernst Schmidt and Fritz Wurlitzer. This has where possible double toneholes for each note, including those operated by keys, so that intonation and venting can to some extent be adjusted separately. However, this system has not been well studied outside the makers; no impedance spectra or cutoff data is available and acoustical information on it is mainly anecdotal.

This discussion provides both qualitative and quantitative foundations for Benade's insight that specifying the cutoff frequency is akin to specifying the personality of a woodwind instrument, and that instrument makers developed their instruments to have approximately constant cutoff frequencies from the top to the bottom of the ranges. What is seen in this study is the process and mechanism of this development. A significant conclusion is that the straight-form bass clarinet has acoustic characteristics that make it preferable to the bassoon-form instrument, *for certain purposes*. These include:

- A more individual and characteristic sound;
- A more even sound across the range of the instrument, with fewer blaring or muffled notes;
- The ability to play at higher dynamic levels (as well as preserving good *pp* playing).
- The ability to provide a more strongly-flaring bell because of the restricted lower range. This was taken advantage of by French-style makers following Adolphe Sax, resulting in more flexible tuning and a different sonority. German-style makers, however, retained the long cylindrical bore with minmal flare. This difference is retained to the present day.

These characteristics are well adapted to orchestral and operatic performance, especially as orchestra and concert hall sizes grew during the nineteenth century and probably account for the dominance of the straight form in Art music. However, they were not enough to prevent the use of the bassoon-form instruments in bands, for some 50 years after their discontinuation in the opera house and orchestra for Art music, for the reasons discussed above. They rarely played solo parts in bands, so the quality of the sound would be a secondary consideration; but I suggest that, because of their lower cut-off frequencies, bandmasters may have preferred the sound less rich in upper harmonics that is produced by the bassoon-form wing joint and the thick butt joint, in order to better match and supplement the low brasses. In bands, there was also a clear preference for straightforward, uncomplicated keywork, with the Boehm system appearing relatively rarely in the context of band instruments (and never, so far as is known, in bassoon-form instruments). This may have reflected both the rigours of army life on campaign, and the lack of need for an instrument that could play challenging and complicated solos.

In summary, a variety of methods has been devised in this thesis to understand the development and qualities of historical bass clarinets, using primarily the mode of construction of the instruments themselves. These have been complemented by contemporary reports on the instruments as they were invented, by study of the repertoire and musical scores in which they occur and by study of the context of their use. The major novel contribution put forward in this thesis is the acoustic analysis, which may be performed on any complete instrument that is not too fragile to handle. This gives much valuable and novel musical information.

What of the future? We may first expect metrology of the instruments to improve and to become much more rapid and convenient in the future with the more widespread availablity and use of accurate radiographic computer tomography, on either medical or industrial systems.[13] This has been inhibited in recent times by the direct and indirect effects of the Covid-19 pandemic but will surely resume, and an indication has been given in this thesis of novel and more economical systems that are becoming available. However, in contrast to its quite frequent and straightforward present use on instruments such as recorders, cornetti and early flutes, it is necessary to remove as much as possible of the metal keywork from clarinets in order to obtain good data from radiographic methods.

The acoustic analysis developed in this thesis is not yet a complete solution. Importantly, there is a lack of theory on the effect of undercutting toneholes. There have been advances in understanding of the theoretical treatment of tone holes since the equations used here were derived, but these have not yet been applied to the case of pad-covered tone holes, which are essential on the bass clarinet. The treatment of the mouthpiece by substituting an equivalent volume is demonstrably adequate to obtain the resonances of the instrument. However, every player and mouthpiece maker knows that adjustments of fine features in the mouthpiece, such as the shape of the baffle, can make substantial differences in the way the instrument plays. We are far from being able to model such fine features but there is every hope that the modelling, and most importantly its experimental confirmation, will significantly improve.

The observation of the number of harmonics that cooperate to produce the sound of every note has been used as an indication of the 'fullness' of tone that an instrument can produce. However, this is a long way from specifying its timbre in a quantitative manner. The specification, psychological evaluation and machine recognition of timbre is currently a very active area of research, in part driven by the recording and electronic synthesising industries.[14] It may eventually be possible to bring the study of timbre into the computerised modelling of an instrument by reconstructing the entire sound. Appropriate methods have been pioneered by Pierre-André Taillard and his associates, which involve also the more detailed non-linear treatment of the reed/mouthpiece generator.[15] However, the first step for that process is the

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[13] Bär, Frank, Theobald Fuchs, Rebecca Wagner, Gabriele Scholz, Christian Kretzer, Richard Schielein, Michael Boehnel, et al. 'Three-Dimensional Computed Tomography Scanning of Musical Instruments'. In Emanuele Marconi and Marco A. Pérez (Eds.), Wooden Musical Instruments Different Forms of Knowledge Book of End of WoodMusICK COST Action FP1302. Paris: Cité de la Musique - Philharmonie de Paris, 2018.

[14] e.g. Freya Bailes, 'Timbre as an Elusive Component of Imagery for Music,' *Empirical Musicology Review* 2 (2007). https://doi.org/10.18061/1811/24476. Bruno Gazengel, 'Caracterisation Objective de La Qualite de Justesse, de Timbre et d'emission Des Instruments a Vent a Anche Simple'. Docteur d'Université Thèse, Nantes, L'Université du Maine, 1994; Mathieu Barthet et al. 'From Clarinet Control to Timbre Perception,' *Acta Acustica United with Acustica* 96, (2010) 678–89. https://doi.org/10.3813/AAA.918322; Karl Jensen, 'The Timbre Model,' *J. Acoust. Soc. Am.* 112 (2001). https://doi.org/10.1121/1.4778881; Grégoire Carpentier et al. 'Predicting Timbre Features of Instrument Sound Combinations: Application to Automatic Orchestration,' *Journal of New Music Research* 39 (2010) 47–61. https://doi.org/10.1080/09298210903581566; Mathieu Barthet et al. 'Acoustical Correlates of Timbre and Expressiveness in Clarinet Performance,' *Music Perception* 28, no. 2 (December 1, 2010) 135–54. https://doi.org/10.1525/mp.2010.28.2.135; Tuomas Eerola, Rafael Ferrer, and Vinoo Alluri, 'Timbre and Affect Dimensions: Evidence from Affect and Similarity Ratings and Acoustic Correlates of Isolated Instrument Sounds,' *Music Perception* 30 (2012). https://doi.org/10.1525/mp.2012.30.1.49; Hassan Ezzaidi, Mohammed Bahoura, and Glenn Hall, 'Towards a Characterization of Musical Timbre Based on Chroma Contours,' in *Communications in Computer and Information Science*, 22 (2012) 162–71. https://doi.org/10.1007/978-3-642-35326-0_17 .

[15] P.-A Taillard and P Sanchez, 'Comparaison de Deux Clarinettes Séparées Par Deux Cent Ans d'évolution : Tentative d'hybridation Amusante et Instructive Entre Facture Instrumentale, Modèles Physiques et Synthèse

measurement or calculation of input impedances to sufficient accuracy. The work described in this thesis therefore offers this first step.

On a final note of humility I observe how impressive were the skills and insights of the instrument makers, who are still ahead of the acoustic analysts. With only a very limited scientific understanding of instrument acoustics available, they empirically improved the acoustic design of the bass clarinet from its rudimentary beginnings to the superb instruments available by the early twentieth century. These designs have since been improved in consistent manufacture and in design and quality of the keywork, but not substantially in their acoustic behaviour. It is remarkable that this process only took about a century; it can be enlightened, but at present not surpassed, by computer modelling.

Figure 9.1. The end of the line: the last known (half-) bassoon-form bass clarinet. Schediwa GB.E.u-4819, *c*.1910. Image from MIMO.

Sonore,' in *CFA 2016 / VISHNO*, 1777–83. Le Mans, France. Leuven: Katholieke Universiteit Leuven - Departement Werktuigkunde 2016; Taillard, Silva, and Guillemain, 'Simulation En Temps Réel de l'impédance d'entrée Mesurée Ou Calculée Des Instruments à Vent.'

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Appendix A

Matlab™ Codes – IMPEDV2

Running the codes

The IMPEDV2 program was developed from the FORTRAN IMPEDPS program discussed in Chapter 6. The computational part is mostly a straightforward port from FORTRAN to Matlab syntax, with replacement of the section dealing with the reed impedance with the length-equivalent embouchure correction described in Chapter 6. It has considerable novel additions, namely the graphical outputs that aid in the understanding of the instrument, using the powerful graphics tools in MatLab™; these are described below.

This program script requires a licence from MathWorks for MatLab™ to run, which is normally obtainable through a university. It was developed on version R2019b and currently runs on version R2021b. It may not run on earlier versions without some recoding. It requires the Signal Processing Toolbox as well as the basic code.

IMPEDV2 is designed to run in interactive mode. Data entry is at the beginning of the code and each input parameter is explained in a comment in the program as well as below.

- The following parameters should be entered as appropriate for the instrument. These do not affect the computation itself but affect the display of results on the impedance maps and their interpretation.
    - PITCH : e.g. 440 ; the value in Hz of the tuning pitch. This controls the equal temperament frequency value chosen for the vertical lines representing resonances.
    - CLASS: 1 for C, 2 for Bb, 3 for A. Other pitches are not included but it would be straightforward to modify the code appropriately
    - CutOffM : the cutoff frequency, which is displayed as a diagonal line (of constant frequency) running across the plot. For consistency, this is taken from an impedance map by noting the *x,y* values of a point in the cutoff regime corresponding to the third resonance peak (fifth harmonic). The product *xy* is the cutoff frequency.
- Parameters for the computation should be entered as follows
    - EMB: the equivalent-length embouchure correction, set at 20 mm for bass clarinets (see chapter 6). This is the only input parameter that affects the computation itself.
    - SELECT: 0 for normal plots, 1 for a magnified limited range around the fundamental for investigating the tuning, 2 for Jplot only. This is useful when the spectra have already been computed and it is desirable to check the pitch that best fits the data.
    - LOFREQ = 20;low end of range of frequency sweep.
    - HIFREQ = 2000;high end of range of frequency sweep.
    - DELFREQ = 0.5;step of frequency sweep.
- The paths for the Excel data files for each instrument are written into the code. Most of them are commented out with a % symbol. The pair of files not commented out is the

instrument that will be calculated. To add a new instrument simply add the paths to the files and alter the PITCH, CLASS and CutOffM parameters according to the instrument.

In the case shown in the printout below, there is a parent folder (in Mac OS format): '/Users/KeithBowen/Acoustics/INSTRUMENT_RESULTS/'

which is the same for all instruments. Each instrument has a subsidiary folder; in the case shown, the active one is

```
instrumentfolder = 'Streitwolf-D.LE.U.1539/' % folder containing Excel data file
```

and within this folder the name of the Excel file holding the instrument data is found (the Streitwolf in Leipzig):

```
instrumentfile = 'Streitwolf-D.LE.U.1539.xlsx' % Excel data file
```

The folders may be renamed, but the path data and the instrument filename must obviously be exactly correct or the file will not be found. In this thesis, the maker's name then the full CIMCIM siglum of the country, city, museum and instrument number is used as the instrument filename.

The **parentfolder, instrumentfolder and instrumentfile** names are then concatenated to form the exact path to the Excel data file. Appendix B defines the format of the data file and Appendix C contains printouts of the measurement and fingering data, for the convenience and reference of museum directors and scholars. The Excel data files themselves are available in the digital repository with this thesis.

If the program stops executing the problems are likely to be one or more of the following on the Excel data file:

- The pathname is incorrect
- A number in the Excel file has been omitted or is logically incorrect
- A fingering description is incorrect, e.g. a hole label in the 'Fingering1' sheet does not appear in the 'Measurements' sheet. There is no restriction on the naming of the holes, as long as they are the same in both worksheets. If calculating more than 24 notes, the note named 'B3' is used as the switch to the plot of the second register. For a soprano clarinet, change this to 'B4'.
- The naming of the colums (third row of the 'Measurements' sheet) must correspond to variables in the program, therefore these should not be altered.

The code is heavily commented and each section and procedure is defined and explained.

The outputs are as follows, all being in the same data folder as the Excel data file. Sections may be commented out as indicated if certain outputs are not required.

- A spectrum for each note defined in the 'fingerings' sheet of the Excel data file, with the extension '.DAT', e.g. E2.DAT. These are ASCII files containing four columns: frequency, Real, Imaginary and Absolute values of the input impedance at that frequency. Spectrum plots in the thesis are all of Absolute Impedance vs frequency.
- A graphics plot (diagonal line) of the cutoff frequencies for the holes entered as data.
- A graphics plot of the tone hole distribution, width and length (chimney height) for each hole
- A graphics plot of the bore vs. the distance from the mouthpiece.
- A graphics plot of the spectrum for each note entered in the data file, for the first register of the instrument, in a compact tiled display.

- A graphics plot of the spectrum for each note entered in the data file, for the second register of the instrument, in a compact tiled display.
- The impedance plot (called Jplot in the code) of the whole instrument.
- Graphics plots are available immediately on the screen and are stored in TIFF files at scales suitable for publication on A4 paper, in the instrument file.

In addition, a table summarising the results for each instrument is written in the Excel file SUMMARY_RESULTS.xlsx, found in the parent folder. This is automatically extended when running a new instrument, and can be edited in Excel to remove earlier calculations.

The Matlab™ codes

```
% PROGRAM IMPEDV2
% © D.Keith Bowen 2021
% used for Applied Acoustics paper
clc; clear;clearvars;
% ****************************** DATA INPUT ***********************************
Emb = 20; % mm, effective length of embouchure. Set this at 0 for "raw"
impedance calculations of the column
% with mouthpiece but without the reed. On the bass clarinet I use an
% empirical correction of 3 mm to get very good agreement between theory
% and measurement, and an additional 17 mm end correction for the reed
% impedance, to make impedance peaks match accurately with playing
% frequencies. Halve these for soprano clarinets as a first try.
PITCH = 440;
CLASS = 2; %1 for C, 2 for Bb, 3 for A
LOFREQ = 20;    %range and step of frequency sweep.
HIFREQ = 2000;
DELFREQ = 0.5;
SELECT = 0; %0 for normal plots, 1 for limited range for tuning, 2 for Jplot
only.
CutOffM = 640; %just used in the impedance plot as a rough indication of cutoff
frequency.
% It should be about 1500-2000 Hz for a soprano clarinet.

MainHoles = ["I" "II" "III" "IV" "V" "VI" "FC" "EB"] % for cutoff calculation
CutOff(1:10) = NaN
% specify data file for instrument. A single spreadsheet holds all the data
parentfolder = '/Users/KeithBowen/Acoustics/INSTRUMENT_RESULTS/'; %parent folder

%HECKEL
%instrumentfolder = 'Heckel_GB.Warwick/Heckel_V2/';
%instrumentfile = 'GB.Warwick.Bowen.Heckel.V2.xlsx';

%SAX 2601
%instrumentfolder = 'Sax-B.B.mim.2601/'; % folder containing Excel data file
%instrumentfile = 'Sax-B.B.mim.2601.xlsx';

%SAX 0175
%instrumentfolder = 'Sax-B.B.mim.0175/'; % folder containing Excel data file
%instrumentfile = 'Sax-B.B.mim.0175.xlsx';

%STENGEL Edinburgh
%instrumentfolder = 'Stengel-GB.E.u.4932/' % folder containing Excel data file
%instrumentfile = 'Stengel-GB.E.u.4932.xlsx'

%KRUSPE Leipzig
%instrumentfolder = 'Kruspe-D.LE.u.4479/' % folder containing Excel data file
%instrumentfile = 'Kruspe-D.LE.u.4479.xlsx'
```

```
%GRENSER
%instrumentfolder = 'Grenser-S.S.m.M2653/';
%instrumentfile = 'Grenser-S.S.m.M2653.xlsx';

%STREITWOLF Nuremberg
%instrumentfolder = 'Streitwolf-D.N.gnm.MIR477/' % folder containing Excel data
file
%instrumentfile = 'Streitwolf-D.N.gnm.MIR477.xlsx' % Excel data file

%STREITWOLF Leipzig
instrumentfolder = 'Streitwolf-D.LE.U.1539/' % folder containing Excel data file
instrumentfile = 'Streitwolf-D.LE.U.1539.xlsx' % Excel data file

%Catterini Oxford
%instrumentfolder = 'Catterini-GB.O.ub.496/' % folder containing Excel data file
%instrumentfile = 'Catterini-GB.O.ub.496.xlsx'

%MAINO Brussels
%instrumentfolder = 'Maino-B.B.mim.0941/' % folder containing Excel data file
%instrumentfile = 'Maino-B.B.mim.0941.xlsx' % Excel data file

%STENGEL Florence
%instrumentfolder = 'Stengel-I.F.ga.170-1-2/' % folder containing Excel data
file
%instrumentfile = 'Stengel-I.F.ga.170-1-2.xlsx'

%STENGEL Brussels
%instrumentfolder = 'Stengel-B.B.mim.0943/' % folder containing Excel data file
%instrumentfile = 'Stengel-B.B.mim.0943.xlsx'

%KRUSPE Basel
%instrumentfolder = 'Kruspe-CH.B.hm.1999.136/' % folder containing Excel data
file%
%instrumentfile = 'Kruspe-CH.B.hm.1999.136.xlsx'


borefile = strcat(parentfolder,instrumentfolder,instrumentfile) % path to Excel
data file
fingerings = 'Fingerings1';

instrumentfile = extractBefore(instrumentfile,".xlsx"); % shorter name for
outputs
%*************************** END OF DATA INPUT ******************************

% Worksheet 'Measurements' holds all the original measurements, in mm. These
% are processed (e.g. to average diameters of elliptical holes) with the output
% going into the worksheet 'Datafile', read directly by this program.
% This worksheet 'datafile' will hold both the bore and hole data, which
% are parsed into the variables 'seg(m,n)' and the table 'H' below.
% seg(m,1) is the length of segment m,
% seg(m,2) is the diameter of segment m at the end nearest the bell
% seg(m,3) is the diameter of segment m at the end furthest from the bell.
% seg(m,2) and seg(m,3) should differ by less than about 10% to deal
% correctly with wall losses, which vary with bore diameter.
% H holds the table of hole names and measurements

% The variable 'fingerings' points to the worksheet that holds the fingerings
% of each note that should be calculated. It is often convenient to have
% one worksheet for each set of holes to be calculated.
% The notes don't have to be in any particular order, but it is
% convenient to go from bottom to top of the instrument. Note that the
% names of holes in the Fingerings worksheet must be exactly the same as
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% the names of the holes in the Measurement worksheet.
% Note also that 'dependent' holes that close/open
% automatically on a certain fingering must be included manually as well as
% the direct fingerings or key presses.


% xxxxxxxxxxxxxxxxxx  READ BOREFILE FOR SEG AND HOLE DATA
% rows: one for each hole
% columns: HOLNAM,HOLTYP,HOLDIA,KEYHT,KEYDIA,HOLLG,HOLLOC,BODIA,RC
% meanings as in IMPEDPS, ie
% HOLNAM: name of note
% HOLTYP: O or C (is the hole normally open or closed)
% HOLDIA: diameter of hole in mm
% KEYHT:  height of pad above hole (= 0 if fingerhole with no pad)
% KEYDIA: diameter of pad over hole (= 0 if fingerhole with no pad)
% HOLLG:  length of hole chimney
% HOLLOC: segment number
% BODIA:  body diameter
% RC   :  radius of curvature of hole edge (outer)


%find number of segments and hence area of worksheet to read
D = readtable(borefile,'range','A3'); %skip first two descriptive lines
NUMSEG = max(D.segno);
range = strcat('C3:W',num2str(NUMSEG+5)); %specify exact table range
D = readtable(borefile,'Range',range,'ReadVariableNames',true);

% We delete unused data from D, immediately if it is not used, otherwise
% immediately after reading it into a program variable
D.Var17 = [];
D.DiaNS = [];
D.DiaEW = [];
D.Ljoint = [];
D.Var18 = [];
D.offset = [];
BELFLG = D.Dbore(1); % read bell flange diameter out of row 1
BELDIA = D.Dbore(2); % read bell inner diameter out of row 2
D.Dbore = [];        % can erase bore column now
D([1,2],:) = [];     % can erase first two rows of data now, leaving segment and
hole data only.
seg(:,1) = D.SEGLEN; % create array seg
seg(:,2) = D.LODIA;  % create array seg
seg(:,3) = D.HIDIA;  % create array seg
seg(:,4) = D.Zbore;  % create array seg
D.Zbore = [];        % erase length data
D.SEGLEN = [];       % erase segment data
D.LODIA = [];        % erase segment data
D.HIDIA = [];        % erase segment data
% what's left is the table of holes, plus NaN cells where there are no
% holes. Make the hole table by eliminating rows including these.
H = rmmissing(D);
NUMHOL = height(H); % number of holes
MPvol = pi*seg(NUMSEG,1)*seg(NUMSEG,3)^2/4000; %volume of last segment =
mouthpiece, in cm^3
% worksheet 'Measurements' now read. Still in mm.

% read borefile for fingerings
F = readtable(borefile,'Sheet',fingerings); % gets variables F.Note, F.ET,
F.Finger.
F.ET = F.ET*PITCH/440; % adjust to probable pitch
% Worksheet 'Fingerings' now read.
% no check that F.Finger names are all recognised in H.Holnam but this
% comes out in computation
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%Embouchure correction,add Emb to mouthpiece segment length.
seg(NUMSEG,1) = seg(NUMSEG,1) + Emb;
% CONVERT MILLIMETERS TO CENTIMETERS (the impedance formulae are in cgs)
BELDIA = 0.1*BELDIA;
BELFLG = 0.1*BELFLG;
for k = 1:NUMSEG
    seg(k,:) = 0.1*seg(k,:); %put segment lengths and diameters in cm
end
H.HOLDIA = 0.1*H.HOLDIA; %******************************************
H.KEYHT = 0.1*H.KEYHT;
H.KEYDIA = 0.1*H.KEYDIA;
H.HOLLG = 0.1* H.HOLLG;
H.BODIA = 0.1* H.BODIA;
H.RC = 0.1* H.RC;

                                %PLOT GEOMETRY OF INSTRUMENT
%{
figure; %plot bore
plot(10*seg(:,4),5*seg(:,3),'LineWidth',1) % plot RADIUSin mm
axis([0 1850 0 100]);
%do labels
str = strcat(instrumentfile,': Bore radius profile');
title([str]);
xlabel('distance along bore, mm')
ylabel('bore radius, mm')
set(gcf, 'PaperPosition',[0 0 20 5]); %x_width= 30cm y_height=5cm
fileout = strcat(parentfolder,instrumentfolder,instrumentfile,':
BoreProfile.tif');
pause(2);
saveas(gcf,fileout);
hold off;
%}
if SELECT<2
figure; %plot holes
%plot([0 2000],[0 0],'-k'); %zero line
LengthTot = 10*seg(NUMSEG,4); %in mm
hold on
offset = 0;
for I = 1:NUMHOL
xpos = LengthTot - 10*seg(H.segno(I),4);
ypos = 10*H.HOLLG(I);
%    if H.HOLTYP{I}=='C'
%   ypos = - ypos; % plot downwards if closed hole
%   end
linewidth = H.HOLDIA(I)*5;
if H.HOLTYP{I}=='O' %plot open holes only
plot([xpos xpos],[0,ypos],'-k','LineWidth',linewidth); %plot line from axis to
HOLLG at each hole point
text(xpos-10,ypos+offset+2,H.HOLNAM{I});
end %if
%do bell
xpos = LengthTot;
ypos = 25;
plot([xpos xpos],[0,ypos],'-k','LineWidth',1);
text(xpos-20,ypos+offset+2,"Bell");
text(5,5,"Mouthpiece");

hold on;
end
%do labels
axis([0 1850 0 30]);
%legend
%text(20,20,'OPEN HOLES');
%text(20,-20,'CLOSED HOLES (shown negative)');
xlabel('distance along bore, mm')
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```
ylabel('tone hole length, mm')
str = strcat(instrumentfile,': open tone holes');
title([str]);
set(gcf, 'PaperPosition',[0 0 30 5]); %x_width= 30cm y_height=5cm
fileout = strcat(parentfolder,instrumentfolder,instrumentfile,':
opentoneHoles.tif');
pause(2);
saveas(gcf,fileout);
hold off;
%return
end %if SELECT<2

                                  %CUTOFF VALUES
% Calculate cutoff frequency
NMH = size(MainHoles,2);
CutOff = CutOffCalc(H,MainHoles,seg)
if SELECT<2
    plot(CutOff);
end
fcalc(:) = LOFREQ:DELFREQ:HIFREQ;   %define array of frequencies
NumFreq = length(fcalc);
Ztotal(1:length(fcalc)) = double(0);
% initialise STATUS variable for hole status
STATUS(1:NUMHOL) = holinit(H.HOLTYP,H.KEYHT,NUMHOL);  %initial setting, no
fingers on.
%set up table S to hold peak location and height results for whole instrument
%declare and initialise variables for summary table, S
%ST(1) = STATUS(1)';
NoteName = F.Note;
NN = height(F);
Nreg = 1; %will be the highest Note in register 1
Pkfund(1:NN) = double(0); Pkfund = Pkfund';
Delta(1:NN) = double(0); Delta = Delta';
Damp(1:NN) = double(0); Damp = Damp';
Pk1(1:NN) = double(0); Pk1 = Pk1';
Ht1(1:NN) = double(0); Ht1 = Ht1';
Pk2(1:NN) = double(0); Pk2 = Pk2';
Ht2(1:NN) = double(0); Ht2 = Ht2';
Pk3(1:NN) = double(0); Pk3 = Pk3';
Ht3(1:NN) = double(0); Ht3 = Ht3';
Pk4(1:NN) = double(0); Pk4 = Pk4';
Ht4(1:NN) = double(0); Ht4 = Ht4';
Pk5(1:NN) = double(0); Pk5 = Pk5';
Ht5(1:NN) = double(0); Ht5 = Ht5';
Pk6(1:NN) = double(0); Pk6 = Pk6';
Ht6(1:NN) = double(0); Ht6 = Ht6';
Pk7(1:NN) = double(0); Pk7 = Pk7';
Ht7(1:NN) = double(0); Ht7 = Ht7';

ET = F.ET;
%define table
S = table(NoteName,ET,Pkfund,Delta,Damp,Pk1,Ht1,Pk2,Ht2,Pk3,Ht3,Pk4,Ht4,Pk5,Ht5,
...
             Pk6,Ht6,Pk7,Ht7);
if SELECT <2
    FigureNo = 1;
    figure(FigureNo);
    tiledlayout(7,4);
    axis([0 HIFREQ 0 60])
end %if SELECT <2
Register = 1;
                                 %MAIN NOTE LOOP
for note = 1:NN
STATUS(1:NUMHOL) = holinit(H.HOLTYP,H.KEYHT,NUMHOL); %must reset STATUS for each
note
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```
[STATUS,HOLSTAT,HOLPNT] = Holset(F,H.HOLNAM,H.HOLLOC,STATUS,NUMHOL,NUMSEG,note);
ST(note,:) = STATUS; % array for diagnostics only
% set up STATUS of holes for given fingering, set up new array HOLSTAT with
% element for each bore segment, set up pointer array HOLPNT linking toneholes
and
% segments (toneholes linked to reed ends of segments)
DF = 1.0; %parameter in impedance equations
%set up plot axes for each of 24 notes in 6x4 setup



                           %FREQUENCY LOOP FOR ONE NOTE
   for q = 1:NumFreq
   omega =  2*pi*fcalc(q); %angular frequency for formulae
   Ztotal(q) = TubeImpedance(omega,seg,H,BELFLG,BELDIA,HOLSTAT,HOLPNT,DF);
   %Ztotal is the output of the impedance computation
   q;  %progress indicator (remove semicolon to see frequency progress)
   end % FREQUENCY LOOP

                              % OUTPUTS FOR ONE NOTE
%write output
Re = real(Ztotal);Re = Re';
Im = imag(Ztotal);Im = Im';
Abs = abs(Ztotal);Abs = Abs';
fcol = fcalc';

if SELECT ==0
G = table(fcol,Re,Im,Abs);
outputfilename = strcat(parentfolder,instrumentfolder,F.Note{note},'.DAT');
writetable(G,outputfilename,'Delimiter','tab');
if string(F.Note{note})=="B3"
   FigureNo = FigureNo +1;
   figure(FigureNo);
   tiledlayout(7,4);
   end %if
end %if SELECT



                            %PEAK ANALYSIS FOR ONE NOTE
% analyse the data to find positions and heights of peaks
[pks,locs,w,p] = findpeaks(Abs);
if string(F.Note{note})=="B3"
   Register = 2;
   Nreg     = note - 1;
end
if Register == 1
    S.Pkfund(note) = fcalc(locs(1));
    else
    S.Pkfund(note) = fcalc(locs(2));
end


S.Pk1(note) = fcalc(locs(1));
S.Ht1(note) = pks(1);
S.Pk2(note) = fcalc(locs(2));
S.Ht2(note) = pks(2);
S.Pk3(note) = fcalc(locs(3));
S.Ht3(note) = pks(3);
S.Pk4(note) = fcalc(locs(4));
S.Ht4(note) = pks(4);
S.Pk5(note) = fcalc(locs(5));
S.Ht5(note) = pks(5);
S.Pk6(note) = fcalc(locs(6));
S.Ht6(note) = pks(6);
```

```
S.Pk7(note) = fcalc(locs(7));
S.Ht7(note) = pks(7);

if note>1
    S.Delta(note) = 1200*log2(S.Pkfund(note)/S.Pkfund(note-1));
    end % if note>1
S.Damp(note) = S.Ht2(note)/S.Ht1(note);

if SELECT==0
ax1 = nexttile;
%title([instrumentfile]);
set(gcf, 'PaperUnits', 'centimeters');
set(gcf, 'PaperPosition',[0 0 20 25]); %x_width= 20cm y_height=15cm


%draw lines at odd harmonics
fund = S.Pkfund(note);
h = 1;
while (h*fund)<HIFREQ
  plot([h*fund h*fund],[0 45],'r','LineWidth',0.3);
  h = h+2;
  hold on
end

plot(ax1,fcalc,Abs/10,'k','LineWidth',1); % plot impedance of current note in SI
Mohm
title(F.Note{note});
xlabel('Frequency, Hz');
ylabel('Acoustic SI M\Omega');
%TIFF FILE OUT need condition for finishing first plot

fileout = strcat(parentfolder,instrumentfolder,instrumentfile);

if string(F.Note{note})=="Bb3" %write plotfile up to Bb3
   fileout = strcat(fileout,"_1st_register",".tif");
   pause(2);
   saveas(gcf,fileout);
   hold off;
end

if note == NN % rest of the notes
   axis([0 HIFREQ 0 60])
   fileout = strcat(fileout,"_2nd_register",".tif");
   pause(2);
   saveas(gcf,fileout);
   hold off;
end
end %if SELECT==0

X = [num2str(note),' ',F.Note{note}];
disp(X); %progress monitor

hold on;

hold off

end %note loop

              % OUTPUTS FOR WHOLE INSTRUMENT
figure;

%write and plot summary table for instrument;
loglog(S.Pk1./S.ET,S.ET, '*k', ...
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```
     S.Pk2./S.ET,S.ET, 'or', ....
     S.Pk3./S.ET,S.ET, 'sb', ...
     S.Pk4./S.ET,S.ET, 'dg', ...
     S.Pk5./S.ET,S.ET, 'xk', ...
     S.Pk6./S.ET,S.ET, '+m', ...
     S.Pk7./S.ET,S.ET, 'pr');

hold on
%Sax intonations at 464
%XC = [329.9 245.3 166.1 122.9 96.3 90.8 80.5 76.4 369.2 328.4 165.1 129.7 76.8
76.8]
%YC = [328.1 245.8 164.0 122.9 97.5 92.1 82.0 77.4 368.3 328.1 164.0 130.2 77.4
77.4]
%loglog(XC./YC,YC,'pb')
%hold on
if SELECT~=1
    %draw vertical lines at odd harmonics of nominal frequency of peak 1
loglog([1 1],[50 500],'-m',[3 3],[50 500],'-m',[5 5],[50,500],'-m', ...
    [7 7],[50 500],'-m',[9 9],[50 500],'-m',[11 11],[50,500],'-m', ...
    [13 13],[50 500],'-m');
%plot nominal cutoff frequency onset
loglog([CutOffM/500 CutOffM/50],[500 50],'-b');
%xtextpos = CutOffM/50;
xtextpos = 18;

       %STANDARD DEVIATIONS

STD1 = 100*std(S.Pkfund(1:Nreg)./S.ET(1:Nreg));
STD2 = 100*std(S.Pkfund(Nreg+1:NN)./S.ET(Nreg+1:NN));
MEAN1 = mean(S.Pkfund(1:Nreg)./S.ET(1:Nreg)-1);
MEAN2 = mean(S.Pkfund(Nreg+1:NN)./S.ET(Nreg+1:NN)-1);

str = strcat("cutoff ",num2str(CutOffM,3)," Hz");
text(xtextpos,60,str);

%do labels
formatSpec = "%.1f";
subtitle = strcat('Pitch A4 = ',num2str(PITCH),' Hz   MPvol =
',num2str(MPvol,formatSpec)," cm^{3}");
title([instrumentfile],subtitle);
set(gcf, 'PaperPosition',[0 0 20 15]); %x_width= 20cm y_height=15cm
axis([0.3 40 50 500])
legend('1st. resonance', ...
       '2nd. resonance', ...
       '3rd. resonance', ...
       '4th. resonance', ...
       '5th. resonance', ...
       '6th. resonance', ...
       '7th. resonance', ...
       'Location','northeast');
yyaxis left
xlabel('Resonance peak relative to nominal ET frequency (log scale)')
ylabel('Fingered note')

%label y axis left with note names
semitone = exp(log(2)/12);
LF = [65.4 82.4 98 130.8 164.8 196 261.6 329.6 392 523.25] %440 pitch main note
freqs
switch CLASS
    case 1 %C clarinet at 440
    LF = LF;
    case 2 % Bb clarinet at 440
    LF = LF./(semitone^2);
    case 3 %A clarinet at 440
```

```
    LF = LF./(semitone^3);
end %switch CLASS
LF = LF*PITCH/440; % correct for pitch
yticks([LF(1) LF(2) LF(3) LF(4) LF(5) LF(6) LF(7) LF(8) LF(9) LF(10)])
yticklabels({'C2','E2','G2','C3','E3','G3','C4','E4','G4','C5'});
grid on
xticks([1 3 5 7 9 11 13])
xticklabels({'1','3','5','7','9','11','13'})
hold on
%label yaxis right with frequencies
yyaxis right
%pause(2);
ylim([log(50) log(500)]);
yticks([log(50) log(100) log(200) log(500)]);
yticklabels({'50','100','200','500'});
ylabel('Nominal ET frequency of note (log scale)');

fileout =
strcat(parentfolder,instrumentfolder,instrumentfile,'_',num2str(PITCH),'_Jplot.t
if');
pause(2);
saveas(gcf,fileout); %tif file sized correctly for paper
hold off
else %SELECT<>0 draw plot round fundamental only
    Hztitle = strcat(num2str(PITCH),' Hz');
    title(Hztitle)
    set(gcf, 'PaperPosition',[0 0 4 10]); %x_width= 4cm y_height=10cm
    axis([0.9 1.1 50 500])
    %for Sax 2601

    loglog(S.Pk1./S.ET,S.ET,'*k');
    loglog([1 1],[50 500],'-m');

    xticks([0.9 1 1.1])
    xticklabels({'0.9','1.0','1.1'});
    yticklabels({'50','100','200','500'})
    yticks([50 100 200 500])
    fileout = strcat(parentfolder,instrumentfolder,instrumentfile,' Jplot of
fundamental ',num2str(PITCH),'.tif');
    pause(2);
    saveas(gcf,fileout); %tif file sized correctly for paper
    hold off
end %else

%SAVE SUMMARY TABLE
fileout =
strcat(parentfolder,instrumentfolder,instrumentfile,'_S_Table_',num2str(PITCH),'
.txt');
writetable(S,fileout);

%ADD TO ALL_INSTRUMENT SUMMARY
if SELECT~=2 %SELECT == 2 is for just plotting Jplot
summaryfile = strcat(parentfolder,'SUMMARY_RESULTS.xlsx');
SUMMARY = readtable(summaryfile,'ReadVariableNames',true)
%compose row of table
InstrumentID = string(instrumentfile)
CutOff_1 = CutOff(1);
CutOff_2 = CutOff(2);
CutOff_3 = CutOff(3);
CutOff_4 = CutOff(4);
CutOff_5 = CutOff(5);
CutOff_6 = CutOff(6);
CutOff_7 = CutOff(7);
CutOff_8 = CutOff(8);
```

```
CutOff_9 = CutOff(9);
CutOff_10 = CutOff(10);

NEWROW =
table(InstrumentID,PITCH,MEAN1,MEAN2,STD1,STD2,CutOffM,CutOff_1,CutOff_2,CutOff_
3,CutOff_4, ...
    CutOff_5,CutOff_6,CutOff_7,CutOff_8,CutOff_9,CutOff_10);

%append table
SUMMARY = [SUMMARY;NEWROW]
writetable(SUMMARY,summaryfile);
end % if SELECT ~=2

%                     END OF MAIN PROGRAM
%                  *******FUNCTIONS*******
%---------------------------------------------------------------------------
function [Zimp] = TubeImpedance(omega,seg,H,belflg,beldia,HOLSTAT,HOLPNT,DF)
%Calculates total impedance of bore over the range of angular frequencies
%specified by the array omega. "seg" contains bore profile data, H the
% data on holes and F the fingering of each tone. If note is an integer
%it calculates one note, if an array it does the set of notes in the array.
%   CALCULATE RADIATION IMPEDANCE OF BELL.*
[Zrad] = RadImpedanceCronin(belflg,beldia,omega);
ZOUT = Zrad; %ZOUT is always the output impedance of the PREVIOUS segment
s = size(seg);                  %bit convoluted but allows to do 1 or 2 seg bores!
N = int8(s(1));                 % number of segments

                               % BORE SEGMENT LOOP*
    for n=1:N
    % calculate impedance of current segment
    %disp(n); %progress monitor
    DIAav = (seg(n,2)+seg(n,3))/2; %average dia over segment
    [INERT,COMPLI,VISCLS,HEATLS] = CALC3(DIAav,omega);
    [GAMMA,ZCHAR] = ZCGAM(VISCLS,INERT,HEATLS,COMPLI,omega);
    [Zseg] = Zconical(seg(n,1),seg(n,2),seg(n,3),ZOUT,ZCHAR,GAMMA); %impedance
of the segment, before adding any hole
    %hole parameters:
    p = HOLPNT(n);

    % physical parameters for this hole diameter
    %calculate hole impedance
    %and (if present) add to segment impedance
    % ZT is shunt, ZS series impedances of hole. ZS is split between the
    % shunt impedance of the hole and the series impedance of the segment.
       switch HOLSTAT(n) % select appropriate hole calculation
         case -1          % no hole at end of segment
           ZOUT = Zseg;
         case 0           % closed finger- or key-hole at input end of segment
           [ZT,HALFZS] = closed_hole(H.HOLDIA(p),H.HOLLG(p),seg(n,3),omega);
           ZOUT = HALFZS+ZT*(Zseg+HALFZS)/(Zseg+ZT+HALFZS);
%            ZOUT = 2*HALFZS+ZT*Zseg/(Zseg+ZT);
         case 1           % open fingerhole at input end of segment
           [ZT,HALFZS] = open_fingerhole(H.HOLDIA(p),H.HOLLG(p),H.BODIA(p), ...
              H.RC(p),seg(n,3),DF,omega);
           ZOUT = HALFZS+ZT*(Zseg+HALFZS)/(Zseg+ZT+HALFZS);
%            ZOUT = 2*HALFZS+ZT*Zseg/(Zseg+ZT);
         case 2           % open keyhole at input end of segment
           [ZT,HALFZS] = open_keyhole(H.HOLDIA(p),H.HOLLG(p),H.BODIA(p), ...
              H.KEYHT(p),H.KEYDIA(p),H.RC(p),seg(n,3),DF,omega);
           ZOUT = HALFZS+ZT*(Zseg+HALFZS)/(Zseg+ZT+HALFZS);
       end %switch HOLSTAT
    end % for n=1:N
```

```
Zimp = ZOUT; % infinite reed impedance, correct with Emb instead of reed
impedance expression.
end % function Zimp

%-----------------------------------------------------------------------
function [INERT,COMPLI,VISCLS,HEATLS] = CALC3(DIA,OMEGA)
%THIS SUBROUTINE USES VALUES FOR THE PHYSICAL PROPERTIES OF WARM, MOIST AIR. IN
CGS UNITS:
%  DENSITY=.00119 GM/CM**3,
%   SPEED OF SOUND=34700 CM/SEC,
%   VISCOSITY=1.848E-4 GM/(CM*SEC),
%   RATIO OF SPECIFIC HEATS=1.4,
%   THERMAL CONDUCTIVITY=6.27E-5 CAL/(SEC*CM*DEG C),
%   HEAT CAPACITY AT CONSTANT PRESSURE=.2405 CAL/(GM*DEG C).
%Returns INERT, COMPLI, VISCLS, HEATLS, GAMMA, ZCHAR as field of table T??
ROMEGA = sqrt(OMEGA);
AREA   = 0.785398*(DIA^2);
INERT  = 0.00119/AREA*(1.+1.115/(DIA*ROMEGA));
COMPLI = AREA/1432867*(1 +0.5296/(DIA*ROMEGA));
VISCLS = (0.001326*ROMEGA/DIA+0.002218/(DIA^2))/AREA;
HEATLS = AREA*(3.696E-7*ROMEGA/DIA - 6.116E-7/DIA^2);
end

%-----------------------------------------------------------------------
function [GAMMA,ZCHAR] = ZCGAM(VISCLS,INERT,HEATLS,COMPLI,OMEGA)
% COMPUTES THE PROPAGATION CONSTANT AND THE CHARACTERISTIC IMPEDANCE*
A = complex(VISCLS,OMEGA*INERT);
B = complex(HEATLS,OMEGA*COMPLI);
GAMMA = sqrt(A*B);
ZCHAR = sqrt(A/B);
end

%-----------------------------------------------------------------------
function [Zr] = RadImpedanceCronin(belflg,beldia,omega) % in cgs
E0 = 0.821 - 0.13*((belflg-beldia)/beldia + 0.42)^(-0.54);
sigma0 = E0 - 0.36;
ka = 1.4409E-5 * beldia*omega;
Zc2 = 52.58/(beldia^2);
Zr = Zc2*complex(sigma0*ka*ka,E0*ka);
end

%-----------------------------------------------------------------------
function Zinput = Zcyl(LG,ZOUT,ZCHAR,GAMMA)
% Computes the input impedance of a cylindrical segment length LG given
% output impedance of previous segment ZOUT
% Calculate pc immediately before this function call.
% Replaces IMPEDPS function ZZEROfunction
TH = tanh(LG*GAMMA);
Zinput = ZCHAR*(ZOUT+ZCHAR*TH)/(ZCHAR+ZOUT*TH);
end %function Zcyl

%-----------------------------------------------------------------------
function [ZT,HALFZS] = closed_hole(DIA,LG,BORE,omega)
%**Computes the shunt and series impedances of a closed hole**
%Calculate pc immediately before this function call.
%REAL DIA,LG,BORE,INERT,COMPLI,VISCLS,HEATLS,DOB,ZC,TA,KTA,OMEGA,FREQ
%COMPLEX ZT,HALFZS,GAMMA,ZCHAR,CTANH
[INERT,COMPLI,VISCLS,HEATLS] = CALC3(DIA,omega);
[GAMMA,ZCHAR] = ZCGAM(VISCLS,INERT,HEATLS,COMPLI,omega);
DOB=DIA/BORE;
ZC = 52.58/(DIA^2);
ZT = ZCHAR/tanh(LG*GAMMA);
TA = (.235*DIA*DOB^4)/(1./tanh(3.68*LG/DIA)+.54+.31*DOB^2);
KTA = 2.882E-5*omega*TA;
```

```
HALFZS=.5*ZC*complex(.95*(KTA^2)/(DOB^2),-KTA);
end

%-----------------------------------------------------------------------
function[ZT,HALFZS] = open_fingerhole(DIA,LG,BODIA,RC,BORE,DF,omega)
%SUBROUTINE OPENFH(DIA,LG,BODIA,RC,BORE,DF,ZT,HALFZS)
% Computes the shunt and series impedances of an open hole
%Calculate pc immediately before this function call.
% REAL DIA,LG,BODIA,RC,BORE,INERT,COMPLI,VISCLS,HEATLS,OMEGA,FREQ,
%    +DOB,ZC,SIGMA0,E0,KB,DV,XIV,XIE,TI,TA,KTA
% COMPLEX ZT,HALFZS,GAMMA,ZCHAR,ZEXT
DOB = DIA/BORE;
ZC  = 52.58/(DIA^2);
E0  = 0.393+.205*log(BODIA/DIA);
if(E0 > .85)
   E0=.85;
end
SIGMA0 = E0-0.36;
KB     = 1.4409E-5*DIA*omega;
DV     = 0.5573/sqrt(omega);
if(RC < DV)
   RC=DV;
end
XIV = 3.6023E-6*DF*omega*DV*log(.125*DIA/RC);
XIE = SIGMA0*KB^2+XIV;
ZEXT = ZC*complex(XIE,E0*KB);
[INERT,COMPLI,VISCLS,HEATLS] = CALC3(DIA,omega);
[GAMMA,ZCHAR] = ZCGAM(VISCLS,INERT,HEATLS,COMPLI,omega);
ZT = Zcyl(LG,ZEXT,ZCHAR,GAMMA);
TI = DIA*(0.196-0.143*DOB^2);
ZT = ZT+ZC*complex(XIV,2.882E-5*omega*TI);           %OUTPUT
TA = (0.235*DIA*DOB^4)/(tanh(3.68*LG/DIA)+0.54+0.31*DOB^2);
KTA = 2.882E-5*omega*TA;
HALFZS =0.5*ZC*complex(0.95*KTA*KTA/(DOB*DOB),-KTA);   %OUTPUT
end

%-----------------------------------------------------------------------
function[ZT,HALFZS] = open_keyhole(DIA,LG,BODIA,KEYHT,KEYDIA,RC,BORE,DF,OMEGA)
%Computes the shunt and series impedances of an open keyhole with fontanelle
%Calculate pc immediately before this function call.
%REAL DIA,LG,BODIA,KEYHT,KEYDIA,RC,BORE,INERT,COMPLI,VISCLS,HEATLS,
% +OMEGA,FREQ,DOB,ZC,E0,E00,SIGMA0,KB,DV,XIV,XIE,TI,TA,KTA
%COMPLEX ZT,HALFZS,GAMMA,ZCHAR,ZEXT
DOB = DIA/BORE;
ZC  = 52.58/(DIA^2);
E00=.393+.205*log(BODIA/DIA);
if (E00 > 0.85)
   E00=.85;
end
E0 = 0.7631*E00*((KEYDIA/DIA)^0.18)*(DIA/KEYHT)^0.39;
if (E0 < E00)
   E0=E00;
end
SIGMA0 = E0-0.36;
%      **ADDITIONAL VISCOUS LOSSES DUE TO PRESENCE OF PAD ARE IGNORED*
KB = 1.4409E-5*DIA*OMEGA;
DV = 0.5573/sqrt(OMEGA);
if (RC < DV)
   RC=DV;
end
XIV = 3.6023E-6*DF*OMEGA*DV*log(.125*DIA/RC);
XIE = SIGMA0*KB*KB+XIV;
ZEXT = ZC*complex(XIE,E0*KB);
[INERT,COMPLI,VISCLS,HEATLS] = CALC3(DIA,OMEGA);
[GAMMA,ZCHAR] = ZCGAM(VISCLS,INERT,HEATLS,COMPLI,OMEGA);
```

```
ZT = Zcyl(LG,ZEXT,ZCHAR,GAMMA);                                        %OUTPUT
TI = DIA*(.196-.143*DOB^2);
ZT = ZT+ZC*complex(XIV,2.882E-5*OMEGA*TI);
TA = (0.235*DIA*DOB^4)/(tanh(3.68*LG/DIA)+.54+0.31*DOB^2);
%last term should be 0.31*DOB*DOB (Cronin 2.11.2017 email) was just DOB*DOB
KTA= 2.882E-5*OMEGA*TA;
HALFZS = 0.5*ZC*complex(.95*KTA*KTA/(DOB*DOB),-KTA);
end

function [Zinput] = Zconical(LG,LODIA,HIDIA,ZOUT,ZCHAR,GAMMA)
%Computes the input impedance of a conical segment in terms of output impedance
%of previous segment (nearer bell). Thermal and viscous losses included.
%Call CALC3 immediately before this function, with average value of DIA
%LG = segment length, cm
%LODIA = segment diameter nearer bell, cm
%HIDIA = segment diameter further from bell, cm
%ZOUT = impedance of previous segment (nearer bell), cgs acoustic ohms
%REAL LG,LODIA,HIDIA,A1,A2,A3,A5
%COMPLEX ZOUT,ZCHAR,GAMMA,ZINPUT,GL,A4,A42,TH
GL = GAMMA*LG;
TH = tanh(GL);
if LG == 0                  % zero length segment to deal with two holes at same
length
    Zinput = ZOUT;
elseif (HIDIA <= LODIA)          %     NORMAL CONE OR CYLINDER
   A1 = HIDIA/LODIA;
   A2 = (LODIA-HIDIA)/HIDIA;
   A3 = (LODIA-HIDIA)/LODIA;
   A4 = A2/GL;
   A42 = A4*A4;
   A5 = 1/A1;
   Zinput = ZCHAR*A1*(ZOUT*(1+A4*TH)+ZCHAR*TH)/ ...
          (ZCHAR*A5*(1-A3*TH/GL)+ZOUT*((A5-A42)*TH+GL*A42));
else                        %     INVERTED CONE
   A1=HIDIA/LODIA;
   A2=(HIDIA-LODIA)/HIDIA;
   A3=(HIDIA-LODIA)/LODIA;
   A4=A3/GL;
   A42=A4*A4;
   A5=1/A1;
   Zinput = ZCHAR*(A1*ZOUT*(1-A2*TH/GL)+A5*ZCHAR*TH)/ ...
          (ZOUT*((A1-A42)*TH+A42*GL)+A5*ZCHAR*(1+A4*TH));
end %if
end %function

%---------------------------------------------------------------------------
function STATUS = holinit(HOLTYP,KEYHT,NUMHOL)

%     This function sets the initial status of holes to
%        1 open finger hole
%        2 open key hole
%        0 closed key hole
%     CHARACTER*1 HOLTYP(30)
%     INTEGER STATUS(30),NUMHOL,I
%     REAL KEYHT(30)
   for n = 1:NUMHOL
     switch HOLTYP{n}
       case 'C'
         STATUS(n)=int8(0);
       case 'O'
         if (KEYHT(n) < 0.001)        % it's a finger hole
         STATUS(n)=int8(1);
       else
          STATUS(n)=int8(2);                % it's a key hole
         end
```

```
      end
    end
end

%----------------------------------------------------------------------------
function [STATUS,HOLSTAT,HOLPNT] =
Holset(F,HOLNAM,HOLLOC,STATUS,NUMHOL,NUMSEG,note)
%{
THIS SUBROUTINE SETS STATUS OF TONEHOLES ACCORDING TO FINGERING
IT GENERATES NEW ARRAY HOLSTAT WITH ELEMENT FOR EACH BORE SEGMENT
(-1,NO HOLE; 0, CLOSED; 1, OPEN FINGER HOLE; 2, OPEN KEYHOLE).
IT ALSO SETS UP A POINTER ARRAY LINKING TONEHOLES AND SEGMENTS.
TONEHOLES ARE LINKED TO INPUT ENDS OF SEGMENTS(END OF SEGMENT CLOSEST TO REED).
%}
g = cell2mat(F{note,3});    % result: 'Eflat EB FC etc'
if not (g=="") %exception for empty finger string ie open G
    k = textscan(g,'%s','Delimiter',',');       % result: 1x1 cell array
    NAME = k{1,1};
end
% result: N x 1 cell array, which is
% sequence of hole names in current fingering (N fingers.holes)
% access with e.g. NAME{7} for 7th finger/key pressed

% work out STATUS setting
 if not (g=="")                    % all fingers off ie open G3
   for n = 1:NUMHOL                % closed keyholes stay at 0
   holename = char(HOLNAM{n});
   holedetect = 0;
       for m = 1:length(NAME)
          keyname = char(NAME(m));
          if strcmp(holename,keyname) % hole status has changed
             holedetect = holedetect+1;
             if holedetect == 2 % test for keyname occuring twice in fingering
string
               message = strcat('Error: duplicate hole name in
Fingering:',keyname);
               disp(message);
               return
             end %if holedetect
          if STATUS(n) == 0          % if hole was closed
             STATUS(n)  = 2;              % if the keyhole is opened by the
fingering
          else
             STATUS(n) = 0;              % hole was open and is now closed
          end %if STATUS- no need to set an open finger hole to 1 as this is the
default after holeinit
          end %if strcomp
       end %for m = 1:length(NAME)
   end
   %check that each element of all used fingerings (NAMEs) are found in HOLNAM
   for m = 1:length(NAME)
      holedetect = 0;
      keyname = char(NAME(m));
      for n = 1:NUMHOL                % run through all hole names
         holename = char(HOLNAM{n});
         if strcmp(holename,keyname) % hole name is detected
            holedetect = holedetect+1;
         end
      end
      if holedetect == 0 % test for keyname not occuring in set of hole names
         message = strcat('Error: Key name not found in set of hole
names:',keyname);
         disp(message);
         return
      end %if holedetect
```

```
   end %for m = 1:length(NAME)
 end %if not (g=="")
  % initialise HOLSTAT and HOLPNT
   for n=1:NUMSEG
        HOLSTAT(n) = int8(-1);          % no hole
        HOLPNT(n)  = int8(0);
   end

   % calculate HOLSTAT from STATUS and HOLLOC (segment location) and HOLPNT
(link of toneholes and segments)
   for n=1:NUMHOL
     m = HOLLOC(n);
     HOLPNT(m) = n;
     HOLSTAT(m)=STATUS(n);
   end
end
%-------------------------------------------------------------------------
function [CutOff] = CutOffCalc(h,mainholes,Seg)
%This function calculates the approximate cutoff for a tube containing tone
holes described in the table h, which is identical format to
%H in the main program. The string array mainholes is the set of holes used
%for the calculation. The segment array is used to find the spacings and
%the bores. Uses Moers & Kegomard formula; see thesis chapter 8.
count = height(h);   % no of holes
NMH = length(mainholes); % no. of mainholes
%reduce h to mainholes only
I=height(h);
while I>0 %go from bottom
   flag(1:NMH) = false;
   for J=1:NMH
       if string(h.HOLNAM(I))==mainholes(J)        %if true leave arrary alone
       flag(J) = true;
       end
   end %for J
   if any(flag) % hole is found in mainholes
   %do nothing
   else
   h([I],:) = []   %erase line
   end
      I=I-1;
   end %while I
C = 34700; %cm/sec
   %Calculate cutoff for subsequent pairs of holes by Moers/Kergomard formula
for I = NMH:-1:2
   SN1 = h.segno(I);
   SN2 = h.segno(I-1); % - because seg nos run backwards in h
   a0 = (Seg(SN1,3)+Seg(SN2,3))/4; %average tube radius
   const = C/(2*pi*a0); %average radius
   b1 = h.HOLDIA(I)/2;
   b2 = h.HOLDIA(I-1)/2;
   l1 = h.HOLLG(I)+1.6*b1;    %correction for hole mass & radiation
   l2 = h.HOLLG(I-1)+1.6*b2;
   LL=0; %distance between end holes of pair
      for J = (h.segno(I)):-1:(h.segno(I-1)+1)
      LL = LL + Seg(J,1);                %distance between holes
      end %for J
   CutOff(NMH-I+1) = const*sqrt((b1^2/l1 + b2^2/l2)/(2*LL));
   end %for I
   for I=NMH:10
   CutOff(I) = NaN;
end

end
```

Appendix B

Instrument measurements

This section contains measurement data for each instrument, containing the final measurement information:

- First entry: a table containing
  - the joint description
  - the segment description (segment or named note)
  - the segment number, counting from the bell,
  - the total length at the end of each segment, starting from the bell,
  - the bore measurement at the end of each segment, starting from the bell,
- Second entry: a table showing the hole name, the segment number and the variables describing the tone hole geometry at the end of the segment in the bore at which the tonehole occurs, as described in chapter 6
- Third entry: a graph of the bore profile along the instrument,
- Fourth entry: the table of fingering for each note.
  - Column 1: listing of the notes as described in the datafile for that instrument and shown on the impedance spectra
  - Column 2: f_{440} : the nominal frequencies for the note on the instrument for a tuning pitch of A4 = 440 Hz
  - Column 3: table of the toneholes that are opened for each note. This is corresponds to the keys that are pressed on the earlier instruments. On the later instruments, auxiliary holes may be automatically operated by the fingering, namely those labelled Iaux and Vaux for the left- and right-hand brilles on the later instruments, these must be specifically included in the table. This detail is normally not shown in a conventional fingering chart.

This appendix is intended for scholars and for museum curators as a reference for their instruments. It is a reduced form of the full data file, which includes some processing to arrive at these tables (for example, averaging of elliptical holes). The raw data are available in the Excel files that accompany this thesis, whose structure is described in Appendix C. In this appendix the instruments are arranged in alphabetical order of museum sigla. The cell labels should be self-explanatory apart from the segment description 'Slug'. These rows give the dimensions of the inertance on either side of the hole between the tubes at the bottom of the butt joint, treated as closed holes in the modelling program. If a bassoon-form instrument does not have these entries for the bottom of the butt joint, it is constructed with a simple channel between the down and up tubes; this is a plain segment with no extra inertances.

These are reference tables. All discussions of the instruments are in Chapters 7 and 8 of the thesis.

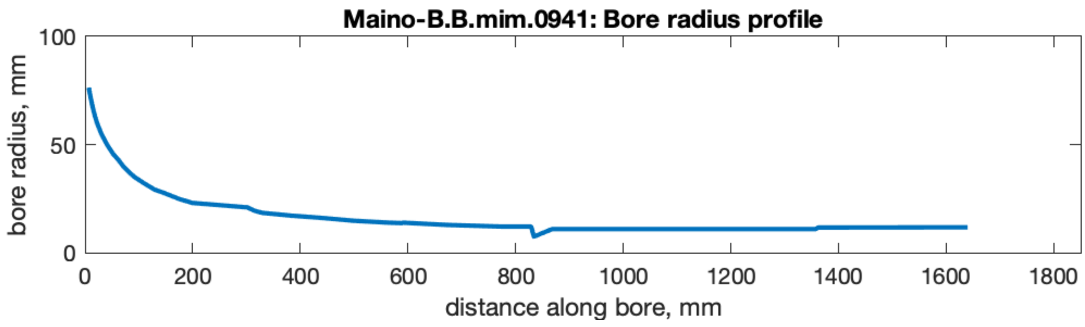
Maino B.B.mim.0941

Maino B.B.mim.0941 Bore dimensions

Joint description	Segment description	Segment No.	Length along bore from bell	Bore diameter
BELL FLANGE	Bell outside	-1	0.00	178.00
	Bell inside	0	0.00	173.00
BELL	Segment	1	7.00	152.60
	Segment	2	10.60	142.60
	Segment	3	16.00	130.75
	Segment	4	21.50	120.90
	Segment	5	30.50	109.70
	Segment	6	40.50	100.30
	Segment	7	52.00	91.45
	Segment	8	61.50	86.10
	Segment	9	71.50	79.70
	Segment	10	84.00	73.50
	Segment	11	92.50	69.80
	Segment	12	108.00	64.75
	Segment	13	128.60	58.60
	Segment	14	148.40	55.00
	Segment	15	174.80	49.80
	Segment	16	199.50	46.12
	Segment	17	302.00	42.00
BASS JOINT	Segment	18	304.00	41.40
	Segment	19	314.20	39.00
	Segment	20	317.90	38.50
	Segment	21	329.20	36.95
	Bb	22	344.00	36.25
	Segment	23	351.40	35.90
	Segment	24	383.90	34.35
	Segment	25	439.50	32.30
	Segment	26	498.00	29.70
	C	27	518.00	29.15
	Segment	28	561.60	27.95
	Segment	29	589.00	27.50
BUTT JOINT UP	Segment	30	590.00	27.90
	D	31	609.50	27.40
	Segment	32	634.50	26.75
	Segment	33	672.50	25.80
	RT	34	682.50	25.65

	EB	35	739.00	24.82
	Segment	36	774.00	24.30
	F#C#	37	803.00	24.30
(no slugs on this one)	Segment	38	829.00	24.30
BUTT JOINT DOWN	Segment	39	834.00	15.00
	FC	40	868.00	22.00
	G#Eb	41	885.00	22.00
	VI	42	946.00	22.00
	BbFcrs	43	977.00	22.00
	V	44	992.00	22.00
	IV	45	1047.00	22.00
	C#G#	46	1063.00	22.00
	Segment	47	1108.00	22.00
WING JOINT	**III**	**48**	1128.00	22.00
	EbBbside	**49**	1137.50	22.00
	II	**50**	1169.00	22.00
	I	**51**	1205.00	22.00
	FCside	**52**	1232.00	22.00
	LT	**53**	1258.00	22.00
	G#	**54**	1286.00	22.00
	A	**55**	1315.00	22.00
	Spkr1	56	1357.50	22.00
	Segment	57	1362.50	23.40
	Segment	58	1380.00	23.40
CROOK	Segment	59	1580.00	23.58
MOUTHPIECE	Segment	60	1640.00	23.58

Maino B.B.mim.0941 Bore graph



Maino B.B.mim.0941 Tonehole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BASS JOINT	Bb	22	O	16.60	2.00	20.27	8.70	48.00	0.50
BUTT JOINT UP	C	27	O	8.65	2.50	20.46	8.70	42.60	0.50
	D	31	C	11.70	2.00	18.30	9.12	62.92	0.50
	RT	34	O	13.65	0.00	0.00	14.16	62.45	0.50
	EB	35	O	16.05	6.70	20.70	13.00	60.70	0.50
BUTT JOINT DOWN	F#C#	37	C	11.70	4.00	20.80	12.00	57.05	0.50
	FC	40	O	13.42	6.00	20.48	12.00	58.50	0.50
	G#Eb	41	C	12.80	4.00	20.75	9.00	58.50	0.50
	VI	42	O	9.97	0.00	0.00	12.00	61.00	0.50
	BbFcrs	43	C	11.60	2.00	18.36	7.70	62.00	0.50
	V	44	O	13.20	0.00	0.00	13.50	62.80	0.50
	IV	45	O	13.78	2.50	20.47	13.50	62.85	0.50
WING JOINT	C#G#	46	C	11.28	7.50	20.80	9.20	68.15	0.50
	III	48	O	9.70	0.00	0.00	11.70	55.50	0.50
	EbBbside	49	C	8.70	5.00	14.75	6.30	55.87	0.50
	II	50	O	11.75	0.00	0.00	11.70	57.11	0.50
	I	51	O	14.00	0.00	0.00	11.70	58.52	0.50
	FCside	52	C	9.00	4.00	15.00	9.20	59.58	0.50
	LT	53	O	9.10	7.00	16.00	5.50	60.60	0.50
	G#	54	C	8.90	3.00	15.30	9.20	61.70	0.50
	A	55	C	10.20	2.00	18.00	11.70	62.83	0.50
	Spkr1	56	C	5.50	10.00	11.20	17.50	64.50	0.50

Maino B.B.mim.0941 Fingering table

Note	f_{440}	Fingering
C2	65.41	Bb,C,RT,EB,FC,VI,V,IV,III,II,I,LT
C#2	69.30	C,RT,EB,FC,VI,V,IV,III,II,I,LT
D2	73.42	RT,EB,FC,VI,V,IV,III,II,I,LT
Eb2	77.78	D,RT,EB,FC,VI,V,IV,III,II,I,LT
E2	82.41	EB,FC,VI,V,IV,III,II,I,LT
F2	87.31	FC,VI,V,IV,III,II,I,LT
F#2	92.50	F#C#,FC,VI,V,IV,III,II,I,LT
G2	98.00	VI,V,IV,III,II,I,LT
G#2	103.83	G#Eb,VI,V,IV,III,II,I,LT
A2	110.00	V,IV,III,II,I,LT
Bb2	116.54	BbFcrs,V,IV,III,II,I,LT
B2	123.47	BbFcrs,IV,III,II,I,LT
C3	130.81	III,II,I,LT
C#3	138.59	C#G#,III,II,I,LT
D3	146.83	II,I,LT
Eb3	155.56	EbBbside,II,I,LT
E3	164.81	I,LT
F3	174.61	LT
F#3	185.00	FCside,LT
G3	196.00	
G#3	207.65	G#
A3	220.00	A
Bb3	233.08	A,Spkr1
B3	246.94	EB,FC,VI,V,IV,III,II,I,LT,Spkr1
C4	261.63	FC,VI,V,IV,III,II,I,LT,Spkr1
C#4	277.18	FC,F#C#,VI,V,IV,III,II,I,LT,Spkr1
D4	293.66	VI,V,IV,III,II,I,LT,Spkr1
D#4	311.13	G#Eb,VI,V,IV,III,II,I,LT,Spkr1
E4	329.63	V,IV,III,II,I,LT,Spkr1
F4	349.23	BbFcrs,V,IV,III,II,I,LT,Spkr1
F#4	369.99	IV,III,II,I,LT,Spkr1
G4	392.00	III,II,I,LT,Spkr1
G#4	415.30	C#G#,III,II,I,LT,Spkr1
A4	440.00	II,I,LT,Spkr1
Bb4	466.16	EbBbside,II,I,LT,Spkr1
B4	493.88	I,LT,Spkr1
C5sk	523.25	FCside,I,LT,Spkr1

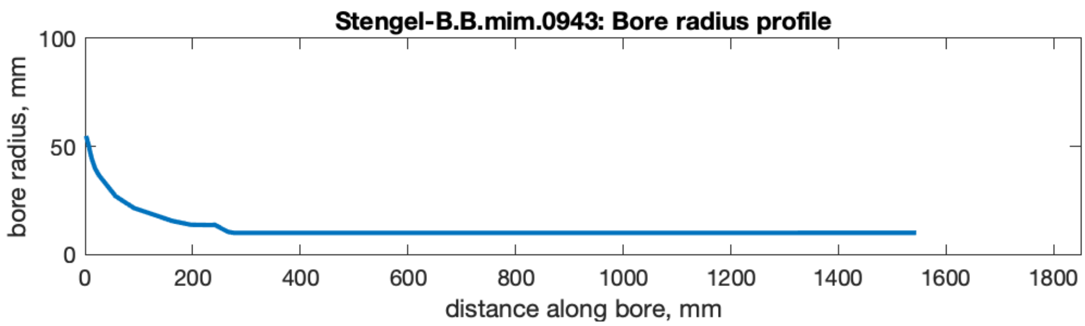
Stengel B.B.mim.0943

Stengel B.B.mim.0943 Bore dimensions

Joint description	Segment description	Segment No.	Length along bore from bell	Bore diameter
BELL FLANGE	Bell outside	-1	0.00	122.30
	Bell inside	0	0.00	119.70
BELL	Segment	1	2.00	109.70
	Segment	2	7.00	100.30
	Segment	3	10.90	91.45
	Segment	4	14.00	86.10
	Segment	5	18.50	79.70
	Segment	6	25.50	73.50
	Segment	7	55.00	55.00
	Segment	8	56.00	54.17
	Segment	9	91.00	42.90
	Segment	10	162.00	31.01
	Segment	11	197.00	27.47
	Segment	12	236.50	27.20
	Segment	13	240.00	27.20
BASS JOINT	Segment	14	240.00	27.70
	Segment	15	245.70	26.20
	Segment	16	247.00	25.80
	Segment	17	250.00	25.18
	Segment	18	251.10	24.69
	Segment	19	253.20	24.20
	Segment	20	254.25	23.89
	Segment	21	257.10	23.00
	Segment	22	259.55	22.55
	Segment	23	261.60	22.00
	Segment	24	263.30	21.45
	Segment	25	266.30	20.92
	Segment	26	267.70	20.70
	Segment	27	277.00	20.00
	C	28	307.50	20.00
	C#	29	364.00	20.00
	D	30	422.00	20.00
	Eb	31	481.00	20.00
	Segment	32	535.00	20.00
BUTT JOINT UP	**EB**	33	570.00	20.00

	F#C#	34	621.00	20.00
	FC	35	666.00	20.00
	slug up	36	714.00	20.00
	G#Eb	37	716.50	20.00
BUTT JOINT DOWN	slug down	38	719.00	20.00
	VI	39	759.00	20.00
	BbFcrs	40	808.40	20.00
	V	41	810.00	20.00
	Va	42	871.00	20.00
	IV	43	887.50	20.00
WING JOINT	**C#G#**	44	945.00	20.00
	EbBbside	45	987.40	20.00
	III	46	1000.50	20.00
	II	47	1047.50	20.00
	FCside	48	1048.50	20.00
	Btrill	49	1080.00	20.00
	I	50	1083.00	20.00
	LT	51	1104.50	20.00
	G#	52	1138.50	20.00
	A	53	1162.00	20.00
	Spkr2	54	1210.00	20.00
	Spkr1	55	1266.00	20.00
	Segment	56	1290.50	20.00
CROOK	Segment	57	1474.50	20.04
MOUTHPIECE	Segment	58	1544.50	20.04

Stengel B.B.mim.0943 Bore graph



Stengel B.B.mim.0943 Tonehole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BASS JOINT	C	28	O	15.26	10.00	23.80	3.00	32.8	0.50
	C#	29	O	16.02	8.90	23.70	3.00	32.6	0.10
	D	30	O	16.11	9.50	23.60	3.00	32.9	0.10
	Eb	31	O	23.29	10.00	31.50	3.00	32.9	0.10
BUTT JOINT UP	EB	33	O	13.80	5.00	19.40	9.50	53.5	0.10
	F#C#	34	C	11.28	5.00	19.26	9.50	54.6	0.10
	FC	35	O	13.50	6.20	19.60	9.50	55.5	0.10
	Slug	36	C	20.00	10.00	10.00	15.00	55.5	0.10
	G#Eb	37	C	11.83	6.50	22.56	9.50	52.5	0.10
BUTT JOINT DOWN	Slug	38	C	20.00	10.00	10.00	15.00	52.5	0.10
	VI	39	O	12.80	3.50	18.97	9.50	53.5	0.10
	BbFcrs	40	C	8.45	4.00	17.77	9.50	54.9	0.10
	V	41	O	12.60	5.00	19.29	9.50	54.9	0.10
	Va	42	O	7.50	1.00	13.25	9.50	56.6	0.10
	IV	43	O	9.40	0.00	0.00	9.50	57.0	0.10
WING JOINT	C#G#	44	C	7.50	4.10	17.44	6.20	32.0	0.10
	EbBbside	45	C	9.40	2.50	17.69	7.70	43.5	0.10
	III	46	O	8.30	0.00	0.00	19.40	45.0	0.50
	II	47	O	9.10	0.00	0.00	19.62	45.0	0.50
	FCside	48	C	6.85	4.00	15.70	7.00	45.0	0.50
	Btrill	49	C	8.00	3.50	15.50	7.00	45.0	0.10
	I	50	O	9.40	0.00	0.00	17.00	45.0	0.10
	LT	51	O	10.60	4.00	22.50	7.00	32.9	0.10
	G#	52	C	7.50	4.20	15.80	8.00	32.5	0.10
	A	53	C	8.60	3.80	17.80	8.00	31.7	0.10
	Spkr2	54	C	5.40	3.20	14.40	6.20	32.3	0.10
	Spkr1	55	C	5.40	2.50	12.45	6.30	32.6	0.10

Stengel B.B.mim.0943 Fingering table

Note	f_{440}	Fingering
C2	58.27	C,C#,D,Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
C#2	61.74	C#,D,Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
D2	65.41	D, Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
Eb2	69.30	Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
E2	73.42	EB,FC,VI,V,Va,IV,III,II,I,LT
F2	77.78	FC,VI,V,Va,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,Va,IV,III,II,I,LT
G2	87.31	VI,V,Va,IV,III,II,I,LT
G#2	92.50	G#Eb,VI,V,Va,IV,III,II,I,LT
A2	98.00	V,Va,IV,III,II,I,LT
Bb2	103.83	BbFcrs,V,Va,IV,III,II,I,LT
B2	**110.00**	IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	C#G#,III,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	EbBbside,II,I,LT
E3	146.83	I,LT
F3sk	155.56	FCside,I,LT
F#3	164.81	LT
G3	174.61	
G#3	185.00	G#
A3	196.00	A
Bb3	207.65	A,Spkr2
B3	220.00	EB,FC,VI,V,Va,IV,III,II,I,LT,Spkr2
C4	233.08	FC,VI,V,Va,IV,III,II,I,LT,Spkr2
C#4	246.94	FC,F#C#,VI,V,Va,IV,III,II,I,LT,Spkr2
D4	261.63	VI,V,Va,IV,III,II,I,LT,Spkr2
D#4	277.18	G#Eb,VI,V,Va,IV,III,II,I,LT,Spkr1
E4	293.66	V,Va,IV,III,II,I,LT,Spkr1
F4	311.13	BbFcrs,V,Va,IV,III,II,I,LT,Spkr1
F#4	329.63	IV,III,II,I,LT,Spkr1
G4	349.23	III,II,I,LT,Spkr1
G#4	369.99	C#G#,III,II,I,LT,Spkr1
A4	392.00	II,I,LT,Spkr1
Bb4	415.30	EbBbside,II,I,LT,Spkr1
B4	440.00	I,LT,Spkr1
C5sk	466.16	FCside,I,LT,Spkr1

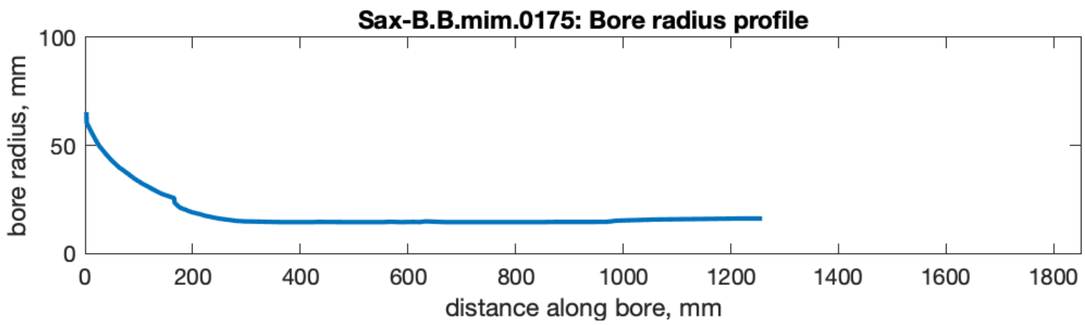
Sax B.B.mim.0175

Sax B.B.mim.0175 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0	170
	Bell inside	0	0.00	141.00
BELL	Segment	1	2.50	130.75
	Segment	2	3.00	120.90
	Segment	3	14.50	109.70
	Segment	4	25.00	100.30
	Segment	5	39.50	91.45
	Segment	6	49.50	86.10
	Segment	7	63.00	79.70
	Segment	8	80.50	73.50
	Segment	9	90.00	69.80
	Segment	10	105.75	64.75
	Segment	11	129.00	58.60
	Segment	12	143.00	55.00
	Segment	13	166.00	51.10
LOWER JOINT	Segment	14	166.00	47.40
	Segment	15	168.00	46.12
	Segment	16	177.00	42.11
	Segment	17	178.50	42.00
	Segment	18	193.80	39.00
	Segment	19	197.10	38.50
	Segment	20	200.10	38.00
	Segment	21	204.50	37.50
	Segment	22	208.20	36.95
	Segment	23	213.00	36.40
	Segment	24	216.50	35.90
	Segment	25	220.30	35.40
	Segment	26	223.50	34.85
	Segment	27	228.70	34.35
	Segment	28	233.70	33.80
	EB	29	236.00	33.53
	Segment	30	238.00	33.30
	Segment	31	248.50	32.30
	Segment	32	280.50	30.20

	Segment	33	295.50	29.70
	F#C#	34	309.00	29.56
	FC	35	365.00	29.00
	G#Eb	36	422.00	29.00
	Segment	37	434.50	29.20
	VI	38	485.00	29.00
	BbFcrs	39	520.00	29.00
	V	40	555.00	29.00
	Segment	41	567.00	29.30
	F#B	42	587.00	29.00
	Segment	43	612.20	29.20
	IV	44	622.00	29.00
	Segment	45	632.50	29.70
UPPER JOINT	**C#G#**	46	668.50	29.00
	III	47	704.50	29.00
	EbBbalt	48	731.50	29.00
	EbBbside	49	733.50	29.00
	II	50	764.50	29.00
	FCside	51	795.50	29.00
	I	52	826.50	29.00
	LT	53	849.50	29.00
	G#	54	878.50	29.20
	A	55	918.00	29.20
	Segment	56	949.80	29.20
	Segment	57	971.00	29.30
CROOK	**Spkr1**	58	986.40	30.30
	Spkr2	59	1058.90	31.40
	Segment	60	1213.00	32.30
MOUTHPIECE	Segment	61	1258.00	32.30

Sax B.B.mim.0175 Bore graph



Sax B.B.mim.0175 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
LOWER JOINT	EB	29	O	26.8	11.2	33.2	10.0	53.5	0.1
	F#C#	34	C	23.4	11.5	33.2	9.9	49.4	0.1
	FC	35	O	25.28	7.5	33.3	9.0	47.0	0.1
	G#Eb	36	C	22.5	4.0	33.2	8.4	45.7	0.1
	VI	38	O	16.59	9.8	25.9	7.7	44.3	0.1
	BbFcrs	39	C	16.3	10.0	25.7	7.5	44.0	0.1
	V	40	O	13.52	9.3	25.8	7.5	44.0	0.1
	F#B	42	C	11.22	5.7	25.6	7.6	44.1	0.1
	IV	44	O	15.93	9.7	25.5	7.7	44.4	0.1
UPPER JOINT	C#G#	46	C	9.76	8.5	23.7	7.6	44.3	0.1
	III	47	O	13.48	8	23.8	7.7	44.3	0.1
	EbBbalt	48	C	10.51	3.6	23.8	7.7	44.3	0.1
	EbBbside	49	C	10.51	5.7	23.8	7.7	44.3	0.1
	II	50	O	13.7	9.5	23.8	7.8	44.5	0.1
	FCside	51	C	12.78	5.5	23.7	7.6	44.15	0.1
	I	52	O	12.2	7	23.8	7.6	44.1	0.1
	LT	53	O	13.78	7.4	25.78	7.6	44.16	0.1
	G#	54	C	11.5	4.45	23.67	7.6	44.36	0.1
	A	55	C	14	4.9	23.9	7.6	44.35	0.1
CROOK	Spkr1	58	C	6.8	5.83	15.2	23.87	17	0.1
	Spkr2	59	C	3.1	10	15.4	7.5	35.8	0.1

Sax B.B.mim.0175 Fingering table

Note	f_{440}	Fingering
E2	73.42	EB,FC,VI,V,IV,III,II,I,LT
F2	77.78	FC,VI,V,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,IV,III,II,I,LT
G2	87.31	VI,V,IV,III,II,I,LT
G#2	92.5	G#Eb,VI,V,IV,III,II,I,LT
A2	98	V,IV,III,II,I,LT
Bb2	103.83	BbFcrs,V,IV,III,II,I,LT
B2	**110**	F#B,IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	C#G#,III,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	EbBbside,II,I,LT
E3	146.83	I,LT
F3sk	155.56	FCside,I,LT
F#3	164.81	LT
G3	174.61	
G#3	184.99	G#
A3	195.99	A
Bb3	207.65	A,Spkr1
B3	220	EB,FC,VI,V,IV,III,II,I,LT,Spkr1
C4	233.08	FC,VI,V,IV,III,II,I,LT,Spkr1
C#4	246.94	F#C#,FC,VI,V,IV,III,II,I,LT,Spkr1
D4	261.62	VI,V,IV,III,II,I,LT
D#4	277.18	G#Eb,VI,V,IV,III,II,I,LT,Spkr1
E4	293.66	V,IV,III,II,I,LT,Spkr1
F4	311.12	BbFcrs,V,IV,III,II,I,LT,Spkr1
F#4	329.62	F#B,IV,III,II,I,LT,Spkr1
G4	349.22	III,II,I,LT,Spkr1
G#4	369.99	C#G#,III,II,I,LT,Spkr1
A4	391.99	II,I,LT,Spkr1
Bb4	415.3	EbBbside,II,I,LT,Spkr1
B4	440	I,LT,Spkr1
C5sk	466.16	FCside,I,LT,Spkr1

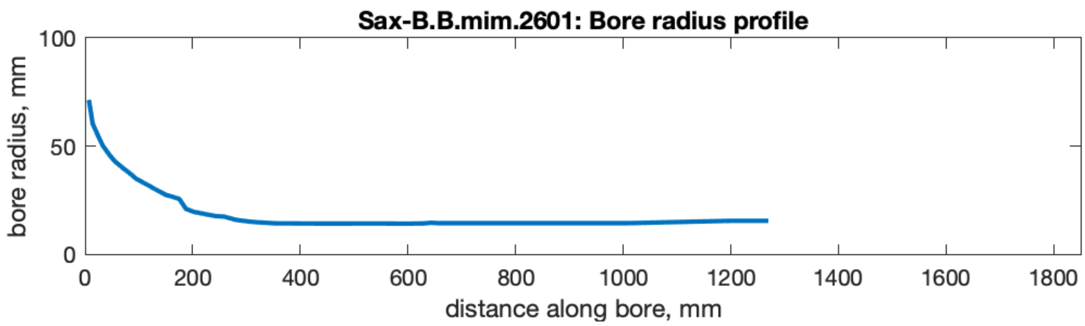
Sax B.B.mim.2601

Sax B.B.mim.2601 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0	171
	Bell inside	0	0.00	160.50
BELL	Segment	1	7.00	142.60
	Segment	2	11.00	130.75
	Segment	3	14.00	120.90
	Segment	4	24.00	109.70
	Segment	5	33.00	100.30
	Segment	6	46.00	91.45
	Segment	7	55.00	86.10
	Segment	8	70.50	79.70
	Segment	9	86.50	73.50
	Segment	10	95.00	69.80
	Segment	11	114.00	64.75
	Segment	12	136.00	58.60
	Segment	13	150.00	55.00
	Segment	14	175.00	51.30
LOWER JOINT	Segment	15	187.50	42.00
	Segment	16	203.50	39.00
	Segment	17	210.50	38.50
	Segment	18	214.00	38.00
	Segment	19	221.00	37.50
	Segment	20	224.50	36.95
	Segment	21	232.00	36.40
	Segment	22	236.50	35.90
	Segment	23	243.00	35.40
	EB	24	255.00	34.97
	Segment	25	258.50	34.85
	Segment	26	281.00	31.80
	Segment	27	306.50	30.20
	F#C#	28	308.00	30.14
	Segment	29	318.50	29.70
	Segment	30	353.00	28.67
	FC	31	374.00	28.61
	G#Eb	32	428.00	28.45
	Segment	33	441.50	28.44
	VI	34	496.00	28.45

	BbF	35	525.00	28.45
	V	36	561.00	28.45
	F#B	37	599.00	28.36
	IV	38	631.00	28.60
	Segment	39	642.00	29.20
UPPER JOINT	Segment	40	656.00	28.80
	C#G#	41	675.20	28.80
	III	42	710.00	28.80
	EbBb	43	738.00	28.80
	II	44	775.00	28.80
	FCside	45	803.00	28.80
	I	46	830.00	28.80
	LT	47	862.00	28.80
	G#	48	885.00	28.80
	A	49	922.00	28.80
	Segment	50	948.00	28.80
CROOK	**Spk1**	51	1008.00	28.80
	Spk2	52	1068.00	29.49
	Segment	53	1199.70	31.00
MOUTHPIECE	Segment	54	1269.70	31.00

Sax B.B.mim.2601 Bore graph



Sax B.B.mim.2601 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
LOWER JOINT	EB	24	O	26	7.5	33.9	9.5	54.0	0.1
	F#C#	28	C	25	6.9	34.0	9.9	50.0	0.1
	FC	31	O	25	9.7	34.0	9.1	46.8	0.1
	G#Eb	32	C	22	4.0	33.5	8.4	45.2	0.1
	VI	34	O	15.23	9.6	26.0	7.8	44.1	0.1
	BbF	35	C	18	7.0	26.0	7.8	44.0	0.1
	V	36	O	12.5	2.5	25.6	7.8	44.0	0.1
	F#B	37	C	11	6.2	26.0	7.6	43.6	0.1
	IV	38	O	13.6	8.7	26.0	7.5	43.6	0.1
UPPER JOINT	C#G#	41	C	9.7	4.6	24.2	7.5	43.8	0.1
	III	42	O	12.4	7.3	24	7.7	44.2	0.1
	EbBb	43	C	11.1	10	24	7.8	44.4	0.1
	II	44	O	12.8	6	25	7.9	44.5	0.1
	FCside	45	C	13	5	24	7.7	44.2	0.5
	I	46	O	13.4	8	24	7.5	43.8	0.1
	LT	47	O	13.4	8.4	26.2	7.4	43.6	0.1
	G#	48	C	13.7	5.7	24	7.8	44.3	0.1
	A	49	C	15	4.5	24	7.9	44.6	0.1
CROOK (from E)	Spk1	51	C	7.5	5.3	15.6	17	15	0.1
	Spk2	52	C	2.35	7.5	15.4	4	32	0.1

Sax B.B.mim.2601 Fingering table

Note	f_{440}	Fingering
E2	73.42	EB,FC,VI,V,IV,III,II,I,LT
F2	77.78	FC,VI,V,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,IV,III,II,I,LT
G2	87.31	VI,V,IV,III,II,I,LT
G#2	92.5	G#Eb,VI,V,IV,III,II,I,LT
A2	98	V,IV,III,II,I,LT
Bb2	103.83	BbF,V,IV,III,II,I,LT
B2	**110**	F#B,IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	C#G#,III,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	EbBb,II,I,LT
E3	146.83	I,LT
F3sk	155.56	FCside,I,LT
F#3	164.81	LT
G3	174.61	
G#3	184.99	G#
A3	195.99	A
Bb3	207.65	A,Spk1
B3	220	EB,FC,VI,V,IV,III,II,I,LT,Spk1
C4	233.08	FC,VI,V,IV,III,II,I,LT,Spk1
C#4	246.94	F#C#,FC,VI,V,IV,III,II,I,LT,Spk1
D4	261.62	VI,V,IV,III,II,I,LT
D#4	277.18	G#Eb,VI,V,IV,III,II,I,LT,Spk1
E4	293.66	V,IV,III,II,I,LT,Spk1
F4	311.12	BbF,V,IV,III,II,I,LT,Spk1
F#4	329.62	F#B,IV,III,II,I,LT,Spk1
G4	349.22	III,II,I,LT,Spk1
G#4	369.99	C#G#,III,II,I,LT,Spk1
A4	391.99	II,I,LT,Spk1
Bb4	415.3	EbBb,II,I,LT,Spk1
B4	440	I,LT,Spk1
C5	466.16	FCside,I,LT,Spk1

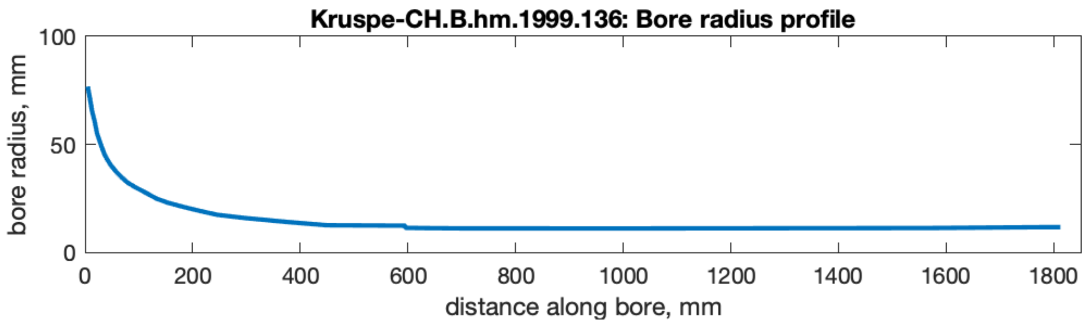
Kruspe CH.B.hm.1999.136

Kruspe CH.B.hm.1999.136 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0.00	168.00
	Bell inside	0	0.00	167.00
BELL	Segment	1	5.00	153.55
measure from exit	Segment	2	9.00	142.60
	Segment	3	13.00	130.75
	Segment	4	18.50	119.75
	Segment	5	22.50	109.70
	Segment	6	28.00	101.60
	Segment	7	35.50	91.45
	Segment	8	40.50	86.60
	Segment	9	48.00	80.60
	Segment	10	58.70	74.20
	Segment	11	68.80	69.10
	Segment	12	78.80	64.75
	Segment	13	91.20	60.95
	Segment	14	118.40	53.75
	Segment	15	132.60	49.85
	Segment	16	153.90	46.00
	Segment	17	184.70	41.90
	Segment	18	217.20	38.00
	Segment	19	245.70	34.85
	Segment	20	298.00	31.80
	Segment	21	376.20	28.20
	Bb	22	408.00	26.89
	Segment	23	446.80	25.30
	Segment	24	455.70	25.18
	Segment	25	595.00	24.80
BASS JOINT	Segment	26	595.00	22.80
	C	27	607.00	22.72
	Segment	28	632.00	22.55

	D	29	684.00	22.35
	Segment	30	698.50	22.30
	Eb	31	736.50	22.30
	EB	32	785.00	22.30
	F#C#	33	845.00	22.30
BUTT JOINT UP	slug down	34	895.00	22.20
	FC	35	897.50	22.20
	slug up	36	900.00	22.20
BUTT JOINT DOWN	**G#Eb**	37	953.00	22.20
	VI	38	992.00	22.23
	BbFcrs	39	1032.00	22.25
	V	40	1052.00	22.26
	BF#	41	1092.00	22.29
	IV	42	1122.00	22.31
WING JOINT	**C#G#**	43	1173.00	22.34
	III	44	1197.00	22.36
	EbBbside	45	1228.50	22.38
	II	46	1265.00	22.40
	FCside	47	1300.00	22.43
	I	48	1308.00	22.43
	ANO	49	1340.00	22.45
	LT	50	1373.00	22.47
	G#	51	1392.00	22.49
	A	52	1415.00	22.50
	Spkr1	53	1537.50	22.58

Kruspe CH.B.hm.1999.136 Bore graph



Kruspe CH.B.hm.1999.136 Tonehole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BELL	Bb	22	O	15.88	6.40	21.60	3.00	28.30	0.5
BASS JOINT	C	27	O	17.38	7.50	25.00	9.00	37.70	0.5
	D	29	O	17.38	7.50	25.00	9.00	37.80	0.5
	Eb	31	O	17.38	7.50	25.00	9.00	37.70	0.5
	EB	32	O	17.38	7.50	25.00	9.00	37.00	0.5
	F#C#	33	C	17.38	7.50	25.00	9.00	36.60	0.5
BUTT JOINT UP	slug down	34	C	22.20	10.00	10.00	17.00	55.00	0.5
	FC	35	O	17.38	7.50	25.00	9.00	58.80	0.5
	slug up	36	C	22.20	10.00	10.00	17.00	55.00	0.5
BUTT JOINT DOWN	G#Eb	37	C	12.20	5.70	20.40	6.10	37.40	0.5
	VI	38	O	16.40	7.50	23.20	5.59	37.40	0.5
	BbFcrs	39	C	17.25	5.00	22.80	5.56	37.40	0.5
	V	40	O	12.43	0.00	0.00	7.57	37.40	0.5
	BF#	41	C	13.50	4.00	20.40	5.48	37.40	0.5
	IV	42	O	16.50	5.00	22.70	5.43	37.40	0.5
WING JOINT	C#G#	C	C	8.00	3.00	18.00	5.41	37.5	0.5
	III	44	O	18.10	5.00	21.00	4.33	37.50	0.5
	EbBbside	45	C	12.00	1.00	19.60	5.56	37.50	0.5
	II	46	O	11.40	0.00	0.00	7.55	37.50	0.5
	FCside	47	C	10.15	3.00	20.80	4.02	37.50	0.5
	I	48	O	11.40	0.00	0.00	7.53	37.50	0.5
	ANO	49	C	13.40	4.00	20.60	4.52	37.50	0.5
	LT	50	O	10.60	4.50	20.50	5.64	37.50	0.5
	G#	51	C	8.65	3.00	17.70	5.00	37.50	0.5
	A	52	C	12.00	4.00	23.00	4.35	37.50	0.5
	Spkr1	53	C	4.50	4.00	17.80	19.50	37.50	0.5

Kruspe CH.B.hm.1999.136 Fingering table

Note	f_{440}	Fingering
Bb1	51.91	Bb,C,D,Eb,EB,FC,VI,V,IV,III,II,I,LT
C2	58.27	C,D,Eb,EB,FC,VI,V,IV,III,II,I,LT
D2	65.41	D,Eb,EB,FC,VI,V,IV,III,II,I,LT
Eb2	69.30	Eb,EB,FC,VI,V,IV,III,II,I,LT
E2	73.42	EB,FC,VI,V,IV,III,II,I,LT
F2	77.78	FC,VI,V,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,IV,III,II,I,LT
G2	87.31	VI,V,IV,III,II,I,LT
G#2	92.50	G#Eb,VI,V,IV,III,II,I,LT
A2	98.00	V,IV,III,II,I,LT
Bb2	103.83	BbFcrs,V,IV,III,II,I,LT
B2	**110.00**	BF#,IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	C#G#,III,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	EbBbside,II,I,LT
E3	146.83	I,LT
F3sk	155.56	FCside,I,LT
F#3	164.81	LT,FCside
G3	174.61	
G#3	185.00	G#
A3	196.00	A
Bb3	207.65	A,Spkr1
B3	220.00	EB,FC,VI,V,IV,III,II,I,LT,Spkr1
C4	233.08	FC,VI,V,IV,III,II,I,LT,Spkr1
C#4	246.94	FC,F#C#,VI,V,IV,III,II,I,LT,Spkr1
D4	261.63	VI,V,IV,III,II,I,LT,Spkr1
D#4	277.18	G#Eb,VI,V,IV,III,II,I,LT,Spkr1
E4	293.66	V,IV,III,II,I,LT,Spkr1
F4	311.13	BbFcrs,V,IV,III,II,I,LT,Spkr1
F#4	329.63	BF#,IV,III,II,I,LT,Spkr1
G4	349.23	III,II,I,LT,Spkr1
G#4	369.99	C#G#,III,II,I,LT,Spkr1
A4	392.00	II,I,LT,Spkr1
Bb4	415.30	EbBbside,II,I,LT,Spkr1
B4	440.00	I,LT,Spkr1
C5sk	466.16	FCside,I,LT,Spkr1

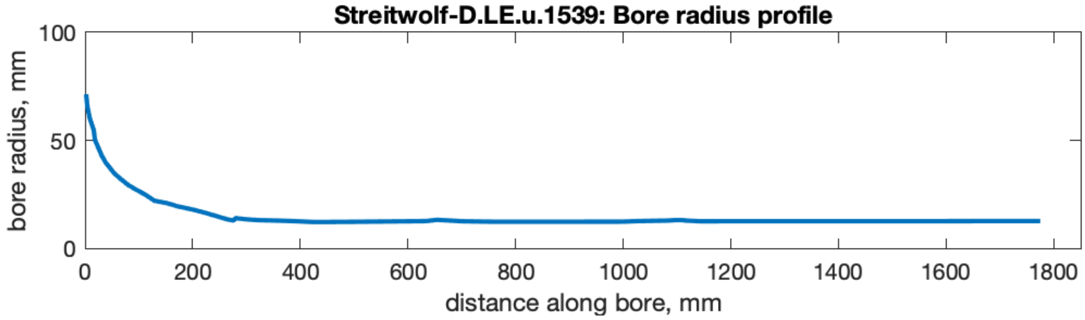
Streitwolf D.LE.u.1539

Streitwolf D.LE.u.1539 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0.00	155.50
	Bell inside	0	0.00	151.00
BELL	Segment	1	2.00	142.60
	Segment	2	4.50	130.75
	Segment	3	8.50	120.90
	Segment	4	16.00	109.70
	Segment	5	18.50	100.30
	Segment	6	30.75	86.10
	Segment	7	38.00	79.70
	Segment	8	47.80	73.50
	Segment	9	53.80	69.80
	Segment	10	65.00	64.75
	Segment	11	80.50	58.60
	Segment	12	92.80	55.00
	Segment	13	111.90	49.80
	Segment	14	129.00	44.12
	Segment	15	151.50	41.99
	Segment	16	172.00	39.00
	Segment	17	200.80	35.90
	Segment	18	224.50	32.80
	Segment	19	245.60	29.70
	Segment	20	265.50	26.75
	Segment	21	276.50	25.90
BASS JOINT	Segment	22	280.00	28.20
	Segment	23	284.60	27.75
	Segment	24	305.20	26.75
	Bb	25	306.50	26.71
	Segment	26	321.80	26.20
	Segment	27	356.90	25.80
	B	28	394.00	25.19
	Segment	29	394.50	25.18
	Segment	30	414.30	24.69
	Segment	31	426.70	24.45
	Segment	32	435.50	24.45
	C	33	478.50	24.61
	Segment	34	501.50	24.69

	C#	35	554.50	24.94
	D	36	614.00	25.23
	Segment	37	632.50	25.32
BUTT JOINT UP	Segment	38	654.59	26.47
	Eb	39	688.00	25.55
	Segment	40	701.59	25.18
	EB	41	741.00	24.86
	Segment	42	742.49	24.85
	Segment	43	770.50	24.69
	F#C#	44	801.50	24.69
	FC	45	856.50	24.69
	Segment	46	880.00	24.69
BUTT JOINT DOWN	Segment	47	885.00	24.69
	G#Eb	48	913.50	24.75
	VI	49	949.00	24.81
	BbFcrs	50	993.50	24.79
	Segment	51	1003.00	24.90
	Segment	52	1025.00	25.30
	V	53	1044.00	25.47
	Segment	54	1081.75	25.80
	IV	55	1095.50	26.20
	Segment	56	1109.70	26.20
WING JOINT	Segment	57	1116.70	25.80
	C#G#	58	1142.70	25.20
	Segment	59	1143.50	25.18
	EbBbside	60	1199.70	25.20
	III	61	1211.70	25.20
	II	62	1253.70	25.20
	FCside	63	1279.70	25.20
	I	64	1297.70	25.20
	LT	65	1330.70	25.20
	G#	66	1365.70	25.20
	A	67	1392.70	25.20
	Spkr1	68	1479.20	25.20
	Segment	69	1514.70	25.20
CROOK	Segment	70	1715.60	25.37
MOUTHPIECE	Segment	71	1775.00	25.37

Streitwolf D.LE.u.1539 Bore Graph



Streitwolf D.LE.u.1539 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BASS JOINT	Bb	25	O	16.55	9.30	24.90	5.80	38.30	0.50
	C	33	C	13.60	6.50	21.20	6.20	37.00	0.50
	C#	35	O	15.80	8.00	24.00	5.70	36.70	0.50
	D	36	O	24.00	8.00	23.00	8.95	36.70	0.50
BUTT JOINT UP	Eb	39	O	17.88	10.50	26.50	19.00	58.90	0.50
	EB	41	O	17.80	6.20	21.80	6.50	57.90	0.50
	F#C#	44	C	13.83	4.50	22.40	6.50	56.30	0.50
	FC	45	O	19.50	5.50	23.90	13.00	54.60	0.10
BUTT JOINT DOWN	G#Eb	48	C	14.80	11.00	22.74	7.00	54.40	0.50
	VI	49	O	15.20	6.50	22.40	9.50	55.70	0.50
	BbFcrs	50	C	14.00	8.50	21.20	7.00	57.25	0.50
	V	53	O	10.75	0.00	0.00	11.10	58.15	0.50
	IV	55	O	11.11	0.00	0.00	10.20	58.70	0.50
WING JOINT	C#G#	58	C	8.25	6.00	17.00	5.50	54.50	0.50
	EbBbside	60	C	7.50	5.60	17.70	5.50	54.50	0.50
	III	61	O	10.90	0.00	0.00	17.00	62.50	0.50
	II	62	O	11.00	0.00	0.00	16.00	62.50	0.50
	FCside	63	C	11.40	4.60	20.30	5.50	62.50	0.50
	I	64	O	11.35	0.00	0.00	16.00	62.50	0.50
	LT	65	O	9.50	8.00	19.30	3.00	62.50	0.50
	G#	66	C	8.50	6.00	19.80	5.50	38.45	0.50
	A	67	C	7.50	9.60	19.90	5.50	38.80	0.50
	Spkr1	68	C	3.70	9.00	14.00	6.50	38.80	0.10

Streitwolf D.LE.u.1539 Fingering table

Note	f_{440}	Fingering
Bb1	51.91	Bb,B,C#,D,Eb,EB,FC,VI,V,IV,III,II,I,LT
B1	55.00	B,C#,D,Eb,EB,FC,VI,V,IV,III,II,I,LT
C2	58.27	D,C#,Eb,EB,FC,VI,V,IV,III,II,I,LT
C#2	61.74	D,C#,C,Eb,EB,FC,VI,V,IV,III,II,I,LT
D2	65.41	D,Eb,EB,FC,VI,V,IV,III,II,I,LT
Eb2	69.30	Eb,EB,FC,VI,V,IV,III,II,I,LT
E2	73.42	EB,FC,VI,V,IV,III,II,I,LT
F2	77.78	FC,VI,V,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,IV,III,II,I,LT
G2	87.31	VI,V,IV,III,II,I,LT
G#2	92.50	G#Eb,VI,V,IV,III,II,I,LT
A2	98.00	V,IV,III,II,I,LT
Bb2	103.83	BbFcrs,V,IV,III,II,I,LT
B2	**110.00**	BbFcrs,IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	C#G#,III,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	EbBbside,II,I,LT
E3	146.83	I,LT
F3	155.56	LT
F#3	164.81	FCside,LT
G3	174.61	
G#3	185.00	G#
A3	196.00	A
Bb3	207.65	A,Spkr1
B3	220.00	EB,FC,VI,V,IV,III,II,I,LT,Spkr1
C4	233.08	FC,VI,V,IV,III,II,I,LT,Spkr1
C#4	246.94	FC,F#C#,VI,V,IV,III,II,I,LT,Spkr1
D4	261.63	VI,V,IV,III,II,I,LT,Spkr1
D#4	277.18	G#Eb,VI,V,IV,III,II,I,LT,Spkr1
E4	293.66	V,IV,III,II,I,LT,Spkr1
F4	311.13	BbFcrs,V,IV,III,II,I,LT,Spkr1
F#4	329.63	IV,III,II,I,LT,Spkr1
G4	349.23	III,II,I,LT,Spkr1
G#4	369.99	C#G#,III,II,I,LT,Spkr1
A4	392.00	II,I,LT,Spkr1
Bb4	415.30	EbBbside,II,I,LT,Spkr1
B4	440.00	I,LT,Spkr1
C5LT	466.16	LT,Spkr1

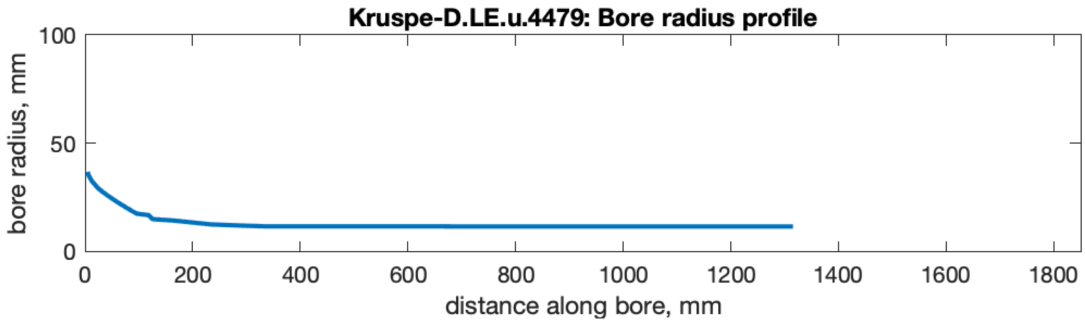
Kruspe D.LE.u.4479

Kruspe D.LE.u.4479 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0	131.2
	Bell inside	0	0.00	75.44
BELL	Segment	1	5.00	73.50
	Segment	2	7.00	69.80
	Segment	3	13.00	64.75
	Segment	4	23.60	58.60
	Segment	5	32.50	55.00
	Segment	6	46.80	49.80
	Segment	7	58.00	46.12
	Segment	8	71.50	41.99
	Segment	9	83.00	38.50
	Segment	10	88.30	36.95
	Segment	11	96.00	34.85
	Segment	12	118.50	33.40
LOWER JOINT	Segment	13	124.50	30.20
	Segment	14	127.50	29.70
	Segment	15	141.90	29.20
	Segment	16	159.20	28.67
	Segment	17	169.30	28.20
	Eb	18	183.50	27.48
	Segment	19	235.30	24.85
	EB	20	254.00	24.50
	Segment	21	284.70	23.93
	F#C#	22	319.50	23.37
	Segment	23	334.00	23.13
	FC	24	379.50	23.10
	G#Eb1	25	444.50	23.10
	VI	26	504.50	23.10
	BbFcrs	27	553.50	23.10
	V	28	575.50	23.10
	Va	29	596.50	23.10

	IV	30	638.50	23.10
	Segment	31	657.10	23.10
UPPER JOINT	Segment	32	683.50	23.00
	C#G#	33	692.10	23.00
	III	34	716.44	23.00
	EbBbside	35	751.10	23.00
	II	36	781.60	23.00
	FCside	37	815.10	23.00
	I	38	823.60	23.00
	Ia	39	854.10	23.00
	LT	40	875.60	23.00
	G#	41	911.10	23.00
	A	42	942.10	23.00
	Trill1	43	1029.60	23.00
	Spkr1	44	1086.60	23.00
	Segment	45	1247.60	23.00
MOUTHPIECE	Segment	46	1315.60	23.00

Kruspe D.LE.u.4479 Bore graph



Kruspe D.LE.u.4479 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
LOWER JOINT	Eb	18	O	18.10	6.1	24.5	6.16	39.8	0.5
	EB	20	O	20.80	6.0	25.2	7.45	39.4	0.5
	F#C#	22	C	17.93	6.2	23.5	7.72	38.8	0.5
	FC	24	O	20.09	6.2	25.0	7.05	37.2	0.5
	G#Eb1	25	C	17.00	5.0	23.2	6.55	37.2	0.5
	VI	26	O	12.75	7.5	23.2	7.05	37.2	0.5
	BbFcrs	27	C	11.10	3.5	17.2	6.55	37.2	0.5
	V	28	O	10.80	5.8	17.6	6.45	37.0	0.5
	Va	29	O	10.20	5.40	16.40	6.90	37.90	0.5
	IV	30	O	12.85	6.50	23.10	6.85	37.80	0.5
UPPER JOINT	C#G#	33	C	8.80	3.60	16.35	7.00	37.30	0.5
	III	34	O	14.20	5.00	22.80	5.00	37.20	0.5
	EbBbside	35	C	9.90	4.50	18.00	6.00	37.30	0.5
	II	36	O	13.50	4.70	23.26	4.50	37.70	0.5
	FCside	37	C	11.50	3.60	17.30	6.90	37.80	0.5
	I	38	O	12.50	5.00	17.25	6.40	37.25	0.5
	Ia	39	O	8.80	5.00	16.10	6.40	37.25	0.5
	LT	40	O	11.20	6.00	23.80	4.40	37.50	0.5
	G#	41	C	9.80	3.50	17.50	6.50	37.50	0.5
	A	42	C	9.30	3.90	23.35	4.40	37.50	0.5
	Trill1	43	C	5.15	3.90	13.19	11.90	27.00	0.5
	Spkr1	44	C	4.00	3.10	13.26	13.90	27.00	0.5

Kruspe D.LE.u.4479 Fingering table

Note	f_{440}	Fingering (incl. auxiliary hole Ia, Va)
E2	73.42	EB,FC,VI,V,Va,IV,III,II,I,Ia,LT
F2	77.78	FC,VI,V,Va,IV,III,II,I,Ia,LT
F#2	82.41	F#C#,FC,VI,V,Va,IV,III,II,I,Ia,LT
G2	87.31	VI,V,Va,IV,III,II,I,Ia,LT
G#2	92.50	G#Eb1,VI,V,Va,IV,III,II,I,Ia,LT
A2	98.00	V,Va,IV,III,II,I,Ia,LT
Bb2	103.83	BbFcrs,V,Va,IV,III,II,I,Ia,LT
B2	**110.00**	IV,III,II,I,Ia,LT
C3	116.54	III,II,I,Ia,LT
C#3	123.47	C#G#,III,II,I,Ia,LT
D3	130.81	II,I,Ia,LT
Eb3	138.59	EbBbside,II,I,Ia,LT
E3	146.83	I,Ia,LT
F3sk	155.56	FCside,I,Ia,LT
F#3	164.81	LT
G3	174.61	
G#3	185.00	G#
A3	196.00	A
Bb3	207.65	A,Spkr1
B3	220.00	EB,FC,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
C4	233.08	FC,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
C#4	246.94	FC,F#C#,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
D4	261.63	VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
D#4	277.18	G#Eb1,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
E4	293.66	V,Va,IV,III,II,I,Ia,LT,Spkr1
F4	311.13	BbFcrs,V,Va,IV,III,II,I,Ia,LT,Spkr1
F#4	329.63	IV,III,II,I,Ia,LT,Spkr1
G4	349.23	III,II,I,Ia,LT,Spkr1
G#4	369.99	C#G#,III,II,I,Ia,LT,Spkr1
A4	392.00	II,I,Ia,LT,Spkr1
Bb4	415.30	EbBbside,II,I,Ia,LT,Spkr1
B4	440.00	I,Ia,LT,Spkr1
C5sk	466.16	FCside,I,Ia,LT,Spkr1

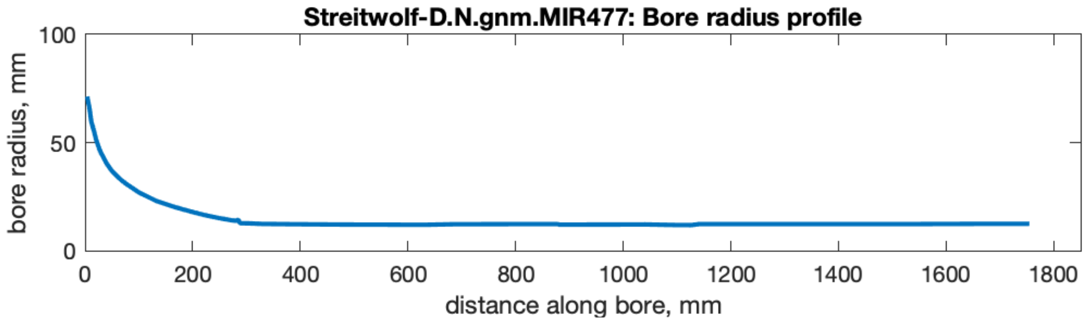
Streitwolf D.N.gnm.MIR477

Streitwolf D.N.gnm.MIR477 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0.00	160.00
	Bell inside	0	0.00	153.00
BELL	Segment	1	4.00	142.60
	Segment	2	8.50	130.75
	Segment	3	11.50	119.75
	Segment	4	17.00	109.70
	Segment	5	21.20	101.60
	Segment	6	28.60	91.45
	Segment	7	33.90	86.60
	Segment	8	40.20	80.60
	Segment	9	49.30	74.20
	Segment	10	59.20	69.10
	Segment	11	68.80	64.75
	Segment	12	79.20	60.95
	Segment	13	100.60	53.75
	Segment	14	117.00	49.85
	Segment	15	133.00	46.00
	Segment	16	157.50	41.90
	Segment	17	176.90	39.00
	Segment	18	199.60	35.90
	Segment	19	224.50	32.80
	Segment	20	249.80	30.20
	Segment	21	272.80	28.20
	Segment	22	280.00	27.80
BASS JOINT	Segment	23	285.00	28.60
	Segment	24	288.00	25.50
	Bb	25	305.40	25.40
	Segment	26	327.70	24.90
	B	27	391.05	24.60
	C	28	478.20	24.30
	C#	29	553.50	24.20
	D	30	614.45	24.10
	Segment	31	633.00	24.10
BUTT JOINT UP	**Eb**	32	685.65	24.60
	EB	33	741.45	24.65
	F#C#	34	799.80	24.70

	FC	35	854.95	24.70
	slug up	36	877.25	24.70
BUTT JOINT DOWN	slug down	37	882.25	24.20
	G#Eb	38	901.05	24.20
	VI	39	943.45	24.30
	BbF	40	988.85	24.30
	V	41	1040.25	24.40
	IV	42	1093.80	23.90
	Segment	43	1126.50	23.80
WING JOINT	**C#G#**	44	1140.90	24.70
	EbBb	45	1204.00	24.70
	III	46	1207.80	24.70
	II	47	1253.60	24.70
	FCside	48	1281.15	24.70
	I	49	1290.80	24.70
	LT	50	1328.70	24.70
	G#	51	1362.35	24.70
	A	52	1386.95	24.70
	Spk1	53	1484.45	24.70
	Segment	54	1509.80	24.70
CROOK	Segment	55	1684.80	25.00
MOUTHPIECE	Segment	56	1754.80	25.00

Streitwolf D.N.gnm.MIR477 Bore graph



Streitwolf D.N.gnm.MIR477 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BASS JOINT	Bb	25	O	16.45	7.00	24.90	4.95	35.30	0.5
	B	27	O	19.10	8.00	25.70	6.06	36.72	0.5
	C	28	C	13.45	7.00	21.20	5.45	35.20	0.5
	C#	29	O	16.80	6.00	25.60	5.50	35.20	0.5
	D	30	C	13.75	7.50	20.30	3.60	35.30	0.5
BUTT JOINT UP	Eb	32	O	16.70	7.50	25.00	17.30	57.30	0.5
	EB	33	O	15.80	9.00	23.80	7.00	57.00	0.5
	F#C#	34	C	11.95	9.50	23.50	7.00	57.00	0.5
	FC	35	O	10.75	5.50	25.60	9.50	54.90	0.1
	Slug	36	C	24.70	6.00	20.00	15.25	55.00	0.1
BUTT JOINT DOWN	Slug	37	C	24.20	6.00	20.00	18.75	55.00	0.1
	G#Eb	38	C	13.75	5.00	22.30	7.50	54.50	0.5
	VI	39	O	14.30	7.00	22.70	7.00	58.50	0.5
	BbF	40	C	14.05	7.50	21.20	7.00	56.51	0.5
	V	41	O	10.50	0.00	0.00	13.55	57.00	0.5
	IV	42	O	11.60	0.00	0.00	13.10	57.30	0.5
WING JOINT	C#G#	44	C	9.30	7.00	18.80	6.30	36.60	0.5
	EbBb	45	C	7.65	9.00	19.00	6.30	36.80	0.5
	III	46	O	10.00	0.00	0.00	17.50	54.50	0.5
	II	47	O	9.50	0.00	0.00	16.50	56.00	0.5
	FCside	48	C	11.05	6.00	18.95	19.20	56.00	0.5
	I	49	O	7.45	0.00	0.00	16.90	56.00	0.5
	LT	50	O	9.00	6.00	19.23	6.40	55.00	0.5
	G#	51	C	6.95	4.00	18.95	6.60	55.00	0.5
	A	52	C	7.60	5.00	18.70	6.30	55.00	0.5
	Spk1	53	C	3.65	2.50	16.50	6.50	55.00	0.5

Streitwolf D.N.gnm.MIR477 Fingering table

Note	f_{440}	Fingering
Bb1	51.91	B**b,B,C#,**Eb,EB,FC,VI,V,IV,III,II,I,LT
B1	55.00	B,C#,Eb,EB,FC,VI,V,IV,III,II,I,LT
C2	58.27	C#,Eb,EB,FC,VI,V,IV,III,II,I,LT
C#2	61.74	C#,C,Eb,EB,FC,VI,V,IV,III,II,I,LT
D2	65.41	Eb,EB,FC,VI,V,IV,III,II,I,LT
Eb2	69.30	D,Eb,EB,FC,VI,V,IV,III,II,I,LT
E2	73.42	EB,FC,VI,V,IV,III,II,I,LT
F2	77.78	FC,VI,V,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,IV,III,II,I,LT
G2	87.31	VI,V,IV,III,II,I,LT
G#2	92.50	G#Eb,VI,V,IV,III,II,I,LT
A2	98.00	V,IV,III,II,I,LT
Bb2	103.83	BbF,V,IV,III,II,I,LT
B2	**110.00**	BbF,IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	C#G#,III,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	EbBb,II,I,LT
E3	146.83	I,LT
F3	155.56	LT
F#3	164.81	FCside,I,LT
G3	174.61	
G#3	185.00	G#
A3	196.00	A
Bb3	207.65	A,Spk1
B3	220.00	EB,FC,VI,V,IV,III,II,I,LT,Spk1
C4	233.08	FC,VI,V,IV,III,II,I,LT,Spk1
C#4	246.94	FC,F#C#,VI,V,IV,III,II,I,LT,Spk1
D4	261.63	VI,V,IV,III,II,I,LT,Spk1
D#4	277.18	G#Eb,VI,V,IV,III,II,I,LT,Spk1
E4	293.66	V,IV,III,II,I,LT,Spk1
F4	311.13	BbF,V,IV,III,II,I,LT,Spk1
F#4	329.63	IV,III,II,I,LT,Spk1
G4	349.23	III,II,I,LT,Spk1
G#4	369.99	C#G#,III,II,I,LT,Spk1
A4	392.00	II,I,LT,Spk1
Bb4	415.30	EbBb,II,I,LT,Spk1
B4	440.00	I,LT,Spk1
C5LT	466.16	LT,Spk1

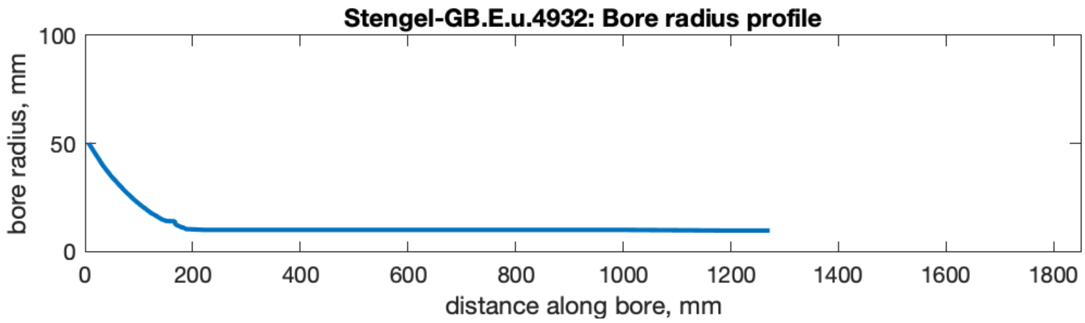
Stengel GB.E.u.4932

Stengel GB.E.u.4932 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0	148.7
	Bell inside	0	0.00	107.60
BELL	Segment	1	6.50	100.30
	Segment	2	33.00	79.70
	Segment	3	48.40	69.80
	Segment	4	69.00	58.60
	Segment	5	76.00	55.00
	Segment	6	87.00	49.80
	Segment	7	95.30	46.12
	Segment	8	105.50	41.99
	Segment	9	113.50	39.00
	Segment	10	121.70	35.90
	Segment	11	132.50	32.80
	Segment	12	142.70	29.70
	Segment	13	150.90	28.20
	Segment	14	167.00	27.84
LOWER JOINT	Segment	15	167.48	25.30
	Segment	16	168.38	25.18
	Segment	17	168.78	24.90
	Segment	18	169.50	24.69
	Segment	19	170.68	24.30
	Segment	20	172.88	23.87
	Segment	21	177.08	22.80
	Segment	22	182.48	22.00
	Segment	23	186.98	20.92
	Segment	24	187.88	20.70
LOWER JOINT	**EB**	25	221.18	20.00
	F#C#	26	287.48	20.00
	FC	27	353.58	20.00
	G#Eb1	28	397.18	20.00
	G#Eb2	29	397.38	20.00
	VI	30	474.18	20.00
	BbFcrs	31	505.18	20.00
	V	32	529.18	20.00
	Va	33	544.18	20.00
	IV	34	583.18	20.00

end of joint H	Segment	35	619.18	20.00
UPPER JOINT	**C#G#**	36	641.24	20.00
	III	37	676.24	20.00
	EbBbside	38	703.74	20.00
	II	39	725.74	20.00
	FCside	40	762.24	20.00
	I	41	771.24	20.00
	Ia	42	789.24	20.00
	LT	43	811.24	20.00
	G#	44	849.74	20.00
	A	45	873.74	20.00
	Trill1	46	898.24	20.00
	Spkr1	47	949.74	20.00
	Trill2	48	950.74	20.00
	Segment	49	986.14	20.00
CROO	Segment	50	1203.14	19.31
MOUTHPIECE	Segment	51	1272.26	19.31

Stengel GB.E.u.4932 Bore graph



Stengel GB.E.u.4932 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
LOWER JOINT	EB	25	O	21.45	7.4	22.4	5.7	33.5	1.0
	F#C#	26	C	12.50	6.5	19.8	5.7	33.3	1.0
	FC	27	O	13.13	5.3	19.4	5.7	32.5	1.0
	G#Eb1	28	C	14.60	4.8	19.4	5.7	32.2	1.0
	G#Eb2	29	C	12.50	5.4	19.4	5.7	32.2	1.0
	VI	30	O	11.60	5.4	17.7	5.7	32.0	1.0
	BbFcrs	31	C	10.60	4.5	17.7	5.7	31.6	1.0
	V	32	O	9.56	0.0	0.0	5.7	31.7	1.0
	Va	33	O	8.45	3.5	12.3	5.7	31.6	1.0
	IV	34	O	12.75	4.6	17.8	5.7	32.0	1.0
UPPER JOINT	C#G#	36	C	9.40	4.9	15.5	5.5	31.8	1.0
	III	37	O	11.40	7.1	17.6	5.5	31.7	1.0
	EbBbside	38	C	10.30	7	16	5.5	31.4	1.0
	II	39	O	9.00	0	0	5.5	31.3	1.0
	FCside	40	C	9.50	3.85	15.3	5.5	31.8	1.0
	I	41	O	8.70	0	0	5.5	31.3	1.0
	Ia	42	O	10.10	2	12.5	5.5	31.7	1.0
	LT	43	O	13.00	3.5	17.2	5.5	32	1.0
	G#	44	C	13.00	4.3	15.75	5.5	31.85	1.0
	A	45	C	14.40	3.5	17.7	5.5	32	1.0
	Trill1	46	C	12.50	4.2	15.6	5.5	32	1.0
	Spkr1	47	C	2.30	3.9	12.34	8.5	31.9	1.0
	Trill2	48	C	6.50	6.9	15.4	5.5	31.9	1.0

Stengel GB.E.u.4932 Fingering table

Note	f_{440}	Fingering (incl. auxiliary holes Ia and Va)
E2	73.42	EB,FC,VI,V,Va,IV,III,II,I,Ia,LT
F2	77.78	FC,VI,V,Va,IV,III,II,I,Ia,LT
F#2	82.41	F#C#,FC,VI,V,Va,IV,III,II,I,Ia,LT
G2	87.31	VI,V,Va,IV,III,II,I,Ia,LT
G#2	92.50	G#Eb1,VI,V,Va,IV,III,II,I,Ia,LT
A2	98.00	V,Va,IV,III,II,I,Ia,LT
Bb2	103.83	BbFcrs,V,Va,IV,III,II,I,Ia,LT
B2	**110.00**	IV,III,II,I,Ia,LT
C3	116.54	III,II,I,Ia,LT
C#3	123.47	C#G#,III,II,I,Ia,LT
D3	130.81	II,I,Ia,LT
Eb3	138.59	EbBbside,II,I,Ia,LT
E3	146.83	I,Ia,LT
F3sk	155.56	FCside,I,Ia,LT
F#3	164.81	LT
G3	174.61	
G#3	185.00	G#
A3	196.00	A
Bb3	207.65	A,Spkr1
B3	220.00	EB,FC,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
C4	233.08	FC,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
C#4	246.94	FC,F#C#,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
D4	261.63	VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
D#4	277.18	G#Eb1,VI,V,Va,IV,III,II,I,Ia,LT,Spkr1
E4	293.66	V,Va,IV,III,II,I,Ia,LT,Spkr1
F4	311.13	BbFcrs,V,Va,IV,III,II,I,Ia,LT,Spkr1
F#4	329.63	IV,III,II,I,Ia,LT,Spkr1
G4	349.23	III,II,I,Ia,LT,Spkr1
G#4	369.99	C#G#,III,II,I,Ia,LT,Spkr1
A4	392.00	II,I,Ia,LT,Spkr1
Bb4	415.30	EbBbside,II,I,Ia,LT,Spkr1
B4	440.00	I,Ia,LT,Spkr1
C5sk	466.16	FCside,I,Ia,LT,Spkr1

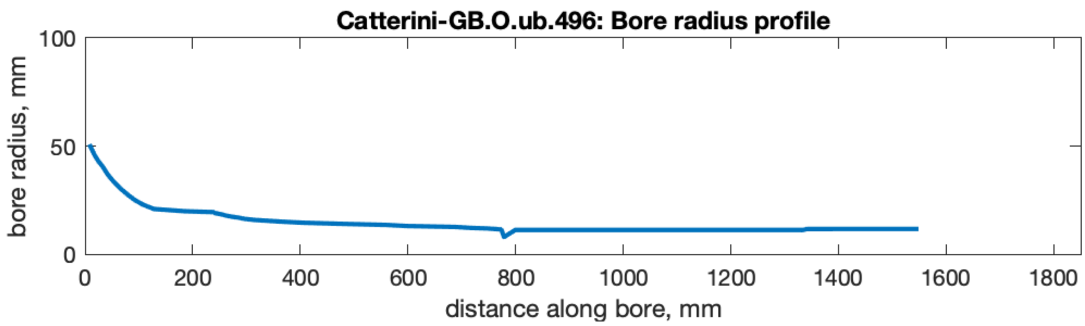
Catterini GB.O.ub.496

Catterini GB.O.ub.496 Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0.00	124.31
	Bell inside	0	0.00	112.70
BELL	Segment	1	8.00	101.60
	Segment	2	18.00	91.45
	Segment	3	24.00	86.60
	Segment	4	33.40	80.60
	Segment	5	41.50	74.20
	Segment	6	49.70	69.10
	Segment	7	58.00	64.75
	Segment	8	65.40	60.95
	Segment	9	82.60	53.75
	Segment	10	93.70	49.85
	Segment	11	107.30	46.00
	Segment	12	128.00	41.90
	Segment	13	187.00	39.80
	Segment	14	240.00	39.00
BUTT JOINT UP	Segment	15	240.00	38.20
	Segment	16	242.80	38.00
	Segment	17	253.50	36.95
	Segment	18	261.20	35.90
	Segment	19	272.10	34.85
	Segment	20	286.80	33.80
	C	21	296.00	32.80
	Segment	22	314.40	31.80
	Segment	23	365.50	30.20
	Segment	24	405.70	29.20
	C#	25	464.50	28.37
	Segment	26	476.20	28.20
	D	27	553.00	27.27
	Segment	28	558.90	27.20
	Segment	29	597.50	26.20
	Eb	30	611.50	26.06
	Segment	31	689.50	25.30

	EB	32	700.50	24.94
	Segment	33	715.80	24.45
	Segment	34	747.50	23.93
	F#C#	35	754.50	23.68
	slug	36	773.50	23.00
BUTT JOINT DOWN	slug	37	778.50	16.00
	FC	38	799.50	22.55
	G#Eb	39	821.50	22.55
	VI	40	886.50	22.55
	BbF	41	910.50	22.55
	V	42	925.50	22.55
	BF#	43	959.50	22.55
	IV	44	981.50	22.55
	C#G#	45	1020.50	22.55
	III	46	1069.50	22.55
	EbBb	47	1080.50	22.55
	II	48	1109.50	22.55
	FCside	49	1126.50	22.55
	I	50	1148.50	22.55
	G#	51	1173.00	22.55
	LT	52	1198.00	22.55
	Btrill	53	1218.50	22.55
	A	54	1240.50	22.55
	Spk1	55	1287.50	22.55
	Segment	56	1331.5	22.55
CROOK	Segment	57	1331.50	22.30
	Segment	58	1341.50	23.40
	Segment	59	1480.50	23.50
MOUTHPIECE	Segment	60	1548.80	23.50

Catterini GB.O.ub.496 Bore graph



Catterini GB.O.ub.496 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BUTT JOINT UP	C	21	O	17.39	5.40	23.10	7.50	70.4	0.10
	C#	25	O	18.87	7.00	22.75	9.00	72.4	0.10
	D	27	C	14.10	2.50	19.50	10.00	73.5	0.10
	Eb	30	O	17.53	5.00	23.00	15.35	74.2	0.10
	EB	32	O	16.19	6.00	19.04	9.36	75.3	0.10
	F#C#	35	C	14.78	4.00	21.30	22.50	75.90	0.10
	slug	36	C	23.90	10.00	10.00	14.00	76.1	0.10
BUTT JOINT DOWN	slug	37	C	22.55	10.00	10.00	14.00	76.2	0.10
	FC	38	O	14.60	4.50	21.10	33.00	76.4	0.10
	G#Eb	39	C	13.96	3.50	18.50	17.50	76.7	0.10
	VI	40	O	17.01	3.50	19.30	19.50	77.5	0.10
	BbF	41	C	11.00	3.50	17.75	9.00	77.8	0.10
	V	42	O	15.15	3.50	17.50	11.83	78.0	0.10
	BF#	43	C	11.53	2.50	17.00	9.00	78.4	0.10
	IV	44	O	15.80	4.00	21.00	26.00	78.6	0.10
	C#G#	45	C	13.80	3.00	21.10	14.00	79.1	0.10
	III	46	O	13.50	3.00	18.70	25.00	79.7	0.10
	EbBb	47	C	11.50	4.00	17.70	7.50	79.8	0.10
	II	48	O	14.28	4.00	21.20	27.00	80.2	0.10
	FCside	49	C	12.50	6.00	18.60	18.50	80.4	0.10
	I	50	O	15.68	4.50	18.70	27.00	80.6	0.10
	G#	51	C	11.47	6.00	17.45	6.00	80.9	0.10
	LT	52	O	11.86	4.00	18.00	20.70	81.2	0.10
	Btrill	53	C	11.33	6.00	17.70	6.00	81.5	0.10
	A	54	C	15.45	3.00	20.70	16.00	81.7	0.10
	Spk1	55	C	5.30	4.00	14.50	34.00	82.3	0.10

Catterini GB.O.ub.496 Fingering table

Note	f_{440}	Fingering
C2	65.41	C,C#,Eb,EB,FC,VI,V,IV,III,II,I,LT
C#2	69.30	C#,Eb,EB,FC,VI,V,IV,III,II,I,LT
D2	73.42	Eb,EB,FC,VI,V,IV,III,II,I,LT
Eb2	77.78	Eb,D,EB,FC,VI,V,IV,III,II,I,LT
E2	82.41	EB,FC,VI,V,IV,III,II,I,LT
F2	87.31	FC,VI,V,IV,III,II,I,LT
F#2	92.50	F#C#,FC,VI,V,IV,III,II,I,LT
G2	98.00	VI,V,IV,III,II,I,LT
G#2	103.83	G#Eb,VI,V,IV,III,II,I,LT
A2	110.00	V,IV,III,II,I,LT
Bb2	116.54	BbF,V,IV,III,II,I,LT
B2	123.47	BF#,IV,III,II,I,LT
C3	130.81	III,II,I,LT
C#3	138.59	C#G#,III,II,I,LT
D3	146.83	II,I,LT
Eb3	155.56	EbBb,II,I,LT
E3	164.81	I,LT
F3	174.61	FCside,I,LT
F#3	185.00	LT
G3	196.00	
G#3	207.65	G#
A3	220.00	A
Bb3	233.08	A,Spk1
B3	246.94	EB,FC,VI,V,IV,III,II,I,LT,Spk1
C4	261.63	FC,VI,V,IV,III,II,I,LT,Spk1
C#4	277.18	FC,F#C#,VI,V,IV,III,II,I,LT,Spk1
D4	293.66	VI,V,IV,III,II,I,LT,Spk1
D#4	311.13	G#Eb,VI,V,IV,III,II,I,LT,Spk1
E4	329.63	V,IV,III,II,I,LT,Spk1
F4	349.23	BbF,V,IV,III,II,I,LT,Spk1
F#4	369.99	BF#,V,III,II,I,LT,Spk1
G4	392.00	III,II,I,LT,Spk1
G#4	415.30	C#G#,III,II,I,LT,Spk1
A4	440.00	II,I,LT,Spk1
Bb4	466.16	EbBb,II,I,LT,Spk1
B4	493.88	I,LT,Spk1
C5sk	523.25	FCside,I,LT,Spk1

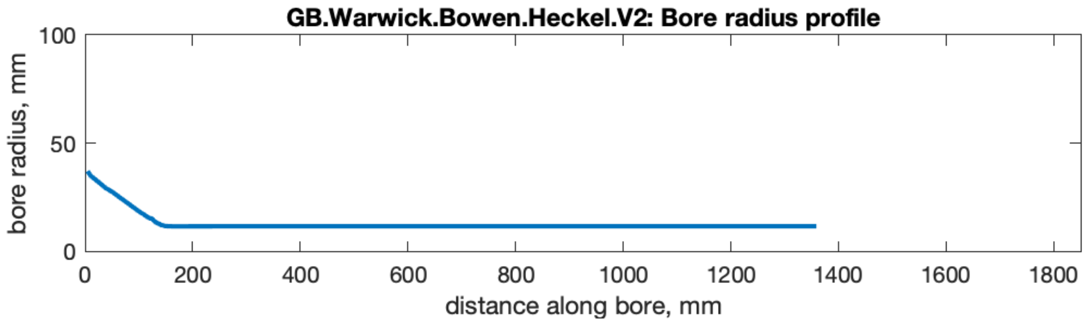
Heckel GB.Warwick.Bowen.Heckel

Heckel GB.Warwick.Bowen.Heckel Bore dimensions

Joint description	Segment description	Segment No.	Z along bore, total	Bore diameter
BELL FLANGE	Bell outside	-1	0	90.00
	Bell inside	0	0.00	80.40
BELL	Segment	1	4.60	74.00
	Segment	2	10.50	69.80
	Segment	3	26.47	63.40
	Segment	4	38.00	58.58
	Segment	5	50.30	55.00
	Segment	6	64.60	49.80
	Segment	7	75.65	45.80
	Segment	8	86.16	42.00
	Segment	9	95.00	38.80
	Segment	10	103.70	35.70
	Segment	11	107.00	34.85
	Segment	12	110.00	33.80
	Segment	13	112.90	32.80
	Segment	14	116.00	31.80
	Segment	15	122.00	30.20
	Segment	16	125.50	30.37
LOWER JOINT	Segment	17	126.00	29.20
	Segment	18	128.17	28.20
	Segment	19	130.61	27.20
	Segment	20	132.40	26.75
	Segment	21	133.50	26.20
	Segment	22	136.00	25.80
	Segment	23	139.70	24.90
	Segment	24	141.20	24.30
	Segment	25	142.70	24.20
	Segment	26	144.00	24.07
	Segment	27	146.00	23.87
	Segment	28	146.50	23.55
	Segment	29	148.50	23.48
	Segment	30	149.50	23.35
	Segment	31	162.60	23.13
	Eb	32	180.80	23.13

	EB	33	251.00	23.20
	F#C#	34	337.00	23.20
	FC	35	341.00	23.20
	C#p	36	392.50	23.20
	G#Eb	37	449.00	23.20
	VI	38	500.50	23.20
	BbF	39	546.50	23.20
	V	40	568.00	23.20
	Va	41	614.60	23.20
	IV	42	639.50	23.20
	Segment	43	687.00	23.25
UPPER JOINT	**C#G#**	44	700.00	23.20
	III	45	727.50	23.20
	EbBb	46	764.50	23.20
	II	47	798.50	23.20
	FCside	48	847.00	23.20
	I	49	866.50	23.20
	Ia	50	871.00	23.20
	LT	51	897.50	23.20
	G#	52	945.00	23.20
	A	53	970.50	23.20
	Bb	54	971.50	23.20
	Bt	55	1019.80	23.20
	Spk1	56	1058.50	23.20
	Segment	57	1124.50	23.20
CROOK	Segment	58	1290.94	23.25
MOUTHPIECE	Segment	59	1359.01	23.25

Heckel GB.Warwick.Bowen.Heckel Bore graph



Heckel GB.Warwick.Bowen.Heckel Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
LOWER JOINT	Eb	32	O	16.3	7.25	23.5	6.1	40.2	1
	EB	33	O	15.8	4.5	23	5.2	38.3	1
	F#C#	34	C	11.65	6.1	19.5	6.44	38.7	1
	FC	35	O	13.2	4	19.8	6.6	38.8	1
	C#p	36	O	13.2	3.4	19.8	6.6	38.5	1
	G#Eb	37	C	12.65	4.5	19	6.1	38.9	1
	VI	38	O	14.98	4.35	20.2	5.4	38.9	1
	BbF	39	C	14.05	4.5	21	5.8	38.7	1
	V	40	O	11.79	4.5	20.2	5.45	38.5	1
	Va	41	O	8.345	3.75	13.6	7.4	38.4	1
	IV	42	O	12.4	0	0	8	38.2	0.1
UPPER JOINT	C#G#	44	C	10.1	2	15.8	6.47	38.6	1
	III	45	O	13.53	4.1	20	6	38.3	1
	EbBb	46	C	10.57	3.7	17	6.9	38.3	1
	II	47	O	14.18	3.8	20	6.7	38.3	1
	FCside	48	C	7.8	3.2	13.7	7.35	38.4	1
	I	49	O	10.21	0	0	11	38.3	0.1
	Ia	50	O	8.275	2.2	14	7.16	38.3	1
	LT	51	O	11.57	3.4	19	6.61	38.6	1
	G#	52	C	7.135	3.2	14.25	7.5	38.5	1
	A	53	C	8.375	4.4	15.5	7	38.8	1
	Bb	54	C	7.8	3.6	15.9	7.04	39.0	1
	Bt	55	C	7.85	4.3	13.3	7	38.6	1
	Spk1	56	C	3.75	3.6	10.2	14	38.4	0.2

Heckel GB.Warwick.Bowen.Heckel Fingering table

Note	f_{440}	Fingering (incl. auxiliary holes Ia, Va and C#p(atent)
Eb2	65.4	Eb,EB,FC,C#p,VI,V,Va,IV,III,II,I,Ia,LT
E2	69.3	EB,FC,C#p,VI,V,Va,IV,III,II,I,Ia,LT
F2	73.42	FC,C#p,VI,V,Va,IV,III,II,I,Ia,LT
F#2	77.78	F#C#,FC,C#p,VI,V,Va,IV,III,II,I,Ia,LT
G2	82.41	VI,V,Va,IV,III,II,I,Ia,LT
G#2	87.31	G#Eb,VI,V,Va,IV,III,II,I,Ia,LT
A2	92.5	V,Va,IV,III,II,I,Ia,LT
Bb2	98	BbF,V,Va,IV,III,II,I,Ia,LT
B2	103.83	IV,III,II,I,Ia,LT
C3	110	III,II,I,Ia,LT
C#3	116.54	C#G#,III,II,I,Ia,LT
D3	123.47	II,I,Ia,LT
Eb3	130.81	EbBb,II,I,Ia,LT
E3	138.59	I,Ia,LT
F3sk	146.83	FCside,I,Ia,LT
F#3	155.56	LT
G3	164.81	
G#3	174.61	G#
A3	184.99	A
Bb3	195.99	A,Bb
B3	207.65	EB,FC,C#p,VI,V,Va,IV,III,II,I,Ia,LT,Spk1
C4	220	FC,C#p,VI,V,Va,IV,III,II,I,Ia,LT,Spk1
C#4	233.08	FC,F#C#,C#p,VI,V,Va,IV,III,II,I,Ia,LT,Spk1
D4	246.94	VI,V,Va,IV,III,II,I,Ia,LT,Spk1
D#4	261.62	G#Eb,VI,V,Va,IV,III,II,I,Ia,LT,Spk1
E4	277.18	V,Va,IV,III,II,I,Ia,LT,Spk1
F4	293.66	BbF,V,Va,IV,III,II,I,Ia,LT,Spk1
F#4	311.12	IV,III,II,I,Ia,LT,Spk1
G4	329.62	III,II,I,Ia,LT,Spk1
G#4	349.22	C#G#,III,II,I,Ia,LT,Spk1
A4	369.99	II,I,Ia,LT,Spk1
Bb4	391.99	EbBb,II,I,Ia,LT,Spk1
B4	415.3	I,Ia,LT,Spk1
C5	440	FCside,I,Ia,LT,Spk1

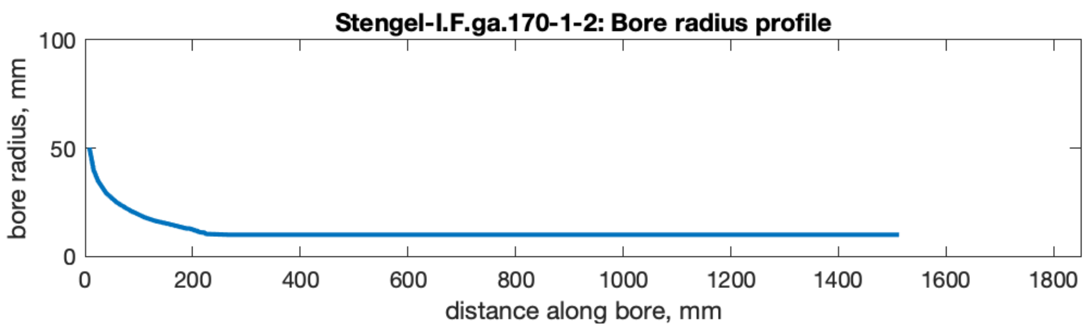
Stengel I.F.ga.170-1-2

Stengel I.F.ga.170-1-2 Bore dimensions

BELL FLANGE	Bell outside	-1	0.00	128.00
	Bell inside	0	0.00	127.00
BELL	Segment	1	8.00	100.30
	Segment	2	16.00	79.70
	Segment	3	24.00	69.80
	Segment	4	39.00	58.60
	Segment	5	47.00	55.00
	Segment	6	59.00	49.80
	Segment	7	71.00	46.12
	Segment	8	85.00	41.99
	Segment	9	111.40	35.90
	Segment	10	129.90	32.80
	Segment	11	153.00	30.20
	Segment	12	189.00	25.70
	Segment	13	194.00	25.70
BASS JOINT	Segment	14	202.10	24.40
	Segment	15	203.75	24.10
	Segment	16	203.93	23.93
	Segment	17	204.98	23.80
	Segment	18	209.18	23.26
	Segment	19	210.24	23.05
	Segment	20	210.33	22.90
	Segment	21	211.89	22.56
	Segment	22	214.65	22.26
	Segment	23	216.37	22.10
	Segment	24	217.85	21.82
	Segment	25	218.25	21.68
	Segment	26	220.44	22.40
	Segment	27	224.33	20.88
	Segment	28	226.30	20.65
	C	29	265.00	20.00
	C#	30	320.00	20.00
	D	31	383.00	20.00
	Eb	32	438.50	20.00
BOOT JOINT UP	**EB**	33	518.00	20.00
	F#C#	34	580.00	20.00

	FC	35	624.00	20.00
	slug	36	668.50	20.00
	G#Eb	37	671.00	20.00
BOOT JOINT DOWN	slug	38	673.50	20.00
	spit	39	674.00	20.00
	VI	40	718.00	20.00
	BbF	41	764.30	20.00
	V	42	768.00	20.00
	Va	43	831.00	20.00
	IV	44	850.00	20.00
	C#G#	45	901.00	20.00
	EbBb	46	940.00	20.00
	III	47	956.50	20.00
	II	48	1007.50	20.00
	FCside	49	1004.00	20.00
	I	50	1044.00	20.00
	B+	51	1039.50	20.00
	LT	52	1067.50	20.00
	G#	53	1098.00	20.00
	A	54	1128.00	20.00
	Spk1	55	1227.00	20.00
	Segment	56	1251.00	20.00
CROOK	Segment	57	1449.00	20.00
MOUTHPIECE	Segment	58	1512.70	20.00

Stengel I.F.ga.170-1-2 Bore graph



Stengel I.F.ga.170-1-2 Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BASS JOINT	C	29	O	19.00	6.00	26.00	6.90	33.7	0.50
	C#	30	O	19.00	6.00	26.00	6.90	33.7	0.50
	D	31	O	19.00	6.00	26.00	6.90	33.7	0.50
	Eb	32	O	19.00	6.00	26.00	6.90	33.7	0.50
BOOT JOINT UP	EB	33	O	14.70	5.00	26.00	12.00	56.0	0.50
	F#C#	34	C	14.70	5.00	26.00	12.00	54.7	0.50
	FC	35	O	16.50	5.00	26.00	12.00	53.8	0.50
	slug up	36	C	20.00	6.00	20.00	14.00	53.8	0.50
	G#Eb	37	C	16.50	5.00	26.00	12.00	53.0	0.50
BOOT JOINT DOWN	slug down	38	C	20.00	6.00	20.00	14.00	53.0	0.50
	spit	39	C	10.80	6.00	26.00	12.00	53.0	0.50
	VI	40	O	12.00	6.00	26.00	12.00	53.8	0.50
	BbF	41	C	13.35	6.00	26.00	12.00	54.6	0.50
	V	42	O	15.70	6.00	26.00	12.00	54.7	0.50
	Va	43	O	9.50	5.00	22.00	12.00	55.6	0.50
	IV	44	O	9.30	0.00	0.00	12.00	56.5	0.50
WING JOINT	C#G#	45	C	9.00	5.00	19.00	6.00	33.8	0.50
	EbBb	46	C	12.50	6.00	19.00	6.00	33.8	0.50
	III	47	O	9.10	0.00	0.00	23.40	50.0	0.50
	II	48	O	9.60	0.00	0.00	25.70	50.0	0.50
	FCside	49	C	11.00	5.00	19.00	6.00	50.0	0.50
	I	50	O	9.60	0.00	0.00	26.50	50.0	0.50
	B+	51	C	11.00	5.00	19.00	6.50	50.0	0.50
	LT	52	O	16.10	5.00	26.00	5.60	33.2	0.50
	G#	53	C	12.60	5.00	17.80	6.65	33.2	0.50
	A	54	C	12.40	5.00	17.30	6.65	33.1	0.50
	Spk1	55	C	4.00	4.00	12.00	12.40	33.7	0.50

Stengel I.F.ga.170-1-2 Fingering table

Note	f_{440}	Fingering (incl. auxiliary hole Va)
C2	58.27	C,C#,D,Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
C#2	61.74	C#,D,Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
D2	65.41	D, Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
Eb2	69.30	Eb,EB,FC,VI,V,Va,IV,III,II,I,LT
E2	73.42	EB,FC,VI,V,Va,IV,III,II,I,LT
F2	77.78	FC,VI,V,Va,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,Va,IV,III,II,I,LT
G2	87.31	VI,V,Va,IV,III,II,I,LT
G#2	92.50	G#Eb,VI,V,Va,IV,III,II,I,LT
A2	98.00	V,Va,IV,III,II,I,LT
Bb2	103.83	BbF,V,Va,IV,III,II,I,LT
B2	**110.00**	IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	C#G#,III,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	EbBb,II,I,LT
E3	146.83	I,LT
F3sk	155.56	FCside,I,LT
F#3	164.81	LT
G3	174.61	
G#3	185.00	G#
A3	196.00	A
Bb3	207.65	A,Spk1
B3	220.00	EB,FC,VI,V,Va,IV,III,II,I,LT,Spk1
C4	233.08	FC,VI,V,Va,IV,III,II,I,LT,Spk1
C#4	246.94	FC,F#C#,VI,V,Va,IV,III,II,I,LT,Spk1
D4	261.63	VI,V,Va,IV,III,II,I,LT,Spk1
D#4	277.18	G#Eb,VI,V,Va,IV,III,II,I,LT,Spk1
E4	293.66	V,Va,IV,III,II,I,LT,Spk1
F4	311.13	BbF,V,Va,IV,III,II,I,LT,Spk1
F#4	329.63	IV,III,II,I,LT,Spk1
G4	349.23	III,II,I,LT,Spk1
G#4	369.99	C#G#,III,II,I,LT,Spk1
A4	392.00	II,I,LT,Spk1
Bb4	415.30	EbBb,II,I,LT,Spk1
B4	440.00	I,LT,Spk1
C5sk	466.16	FCside,I,LT,Spk1
C5fk	466.16	II,LT,Spk1

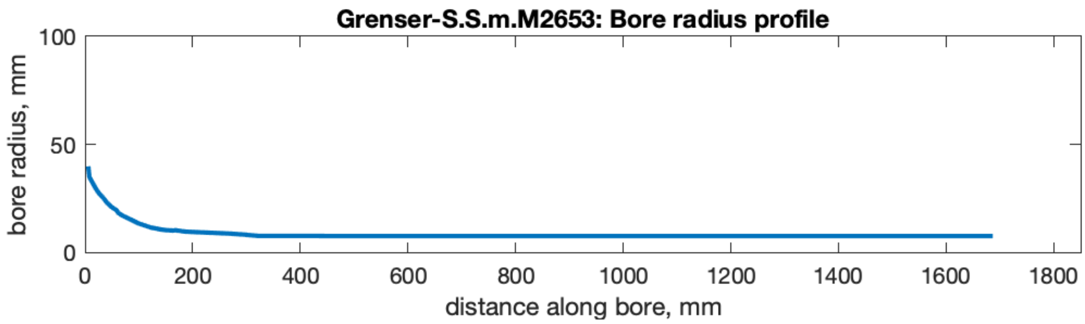
Grenser S.S.m.M2653

Grenser S.S.m.M2653: Bore dimensions

Joint description	Segment description	Segment No.	Length along bore from bell	Bore diameter
BELL FLANGE	Bell outside	-1	0.00	91.00
	Bell inside	0	0.00	87.00
BELL	Segment	1	6.00	79.70
	Segment	2	8.00	69.80
	Segment	3	20.50	58.60
	Segment	4	25.50	55.00
	Segment	5	35.00	49.80
	Segment	6	40.50	46.12
	Segment	7	49.50	41.99
	Segment	8	58.50	39.00
	Segment	9	62.00	36.40
	Segment	10	71.00	33.80
	Segment	11	86.00	30.20
	Segment	12	98.00	27.20
	Segment	13	112.00	24.85
	Segment	14	123.00	23.00
	Segment	15	146.00	20.92
	Segment	16	134.50	21.70
	Segment	17	146.00	20.92
	Segment	18	149.00	20.70
	Segment	19	165.00	20.25
BASS JOINT	Segment	20	166.00	20.70
	Segment	21	185.00	19.37
	Segment	22	191.40	19.19
	Segment	23	199.20	18.97
	Segment	24	228.50	18.36
	Segment	25	269.00	17.47
	Bb	26	283.40	16.96
	Segment	27	288.00	16.80
	Segment	28	297.00	16.50

	Segment	29	304.00	16.15
	Segment	30	312.50	15.75
	Segment	31	322.00	15.32
	Segment	32	419.00	15.34
	Segment	33	456.70	15.20
BUTT JOINT UP	RT	34	491.90	15.20
	D	35	583.40	15.20
	EB	36	672.90	15.20
	F#C#	37	713.40	15.20
	Slug	38	768.40	15.20
BUTT JOINT DOWN	Slug	39	773.40	15.20
	FC	40	814.40	15.20
	G#Eb	41	884.40	15.20
	VI	42	957.40	15.20
	V	43	1001.40	15.20
	IV	44	1048.40	15.20
	Segment	45	1099.40	15.20
WING JOINT	III	46	1143.40	15.20
	II	47	1192.40	15.20
	I	48	1234.90	15.20
	LT	49	1253.90	15.20
	A	50	1341.40	15.20
	Segment	51	1411.40	15.20
CROOK	Spk1	52	1472.85	15.20
	Segment	53	1601.85	15.20
MOUTHPIECE	Segment	54	1686.85	15.20

Grenser S.S.m.M2653: Bore graph



Grenser S.S.m.M2653: Hole dimensions

Joint description	Segment description	Segment	Open or Closed	Average diameter of tonehole	Height of Opened Key	Diameter of keypad	Chimney length	OD of Body at hole	Radius of hole edge
BUTT JOINT UP	Bb	26	O	7.26	4.4	15.1	7.5	31.3	0.5
	RT	34	O	8.71	0.00	0.00	16.00	62.00	0.50
	D	35	O	11.74	5.00	15.60	17.00	58.00	0.50
	EB	36	O	10.10	7.00	14.80	17.00	52.00	0.50
	F#C#	37	C	10.20	5.50	15.00	12.00	40.00	0.50
	Slug	38	C	15.20	10.00	10.00	8.00	50.00	0.50
BUTT JOINT DOWN	Slug	39	C	15.20	10.00	10.00	7.50	50.00	0.50
	FC	40	O	8.50	4.90	15.00	25.00	50.00	0.50
	G#Eb	41	C	7.34	4.40	14.00	29.80	42.00	0.50
	VI	42	O	6.20	0.00	0.00	17.50	58.00	0.50
	V	43	O	7.32	0.00	0.00	17.90	60.00	0.50
	IV	44	O	7.23	0.00	0.00	16.20	62.00	0.50
WING JOINT	III	46	O	6.45	0.00	0.00	14.50	45.00	0.50
	II	47	O	6.70	0.00	0.00	11.90	45.00	0.50
	I	48	O	6.95	0.00	0.00	11.25	45.00	0.50
	LT	49	O	7.60	0.00	0.00	8.00	31.00	0.50
	A	50	C	6.25	3.90	14.50	5.77	28.00	0.50
CROOK	Spk1	52	C	3.70	4.25	9.40	2.30	17.70	0.50

Grenser S.S.m.M2653: Fingering table

Note	Nominal equal temperament frequency at A4 = 440	Fingering
B1	55.00	Bb,RT,D,EB,FC,VI,V,IV,III,II,I,LT
C2	58.27	RT,D,EB,FC,VI,V,IV,III,II,I,LT
D2	65.41	D,EB,FC,VI,V,IV,III,II,I,LT
Eb2	69.30	Bb,RT,EB,FC,VI,V,IV,III,II,I,LT
E2	73.42	EB,FC,VI,V,IV,III,II,I,LT
F2	77.78	FC,VI,V,IV,III,II,I,LT
F#2	82.41	F#C#,FC,VI,V,IV,III,II,I,LT
G2	87.31	VI,V,IV,III,II,I,LT
G#2	92.50	G#Eb,VI,V,IV,III,II,I,LT
A2	98.00	V,IV,III,II,I,LT
Bb2	103.83	EB,FC,VI,IV,III,II,I,LT
B2	110.00	IV,III,II,I,LT
C3	116.54	III,II,I,LT
C#3	123.47	FC,VI,V,IV,II,I,LT
D3	130.81	II,I,LT
Eb3	138.59	IV,III,I,LT
E3	146.83	I,LT
F3	155.56	LT,II
F#3	164.81	I,II,III
G3	174.61	
A3	196.00	III,II,I,A
Bb3	207.65	III,II,I,A,Spk1
B3	220.00	EB,FC,VI,V,IV,III,II,I,LT,Spk1
C4	233.08	FC,VI,V,IV,III,II,I,LT,Spk1
C#4	246.94	FC,F#C#,VI,V,IV,III,II,I,LT,Spk1
D4	261.63	VI,V,IV,III,II,I,LT,Spk1
D#4	277.18	G#Eb,VI,V,IV,III,II,I,LT,Spk1
E4	293.66	V,IV,III,II,I,LT,Spk1
F4	311.13	VI,IV,III,II,I,LT,Spk1
F#4	329.63	IV,III,II,I,LT,Spk1
G4	349.23	III,II,I,LT,Spk1
G#4	369.99	V,IV,II,I,LT,Spk1
A4	392.00	II,I,LT,Spk1
Bb4	415.30	III,I,LT,Spk1
B4	440.00	I,LT,Spk1
C5	466.16	II,LT,Spk1

Appendix C

Excel file structures and links

This section contains a description of the Excel data file structure, and links to the data files in the RCM repository. It is intended for those who wish to repeat or extend the calculations. In the first sheet, 'Measurements' shown below, data entry fields are coloured tan in the file; computed fields are coloured green. Names in red, below, must correspond to those in the program and may not be altered (and are case-sensitive). All measurements are in mm and hole positions are taken to the centre of the holes.

'Measurements' worksheet

Column	Data Type	Description	Used in program?
A	Text	Name of joint in this section	No
B	n/a	Blank column for visibility	No
C	Text	HOLNAM: name of tone hole in program;	Yes
D	Number	segno: segment number starting from the bell. -1 is the outer flange of the bell and 0 is the inner diameter of the bell. Calculated automatically after -1 entered in first row.	Yes
E	Number	Ljoint: measurement in mm along the joint. May be taken from either end of the joint. If taken from the end away from the bell it can be entered as negative, or the formula used in column G can be altered.	No
F	Number	Offset: The number that needs to be added to the last length in the previous segment in order to find the total lengths during this joint. The offset is constant through a single joint. The offset must take account of the mode of connecting the joints (tenon or socket) and the reference used (usually end of joint, shoulder of tenon or end of tenon). Each joint requires thought!	No
G	Number	Zbore: the resulting length of the end of the segment, when the instrument is assembled, starting from the end of the bell. If a hole is present the measurement is to the middle of the hole.	Yes
H	Number	Dbore: the diameter of the bore at the end of a segment. If inaccessible it is calculated by linear interpolation.	Yes
I	Character	HOLTYP: N = no hole, C = closed hole, O = open hole	Yes
J	Number	DiaNS: diameter of tone hole along the axis of the clarinet	No
K	Number	DiaEW: diameter of tone hole across the axis of the clarinet	No

L	Number	HOLDIA: Calculated field: average tone hole diameter.	Yes
M	Number	KEYHT: height of centre of raised pad over tone hole edge. Set to zero if it is an open tonehole.	Yes
N		KEYDIA: diameter of pad over hole. Set to zero if it is an open tonehole.	Yes
O		HOLLG: Chimney length of tonehole; average if oblique.	Yes
P		HOLLOC: number of segment that the tonehole terminates. Copied from column D.	Yes
Q		BODIA: Diameter of the body at the tonehole position. If elliptical, estimate radius near tonehole.	Yes
R		RC: Radius of the edge of the tone hole. Usually chosen as 0.5 for a wooden tonehole, 0.1 if it has a metal insert.	Yes
S		Comment: anything	No
T		Segment number: copied from column D	No
U		SEGLEN: length of segment that ends at Zbore	Yes
V		LODIA: bore at end nearer bell – not necessarily the smaller diameter	Yes
W		HIDIA: bore at end away from bell – not necessarily the higher diameter	Yes
X		Diff_between_seg_ends: calculated automatically; try to keep this below 10%	No

'Fingerings1' worksheet

In the second sheet, 'fingerings' is a table of the fingerings used for each note in the computation, as shown in Appendix C. This is a table of the toneholes that are opened for each note, not the keys that are pressed. If auxiliary holes are automatically operated by the fingering, such as those labelled Iaux and Vaux for the left- and right-hand brilles on the later instruments, these must be specifically included in the table. This detail is normally not shown in a conventional fingering chart; the latter can be derived from the fingerings table given some knowledge about the keys operated by the thumbs.

The sheet 'Fingerings2' is provided for quick computation of a subset of notes; the name of the fingerings sheet must then be changed in the program (near the end of the data input).

Index to Excel data files

The Excel files specified in the following table are provided in the RCM Repository as a zipped file labelled BOWEN_Excel_Files.ZIP. If the files are unzipped and placed in a folder <PATH> then the hyperlinks for the Excel files from the Matlab™ folder are shown below. However, these will only be needed if the MatLab™ code is to be run. All of the measurement data on the instruments is to be found in Appendix B.

Maker	**Location**	**hyperlink**
HECKEL	Warwick	<PATH>/GB.Warwick.Bowen.Heckel_ext.xlsx
SAX2601	Brussels	<PATH>/Sax-B.B.mim.2601_ext.xlsx
SAX0175	Brussels	<PATH>/Sax-B.B.mim.0175_ext.xlsx
STENGEL	Edinburgh	<PATH>/Stengel-GB.E.u.4932_ext.xlsx
KRUSPE	Leipzig	<PATH>/Kruspe-D.LE.u.4479_ext.xlsx
GRENSER	Stockholm	<PATH>/Grenser-S.S.m.M2653_ext.xlsx
STREITWOLF	Nuremberg	<PATH>/Streitwolf-D.N.gnm.MIR477_ext.xlsx
STREITWOLF	Leipzig	<PATH>/Streitwolf-D.LE.U.1539_ext.xlsx
CATTERINI	Oxford	<PATH>/Catterini-GB.O.ub.496_ext.xlsx
MAINO	Brussels	<PATH>/Maino-B.B.mim.0941_ext.xlsx
STENGEL	Florence	<PATH>/Stengel-I.F.ga.170-1-2_ext.xlsx
STENGEL	Brussels	<PATH>/Stengel-B.B.mim.0943_ext.xlsx
KRUSPE	Basel	<PATH>/Kruspe-CH.B.hm.1999.136_ext.xlsx

Appendix D

Romanza by Johann Friedrich Diethe
for solo bass clarinet and pairs of oboes, clarinets, bassoons and horns

There are three sources for this work.

1. The manuscript in the Archivio Biblioteca of the Accademia Filarmonica, comprising full score and set of parts: source I.[693]
2. The publication of the full set of parts (without score) by Merseberger in 1898, obtained from the Swiss National Library: source IIa.[694]
3. The publication of the version for bass clarinet and piano by Merseberger, which ocurred simultaneously with (2) and is included in the same publication: source IIb.

The manuscript is not labelled as an autograph in the Accademia Filharmonia catalogue. It is in the section 1840 – 1860, which are probable dates for the composition.[695] Confusingly, the catalogue entry for this manuscript gives its date as 1911-1940. The first page of the manuscript is shown in Figure D.6 and is in a very clear hand. The composer's name is in a different hand, which also appears on the parts, but since none of the Diethe sources listed in RISM (including this one) is labelled as an 'autograph manuscript', there is no way to tell if this is a signature of the composer. It should be considered as a copyist's manuscript.

Analysis of the differences between the source lead to the following observations (bar numbers as in the new edition, below):

1. Sources I and IIa are generally very similar in notes. The parts and score in I correspond almost exactly. The one exception is the first note of Bassoon 1 in bar 63, which is C4 in the score (Figure D.1), but E♭4 in the part and also in IIa. The bar is repeated three times, all with the note written as E♭4 in both score and part. Since the leger line is correctly written in the score, this seems an obvious misprint.

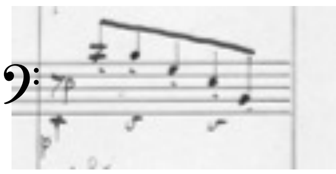



Figure D.1. Bar 63, Bassoons stave in score from Source I.

2. There is one other difference between I and IIa in notes, in bars 107 – 110. In IIa, the second clarinet plays alternating C and F (concert B♭ and G) in the quavers in the second half of the bar (Figure D.2), whereas in I the notes are C and E (concert B♭ and

[693] Diethe, Friedrich. *Romanza per Clarinetto Basso Si♭*. Bologna, Accademia Filarmonica, Archivio Biblioteca. Music manuscripts, 1860-1840. I-Baf.Fondo antico FA1 – 3531; I thank Stefano Cardo for a copy of this manuscript from the C.I.R.C.B. Library.

[694] Johann Friedrich Diethe, *Romanza Für Bass-Klarinette in B* (Leipzig: Carl Merseburger, 1898). I thank Susanne Blatter of ETH Zurich for obtaining a copy of this scarce publication.

[695] Aber, A history of the bass clarinet as an orchestral and solo instrument, 83.

D), Figure D.3. Source IIb is helpful here. The piano arrangement is not a simple transcription, but has been properly arranged for keyboard. One can therefore not deconstruct this to original parts, but can assume that the harmonic structure is preserved in the arrangement. The relevant passage is shown in Figure D.4. It is clear that the piano arrangement is to keep the same harmony, which is E♭ major, first inversion, in the first of these notes and its second inversion in the second note. Therefore it is highly likely that the correct notes should be (written) C and F as in II, rather than introducing an augmented seventh into the chord.

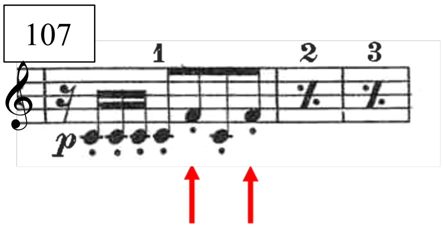


Figure D.2. Bar 107, 2nd clarinet part, source IIa

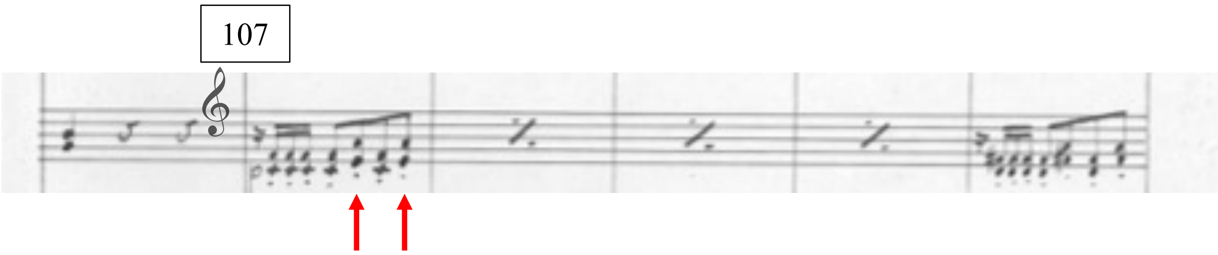



Figure D.3. Bar 107ff, clarinet stave in score, source I

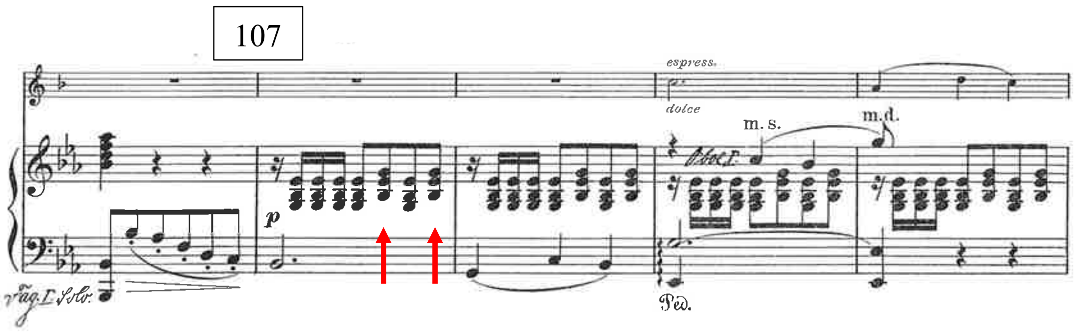


Figure D.4. Bar 107ff, piano score, source IIb

3. The articulation and phrasing has slight differences between I and IIa. Occasional slurs and staccatos are omitted in IIa, especially in the solo bass clarinet part, and, occasionally, crescendos are omitted in IIa and sometimes start in slightly different places in the two sources. Whilst this is a personal judgement my opinion is that source I gives a slightly better reading for performance and is more likely truer to the original.

The conclusion must be drawn that the two sources do not have a filial relationship, but each depends on an unknown source, perhaps the autograph manuscript. For the new edition, at the end of this appendix, I have used source IIa for the notes and source I for the phrasing, articulation and dynamic indications. I have agreement from the CIRCB web site owner, Prof. Stefano Cardo, to publish both score and parts of the new edition in due course.[696]

Most unusually, the manuscript includes, after the solo bass clarinet part in B♭, the complete solo part written out again in a mixture of bass and treble clefs, transposed for clarinets in A, B♭ and C. The first page is shown in Figure D.5.

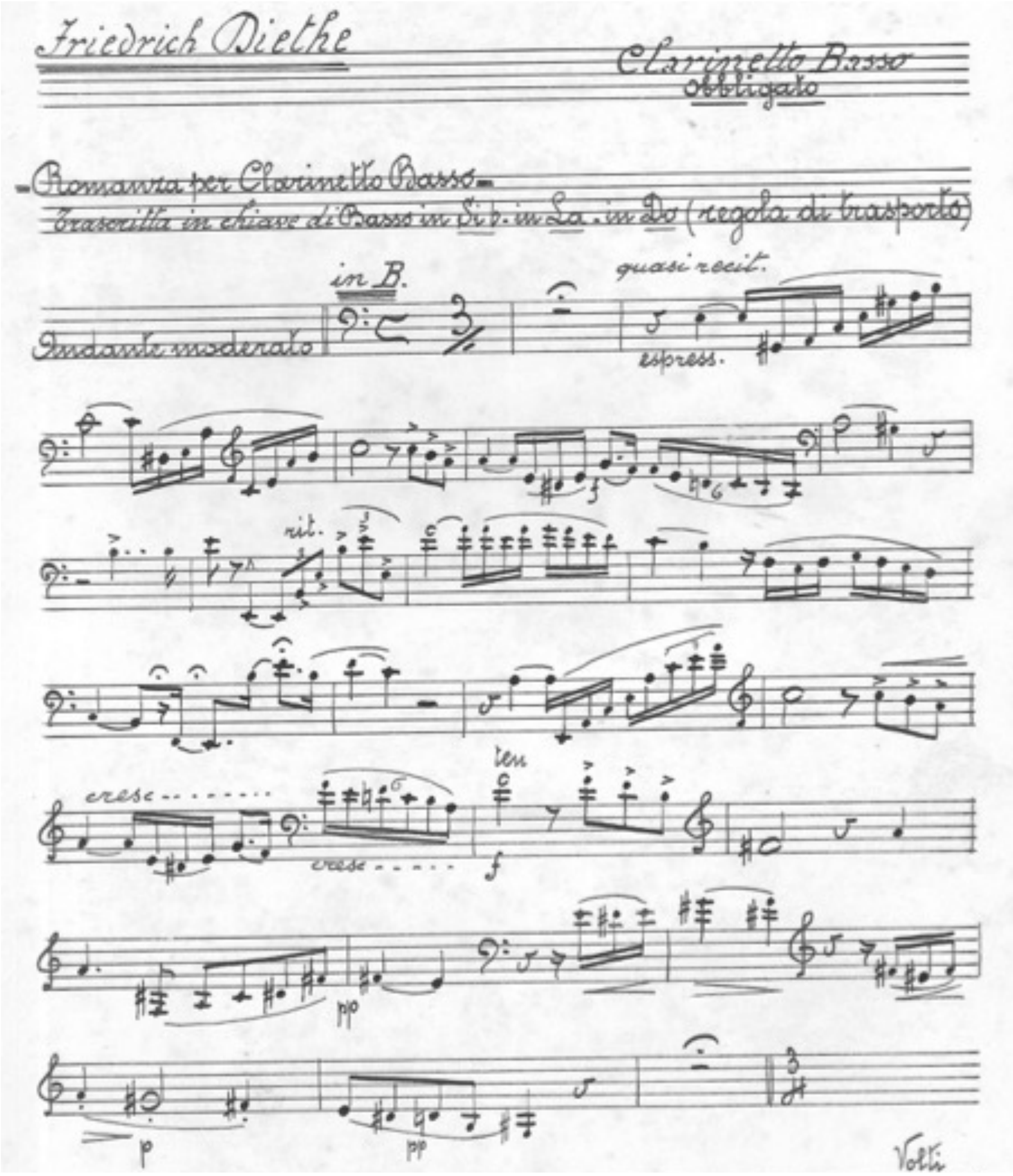



Figure D.5. Page of the copy manuscript I following the solo bass clarinet part in B♭. Passages are written out in treble and bass clefs, and for instruments in A, B♭ and C.

[696] ‘C.I.R.C.B. - International Bass Clarinet Research Center.’ https://www.circb.info/?q=home accessed 10 November 2021.

The heading states

> Transcribed in the key for the bass in B♭, in A and in C (rules of transposition).

This probably indicates that this part was intended as an exercise in transposition on the bass clarinet (required for both orchestras and bands as discussed in Chapter 3). Quite possibly the whole manuscript was produced for a music school. It is quite an unusual find.

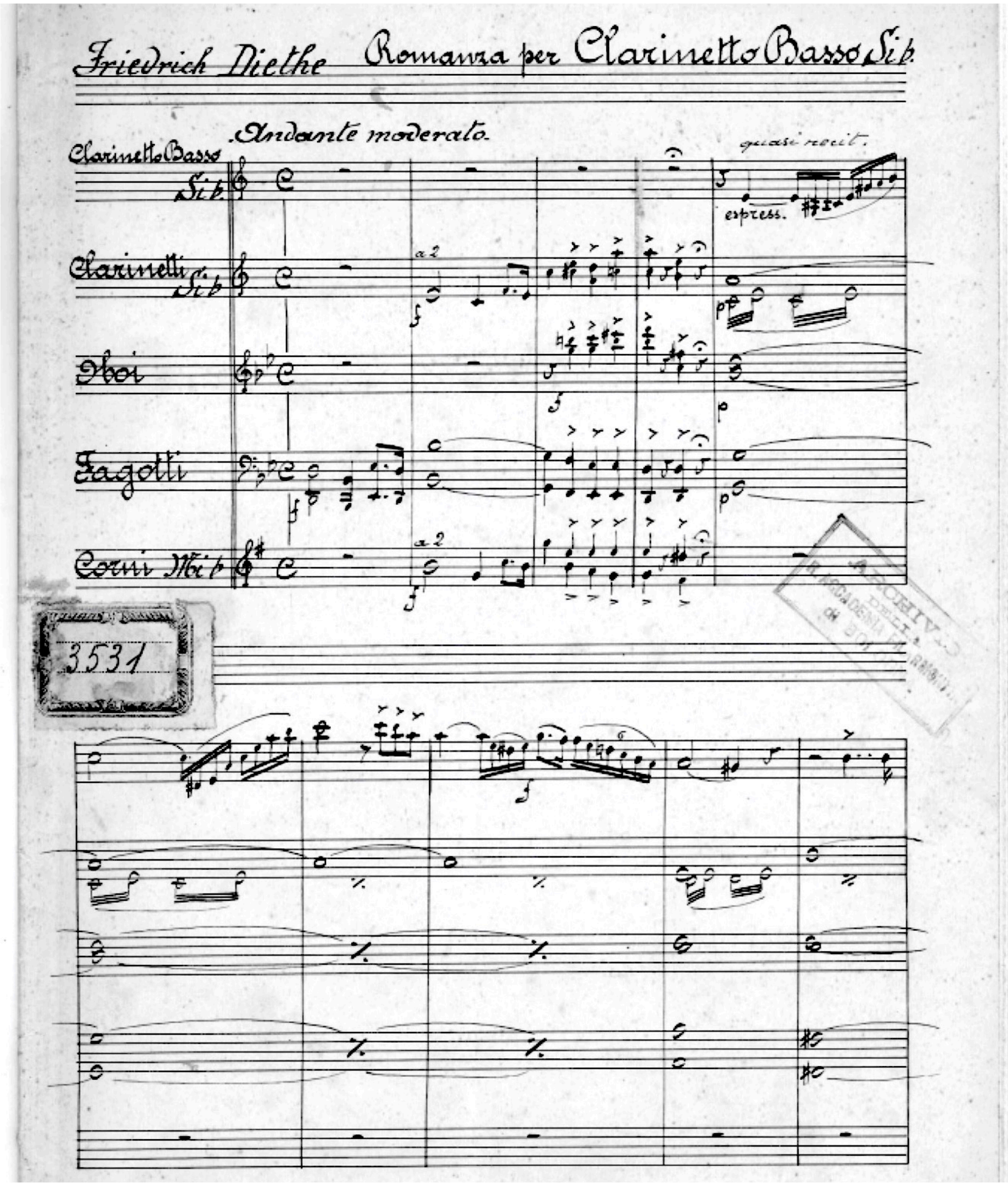
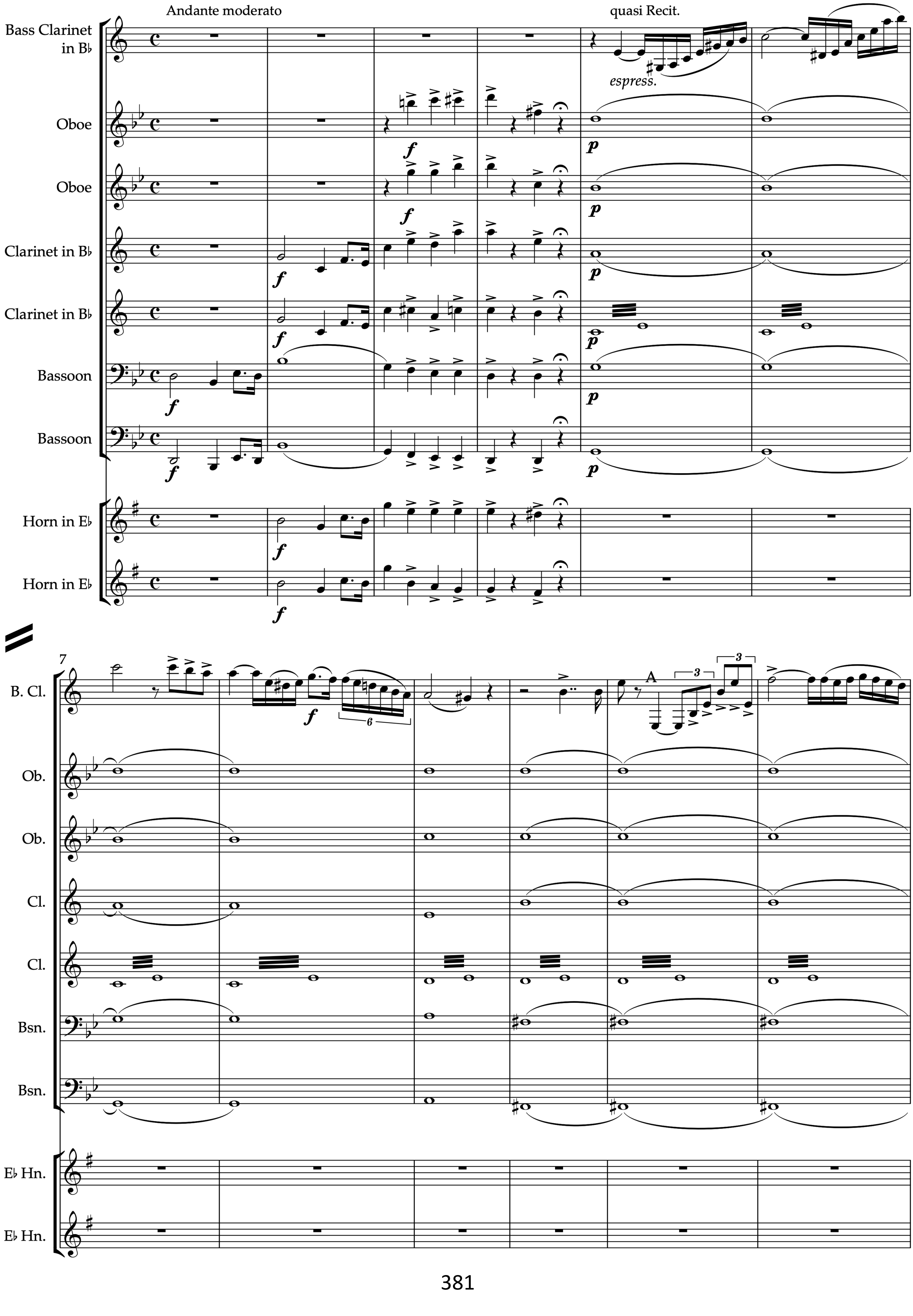
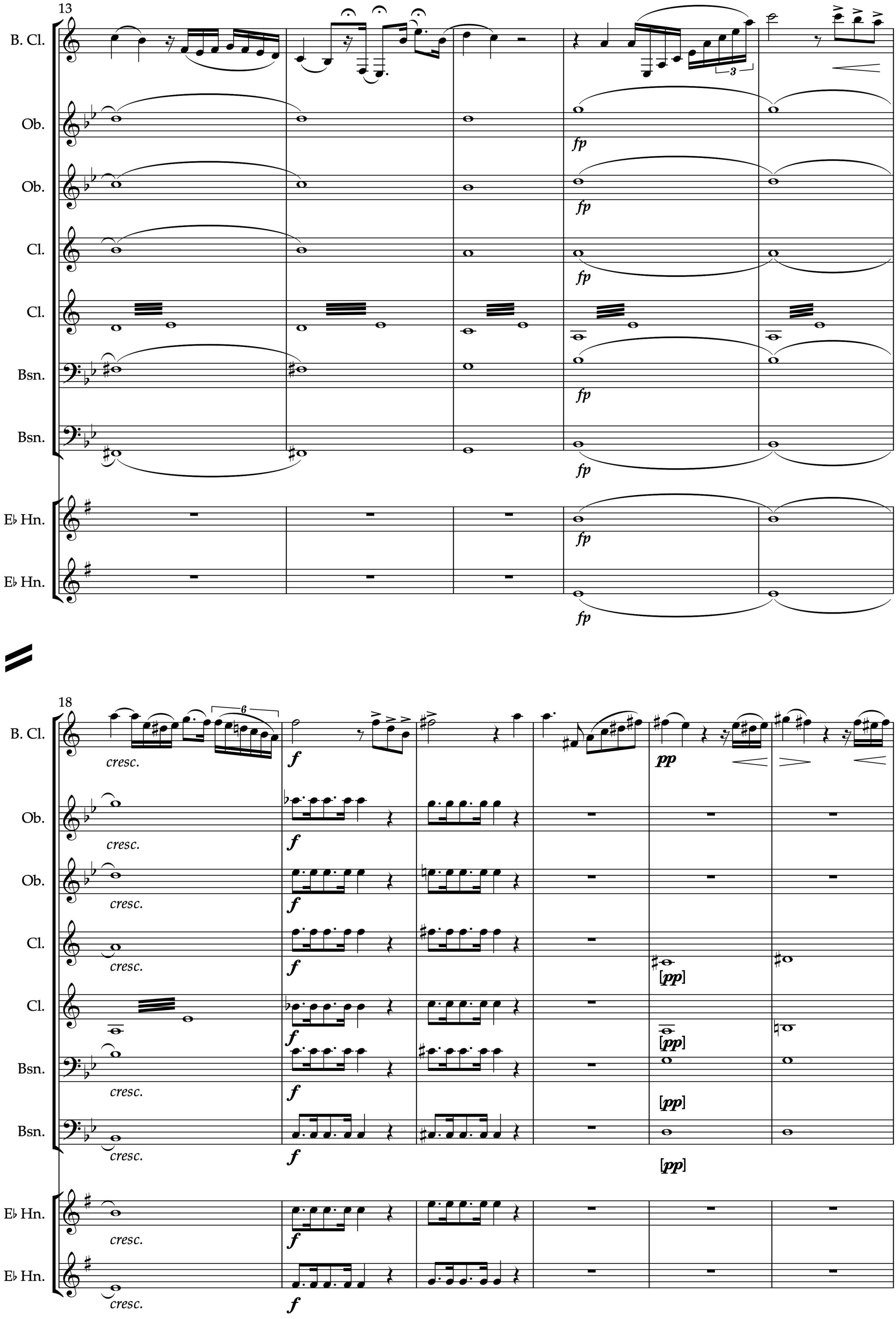
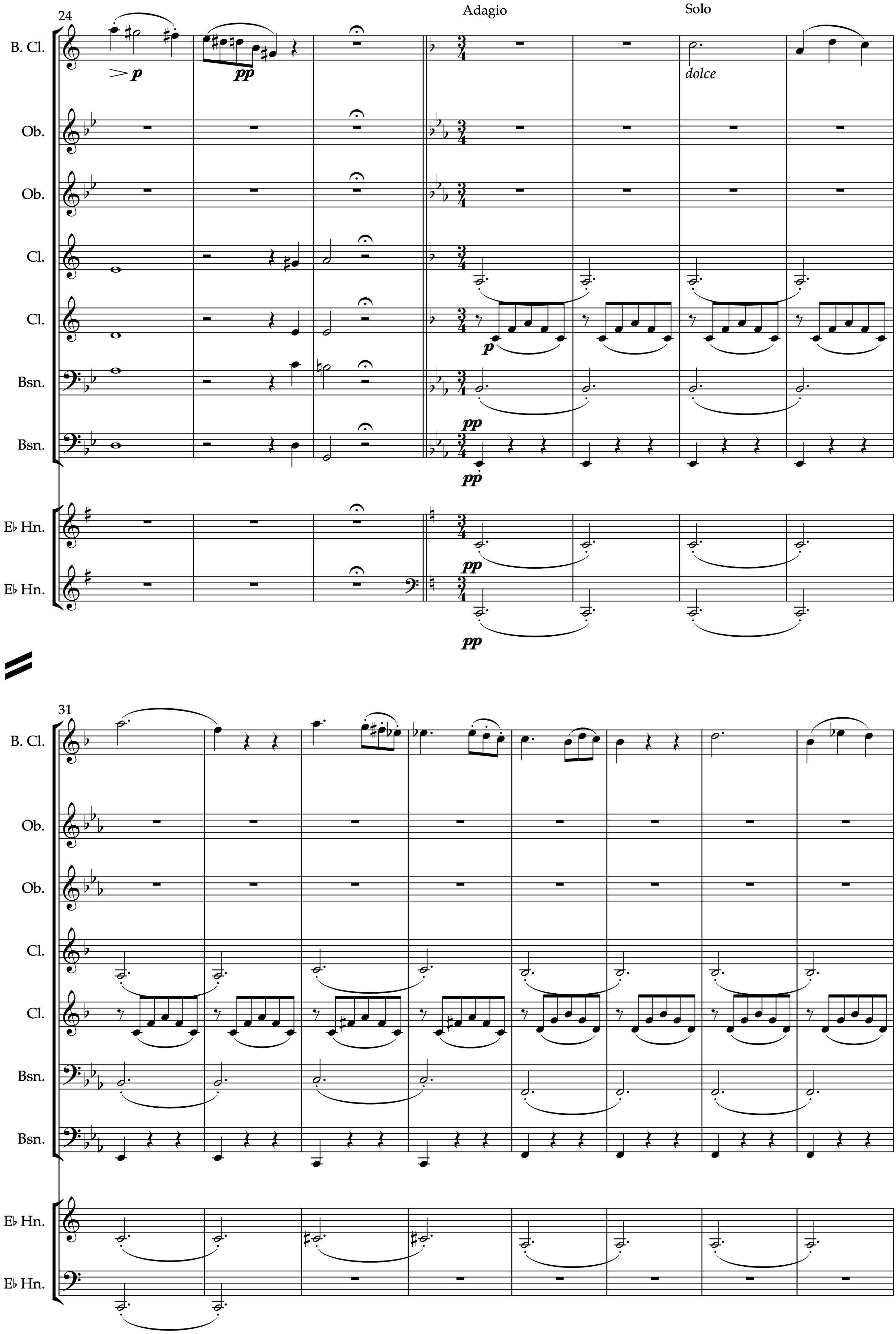



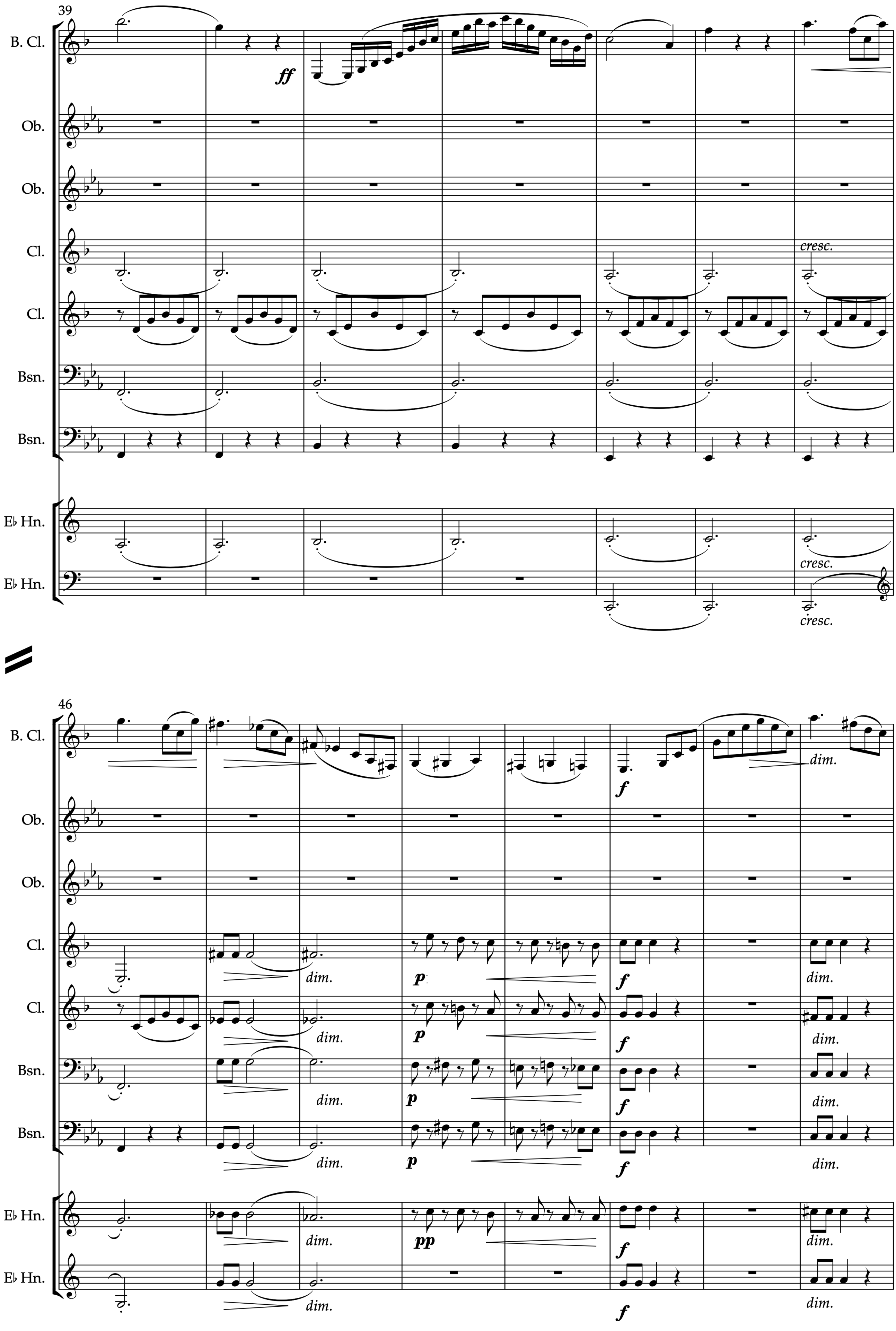
Figure D.6. First page of the Diethe manuscript (source I) in Accademia Filarmonica.

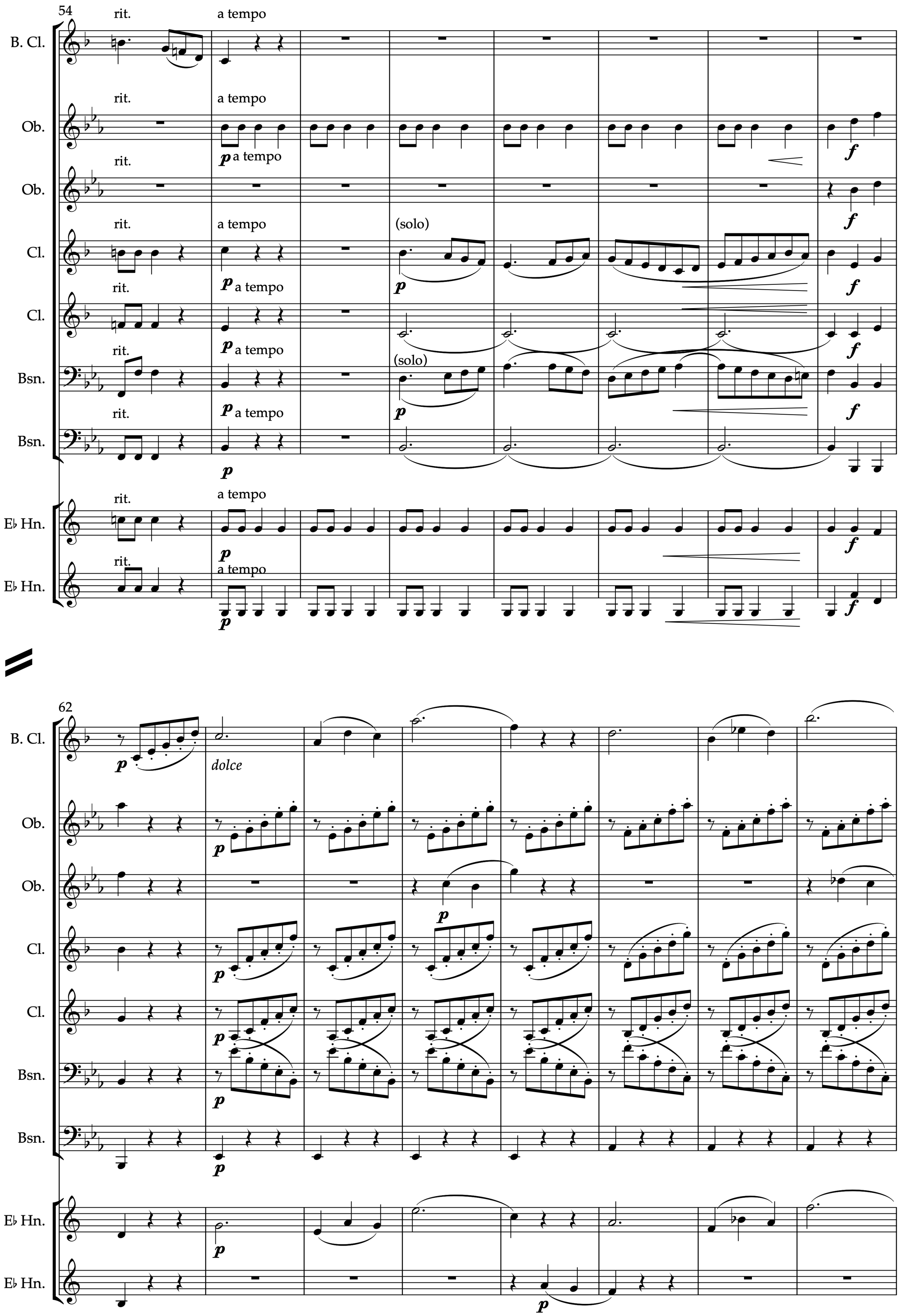
Bass-Klarinetto in B.

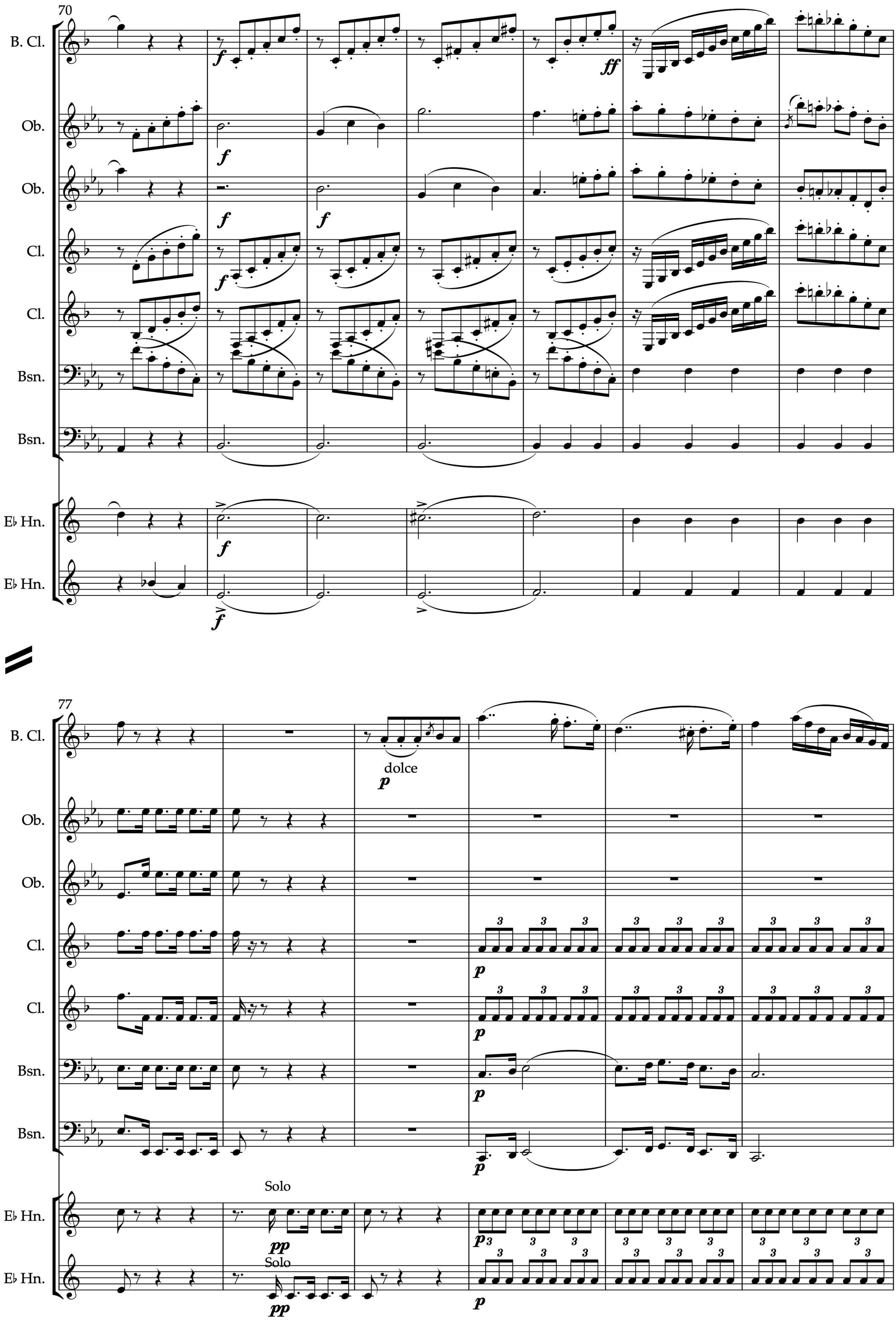
ROM ANZE.

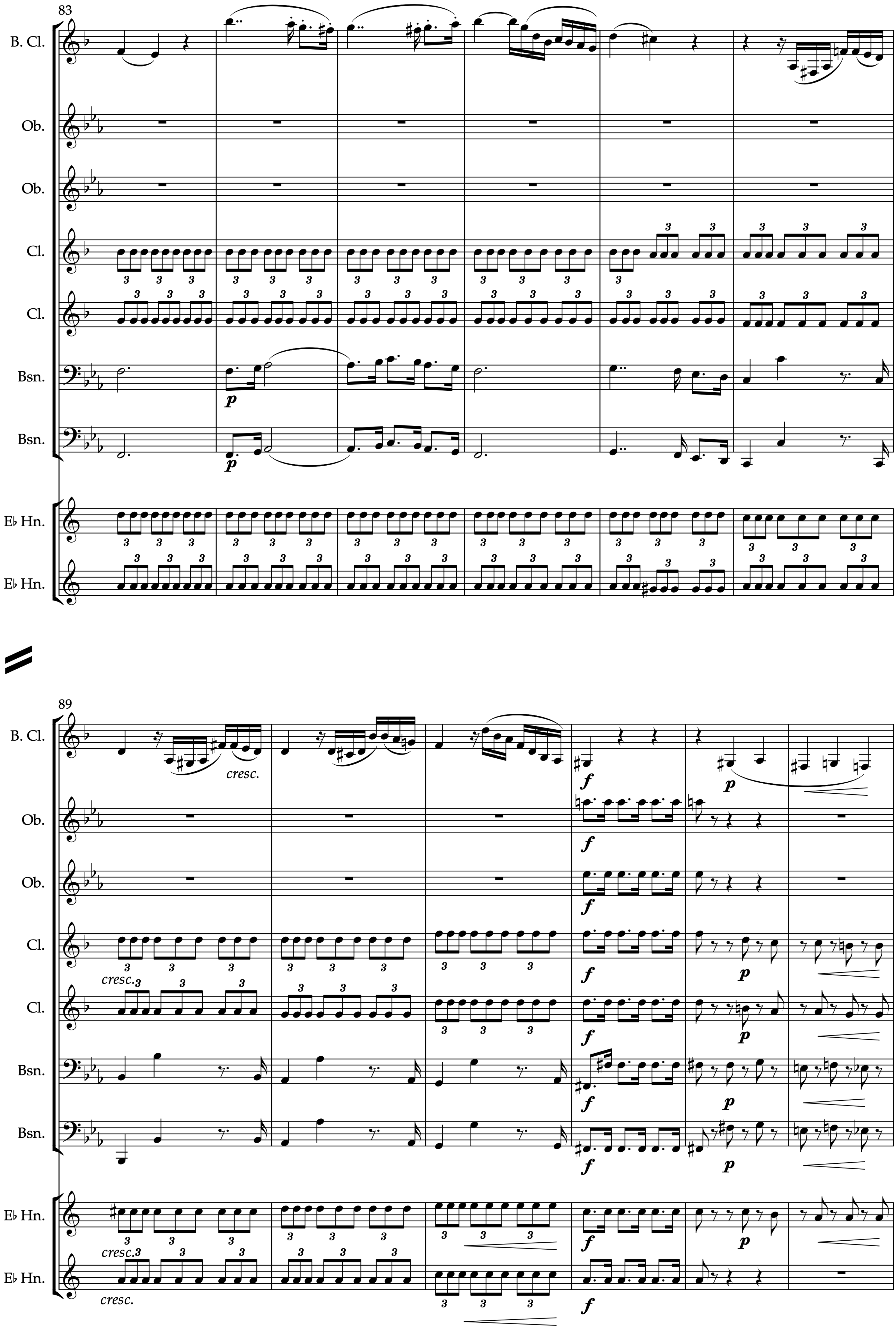
Friedrich Diethe
Edited by Keith Bowen


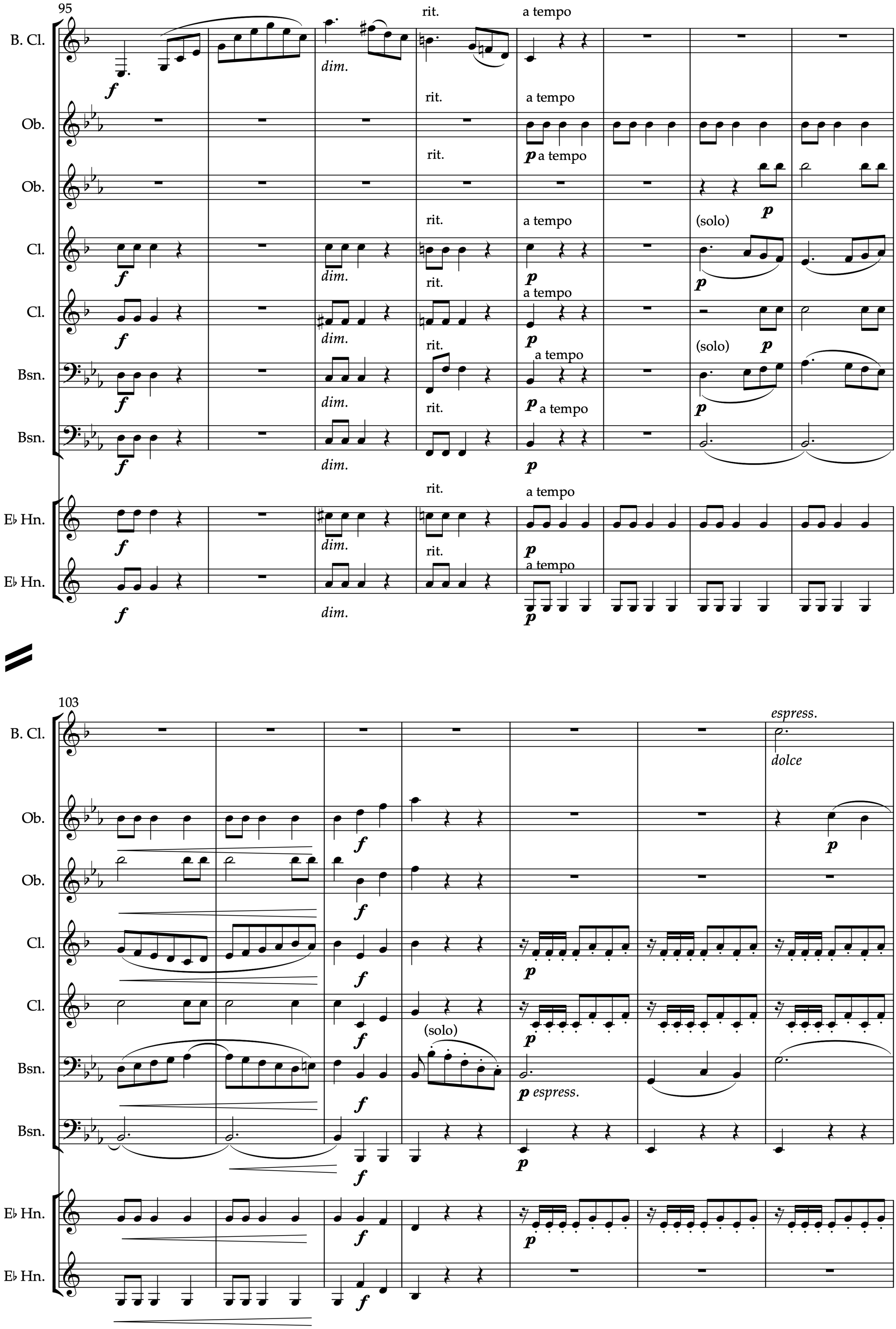
13
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
fp
18
cresc.
f
pp
[pp]


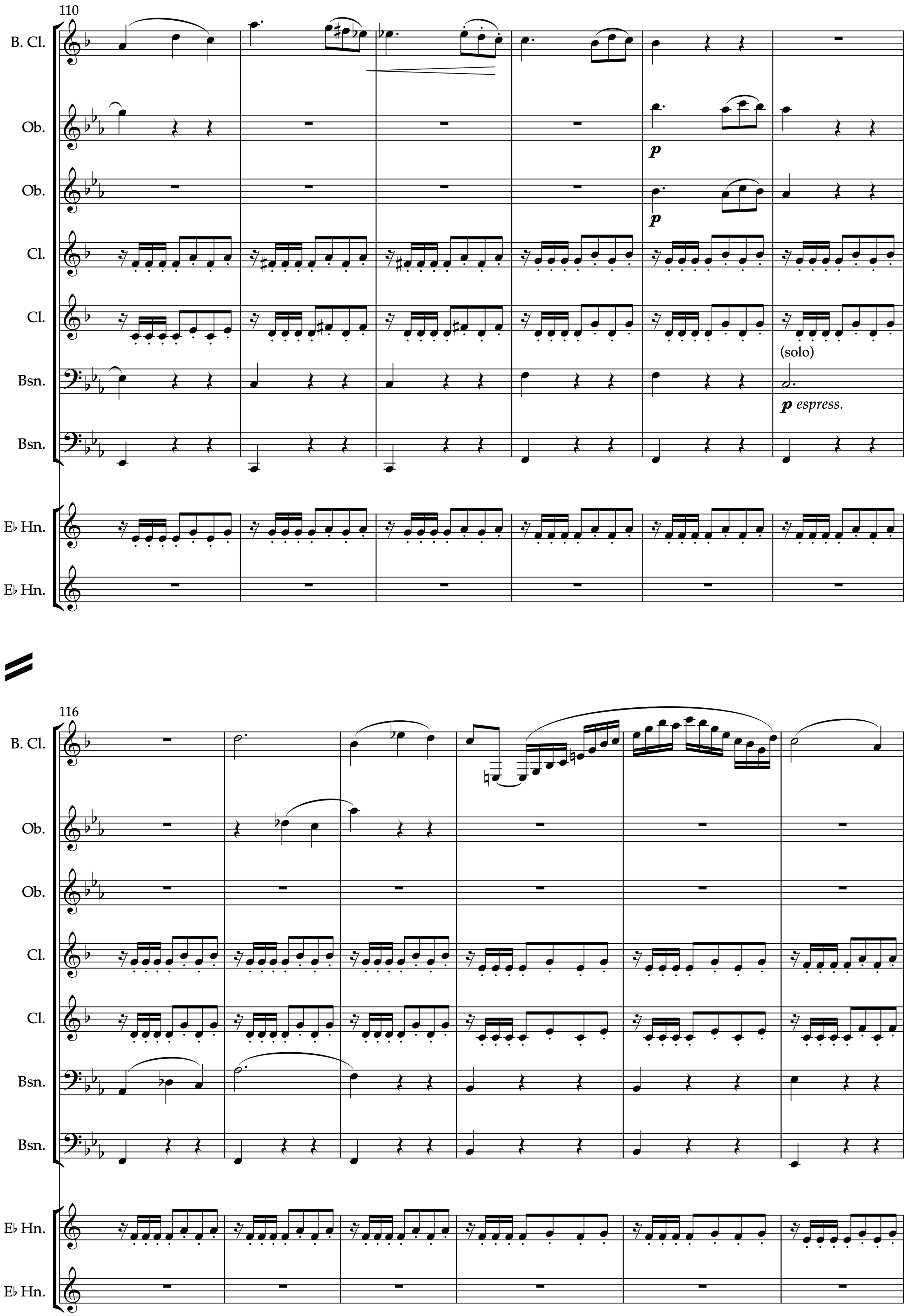
24
Adagio
Solo
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
p
pp
dolce
31


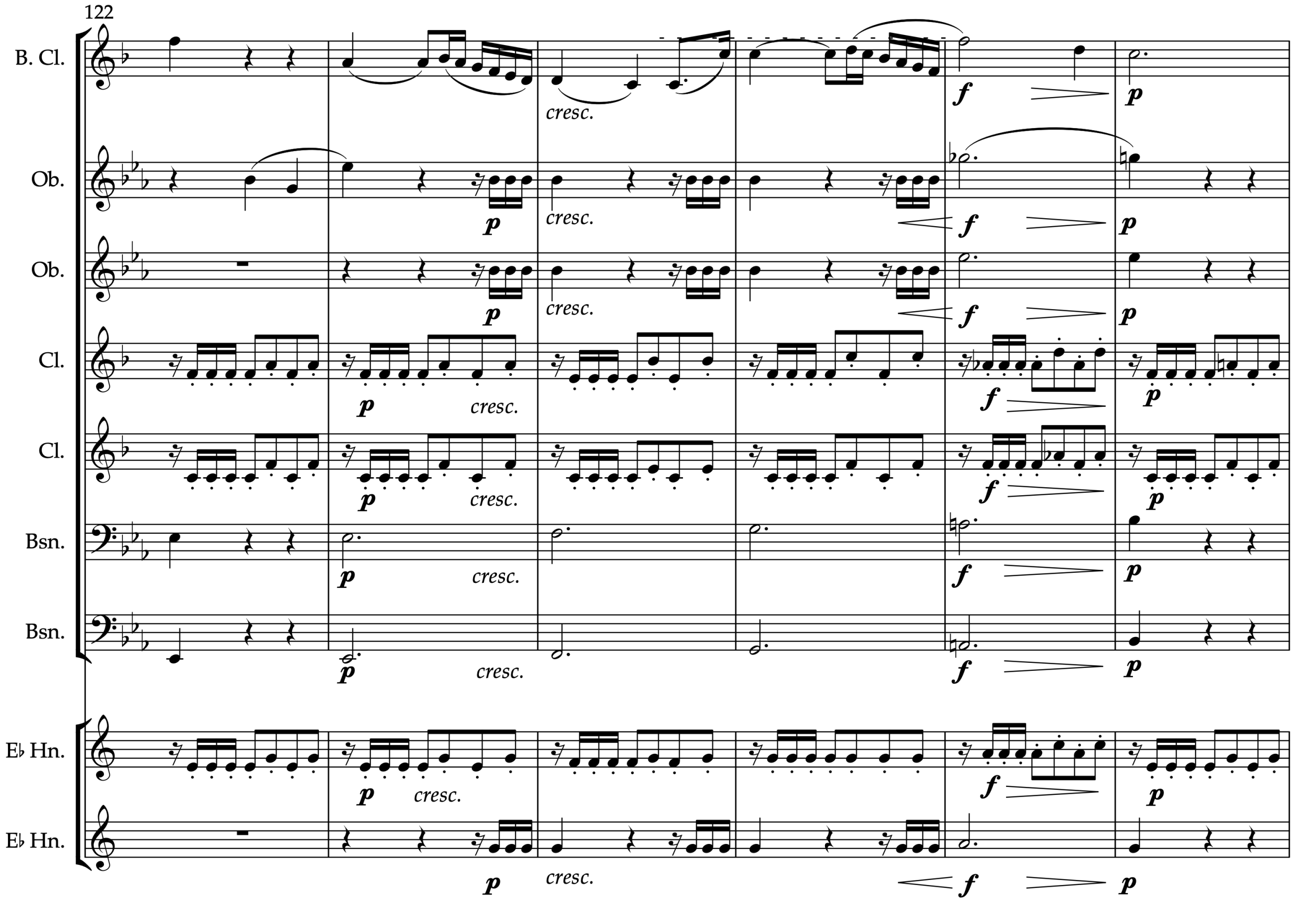
39
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
ff
cresc.
cresc.
cresc.
46
f
dim.
p
pp
dim.


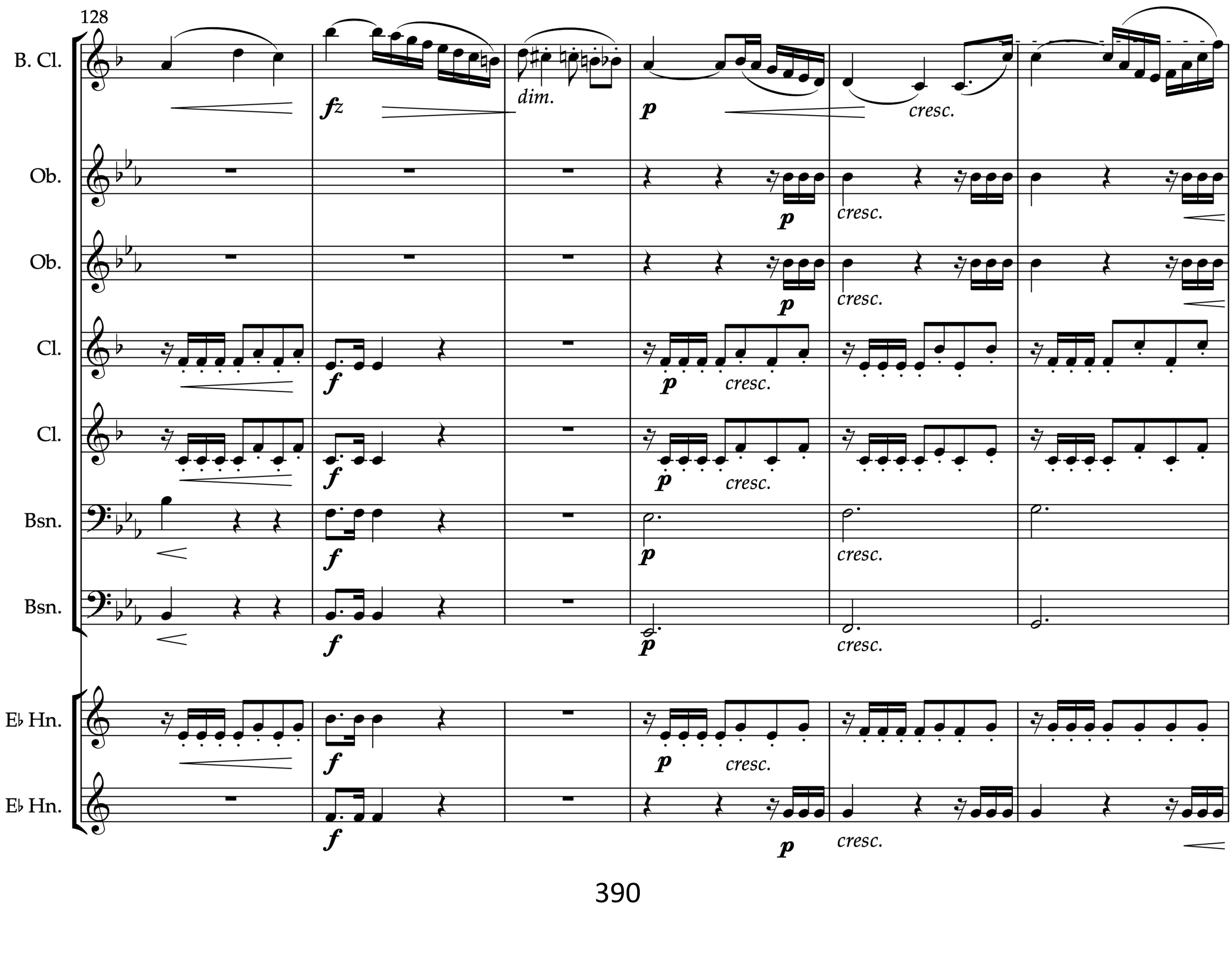
54
rit.
a tempo
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
(solo)
p a tempo
p
f
62
dolce


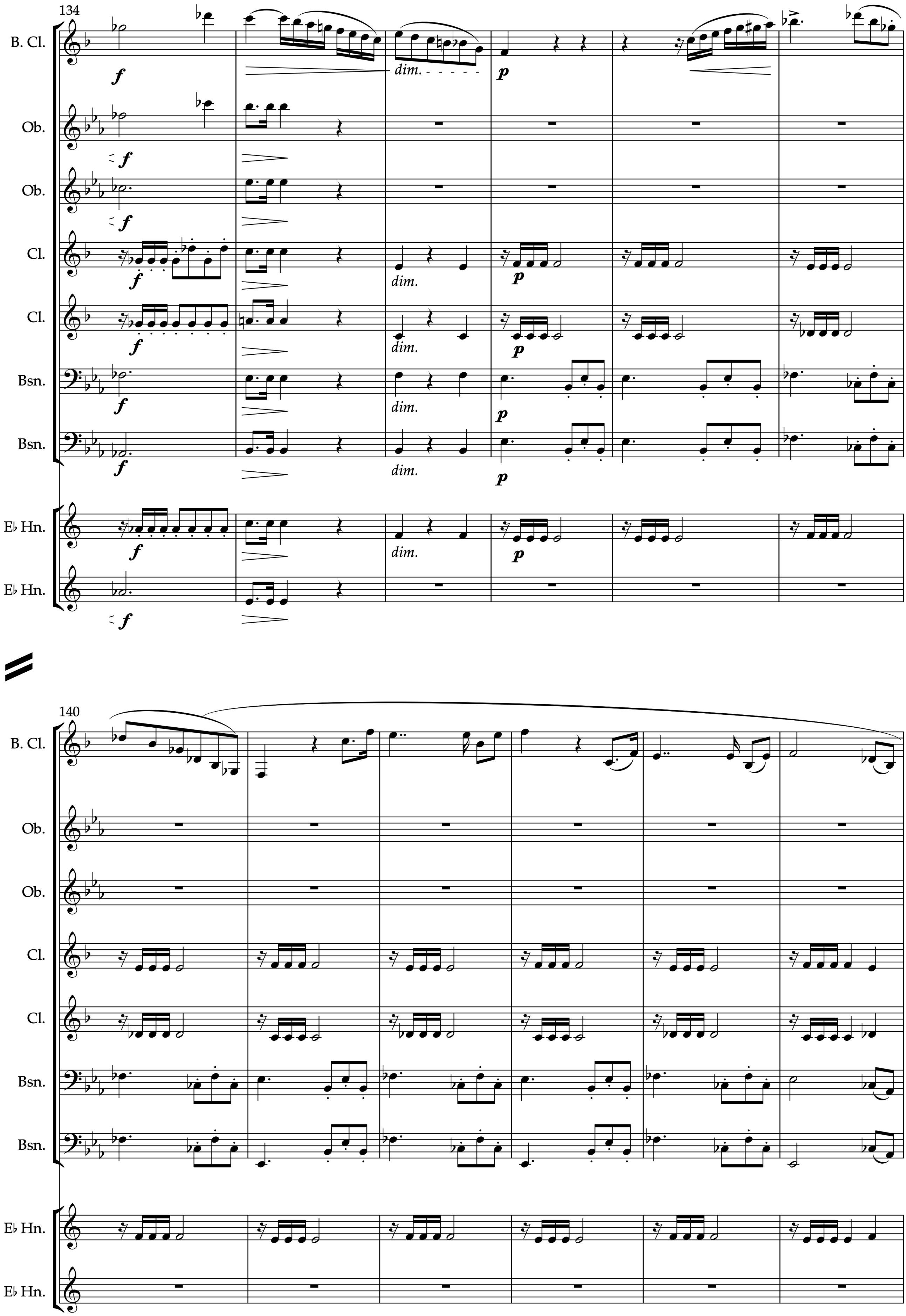
70
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
77
dolce
Solo
Solo


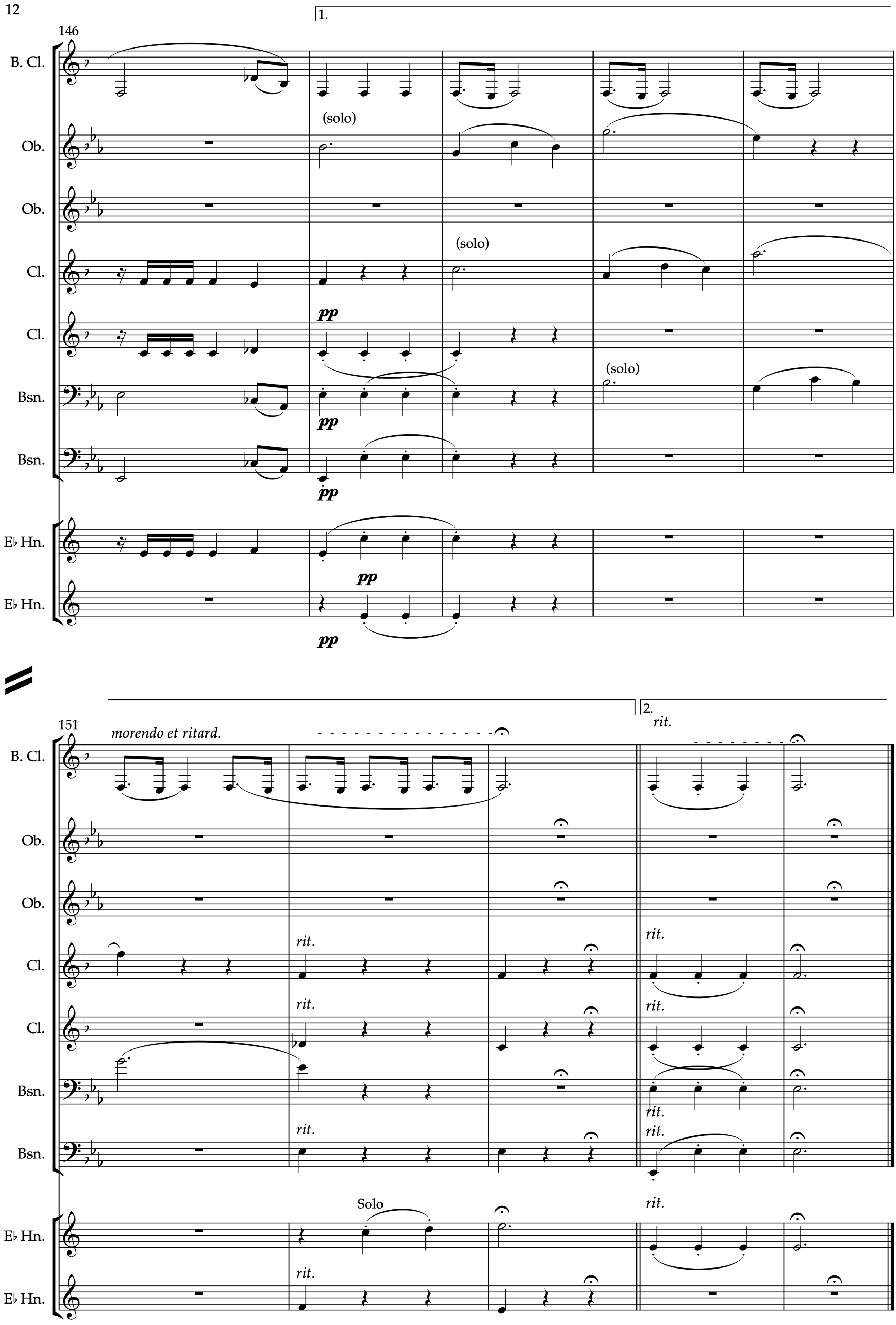
83
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
89
cresc.
f
p
cresc.


95
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
Eb Hn.
Eb Hn.
rit.
a tempo
dim.
(solo)
103
espress.
dolce
p espress.


110
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
p
p
(solo)
p espress.
116
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.


122
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
cresc.


128
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
dim.
cresc.


134
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
f
dim.
p
140


146
1.
B. Cl.
Ob.
Ob.
Cl.
Cl.
Bsn.
Bsn.
E♭ Hn.
E♭ Hn.
(solo)
(solo)
(solo)
pp
pp
pp
pp
pp
151
morendo et ritard.
2.
rit.
rit.
rit.
rit.
rit.
rit.
rit.
rit.
rit.
rit.
Solo

Appendix E

Instrument Database

The database is fully described in Chapter 4. The printout that follows is an abbreviated version, omitting some fields so that it will fit legibly on the page. The omitted fields are:

1. Instrument images. These are given in chapters 2 and 7 for all the instruments discussed. Many of the images have been authorised for personal research but not for distribution, so are not included in material that will be publicly available.
2. Sources: the book, catalogue or other source of the original information. This was only used for reference while compiling the databases, and the resulting information is cross-checked and contained in the museum siglum.
3. Checkboxes: used to confirm that the data for an instrument has been verified from available data, e.g. from museums, and to note which instruments have been examined, and which measured in detail. This is simply to track research progress.
4. Materials of the body and the bell. These do not enter into the discussion in this thesis, but may be of interest in the long term.
5. Latitude and longitude data of the maker's city and of the museum location. The former are used for the distribution maps in Chapter 4 and the latter are not used in the thesis.
6. Notes: These are the notes provided in the museum catalogues, where possible obtained direct from the museums or from public information; some also include my observations on examination. Many of these are quite long.

The accompanying Excel file, labelled « Bass clarinet database for thesis.xlsx » contains all the fields specified in the printout below, plus fields 4, 5 and 6. The Notes field is entered as an Excel Note, accessed where available by clicking on the red triangle in the top right-hand corner of the Notes field.

Database of extant bassoon-form instruments[697]

Maker name (Langwill)	Type	Maker's City	Contemp. State	Museum Sigil	Museum Number	Date	Form	Tonality	Lowest note	Keys	Bore, mm	Military mark
Anon.	Basset horn	Germany	n.k.	I.M.Carbonara	bassethorn	1870 - 1900	H-B	F?	C	n.k.	n.k.	
Anon.	Bass	n.k.	n.k.	F.P.Kampmann	203	1847 - 80	H-B	n.k.	n.k.	n.k.	n.k.	
Anon.	Basset horn	n.k.	n.k.	D.M.dm	43336	1850-1900	H-B	n.k.	n.k.	7	n.k.	
Anon.	Bass	Italy	Lombardy-Venetia?	US.NY.mma	89.1635	1840-60	B-F	B♭	n.k.	7	30	
Anon.	Bass	Italy	Lombardy-Venetia?	US.NY.mma	89.1636	1840-60	B-F	B♭	n.k.	17	25	
Anon. (Catlin type)	Bass	n.k.	USA	US.DM.u	E200	1800-30	B-F	n.k.	n.k.	n.k.	n.k.	
Anon. (Catlin type)	Bass	n.k.	USA	US.CD.hs	1966.544.6	c.1810	B-F	n.k.	n.k.	n.k.	n.k.	
Anon. (English)	Bass	England	UK	US.B.mfa	17.188	1875-1900	H-B	B♭	B1	9	14.3	
Beck, Wilhem	Bass	Weimar	Saxe-Weimar-Eisenach	D.LE.u	1540	1850~	B-F	B♭	B♭1	19	n.k.	
Berthold, Georg Jacob	Bass	Speyer	Rhenish Palatinate	D.Michaelstein	n.a.	1850-1900	B-F	n.k.	n.k.	n.k.	n.k.	
Berthold, Georg Jacob	Bass	Speyer	Rhenish Palatinate	D.M.dm	25966	1850-1900	B-F	n.k.	C2	n.k.	15.7	
Berthold, Georg Jacob	Bass	Speyer	Rhenish Palatinate	D.M.dm	14103	1850-1900	B-F	n.k.	C2	17	n.k.	B. 1. J.R. / 30.
Bimboni, Giovanni	Bass	Florence	Tuscany (Austrian Empire)	D.N.gnm	MIR482	1845-1850	O-F	B♭	B♭1	17	21	
Bohland & Fuchs	Basset horn	Kraslice	Austrian Empire	D.Nauheim. heimatmuseum	157	1900	H-B	F?	C?	n.k.	n.k.	
Buffet, Auguste	Bass	Paris	France	US.AA.s	635	1850	O-F	B♭	n.k.	20	n.k.	
Buffet, Louis Auguste attr.	Bass	Mantes-la-Ville	France	F.Mantes-la-Ville. Buffet	93	1840-1850	O-F	n.k.	C2	20	21	

[697] Abbreviations: B-F = bassoon form, H-B = half-bassoon form, O-F = Ophicleide-form. The five straight-form instruments examined in detail are also included.

Catlin, Geo.	Bass	Hartford, CT	United States	US.DB.hf	77.68.1	1812	B-F	n.k.	n.k.	6	17.3	
Catlin, Geo. & Bacon	Bass	Hartford, CT	United States	US.NY.Castile	n.a.	1812	B-F	n.k.	n.k.	9	17.3	
Catlin, Geo. attr.	Alto	Hartford, CT	USA	US.NY.mma	1994.365.1	1812-1830	B-F	E♭	n.k.	n.k.	n.k.	
Catterini, Catterino	Bass	Padua	Lombardy-Venetia	GB.O.ub	496	1833	D-F	C	C	20	22.55	
Chiesara, Tedesco	Sop.	Venice	Lombardy-Venetia	I.R.ms	3254	1889	D-F	C	C3	8	14.8	
DeAzzi	Bass	Venice	Lombardy-Venetia	D.Uhingen.reil	deazzi	1848~	B-F	C	B♭1	n.k.	23	
Douglas, H.	Bass	Glasgow	UK	GB.E.u	96	1870~	H-B	B♭	n.k.	n.k.	25	
Ghirlanda, Allessandro	Sop.	Verona,	Lombardy-Venetia	I.R.ms	3130	1868	D-F	C	C3	n.k.	n.k.	
Grenser, Augustin	Bass	Dresden	Saxony	D.DS.hl	KG67:133	1795	B-F	B♭	n.k.	n.k.	n.k.	Grand Duke Ludwig I
Grenser, Heinrich	Bass	Dresden	Saxony	S.S.m	M 2653	1793	B-F	B♭	n.k.	9	15.2	
Heckel	Bass	Wiesbaden	German Empire	GB.Warwick. bowen	heckel	1910	S-F	A	Eb	21	23.25	
Kraus	Bass	Augsburg	Bavaria	D.Uhingen.reil	Kraus	n.k.	B-F	n.k.	n.k.	n.k.	n.k.	
Kruspe, F.C.	Bass	Erfurt	Prussia	D.LE.u	4479	1865-75	S-F	B♭	E2	n.k.	23	
Kruspe, F.C.	Contra.	Erfurt	Prussia	D.B.im	591	1850	B-F	B♭	E1	18	35	
Kruspe, F.C.	Bass	Erfurt	Prussia	CH.B.hm	1999-136	1880	B-F	n.k.	C2	n.k.	n.k.	
Kruspe, F.C.	Bass	Erfurt	Prussia	xUS.AA.s	636	missing	B-F	B♭	n.k.	24	n.k.	
Kruspe, F.C. attr.	Bass	Erfurt	Prussia	D.LE.u	4481	1850-1900	O-F	n.k.	n.k.	n.k.	21-26	
Lempp, Friedrich	Basset horn	Vienna	Austrian Empire	A.LI.m	Mu.28	1789~96	B-F	n.k.	n.k.	7	15.5	
Losschmidt, Franz	Bass	Olomouc	Austrian Empire	D.M.dm	20506	1850~	O-F	C	C2	21	n.k.	
Losschmidt, Franz	Bass	Olomouc	Austrian Empire	US.NY.mma	89.4.2459	1852-	O-F	B♭	n.k.	24	25	
Losschmidt, Franz	Bass	Olomouc	Austrian Empire	GB.E.u	5703	1852-	O-F	B♭	n.k.	n.k.	n.k.	
Losschmidt, Franz	Bass	Olomouc	Austrian Empire	D.N.gnm	MIR481	1852-67	B-F	B♭	C2	23	24.8	
Losschmidt, Franz	Bass	Olomouc	Austrian Empire	I.TS.mt	1013	1852	B-F	n.k.	n.k.	n.k.	22.7-23.4	

Ludwig & Martinka	Bass	Prague	Austrian Empire	CZ.P.cmm	E.135	1860-70	B-F	C	n.k.	20	n.k.	
Maino, Paolo	Bass	Milan	Lombardy-Venetia	B.B.mim	941	1838	B-F	B♭	Bb	n.k.	22	
Marsh, Perry & Chase	Bass	Calais, VT	USA	US.NY.Vassar	College	1825	B-F	n.k.	n.k.	20	18.5	
Marsh, Perry or Fischer & Metcalf	Bass	East Calais, VT	USA	US.W.si	65.609	1819-24	B-F	n.k.	n.k.	7	19	
Martin Frères	Bass	Paris	France	F.P.cm	E.1154	19th C	O-F	B♭?	n.k.	21	n.k.	
Miner, Uzal	Bass	Hartford, CT	USA	US.CT.Farmington	167a+b	1810-1830	B-F	n.k.	n.k.	9	17.3	
Miner, Uzal attr.	Bass	Hartford, CT	USA	US.NY.Buffalo	61.259	1810-30	B-F	n.k.	n.k.	9	17.3	
Miner, Uzal attr.	Bass	Hartford, CT	USA	US.DB.hf	n.a.	1810-30	B-F	n.k.	n.k.	9	17.5	
Nechwalsky Anton	Bass	Vienna	Austrian Empire	I.R.ms	3260	1850-60	O-F	B♭?	D2	n.k.	21.15	
Nechwalsky, Anton	Sop.	Vienna	Austrian Empire	I.R.ms	3072	1850-60	O-F	B♭?	C3	15	n.k.	
Nechwalsky, Anton	Basset horn	Vienna	Austrian Empire	I.R.ms	3080	1850-60	O-F	F?	C3	n.k.	n.k.	
Nechwalsky. Anton	Bass	Vienna	Austrian Empire	A.W.gm	144	1850-60	O-F	B♭?	n.k.	16	n.k.	
Ottensteiner Georg	Bass	Munich	Bavaria	D.M.sm	79-28	1869	H-B	B♭	B♭1	18	21.3	I/J.R.19 & B 3.J.R.
Ottensteiner , Georg	Bass	Munich	Bavaria	BHST	38452	1869	H-B	n.k.	C2	20	20	
Pauer, Stephan	Basset horn	Bratislava	Austria	D.N.gnm	MIR476	1875-1900	B-F	B♭	B♭1	19	15	
Riva, Giacinto	Bass	Bologna	Papal States	US.NY.mma	89.4.3124	1860~	B-F	B♭	C2	19	19	
Rott, Franz Karl	Bass	Prague	Austrian Empire	D.M.sm	87-090	1875	O-F	n.k.	n.k.	n.k.	n.k.	
Sax, Adolphe	Bass	Brussels	Belgium	B.B.mim	2601	1838-40	S-F	B♭	E2	n.k.	28.8	
Sax, Adolphe	Bass	Brussels	Belgium	B.B.mim	175	1838-40	S-F	B♭	E2	n.k.	29	
Schediwa, Josef Josefovich	Bass	Odessa	Russian Empire	GB.E.u	4819	1900-18	H-B	B♭	C2	17	n.k.	

Schediwa, Josef Josefovich	Bass	Odessa	Russian Empire	GB.O.ub	401	1900-18	H-B	B♭	C2	20	22	
Schöllnast Co.	Basset horn	Bratislava	Austrian Empire	N.O.k	MH-L7	1880	D-F	F	C	19	n.k.	
Schöllnast Co.	Bass	Bratislava	Austrian Empire	A.W.gm	141	1880?	B-F	n.k.	n.k.	n.k.	n.k.	
Seelhoffer, Rudolf	Bass	Berne	Switzerland	F.P.cm	E956	1850	O-F	n.k.	B♭1	19	n.k.	
Seidel, Josef Franz	Bass	Mainz	Hesse-Darmstadt	D.LE.u	1541	1850-55	B-F	B♭	n.k.	17	n.k.	
Stengel, attr.	Tenor	Bayreuth	Bavaria	D.N.gnm	MI338	1830~	V-type	F	A1	18	18.3	
Stengel, J.S.	Bass	Bayreuth	Bavaria	GB.E.u	4932	1870-80	S-F	B♭	E2	14	20	
Stengel, J.S.	Bass	Bayreuth	Bavaria	I.F.ga	1988/170	1850+	B-F	B♭	C	n.k.	20	
Stengel, J.S.	Bass	Bayreuth	Bavaria	B.B.mim	943	1855	B-F	B♭	C2	20	19.9	
Stengel, J.S.	Bass	Bayreuth	Bavaria	D.N.gnm	MIR479	1860 - 1866	B-F	B♭	B♭1	24	24	
Stengel, J.S. attr,	Bass	Bayreuth	Bavaria	D.M.dm	46262	1865-75	B-F	n.k.	C2	14	20.7	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	D.SH.m	Mu3	1828	B-F	C	n.k.	17	n.k.	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	D.Kronach.wolf	private	1828-37	B-F	n.k.	n.k.	n.k.	n.k.	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	NL.DH.gm	840392	1828-37	B-F	C	n.k.	19	n.k.	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	D.B.im	87	1828-37	B-F	n.k.	n.k.	n.k.	n.k.	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	CH.Z.mb	123	1828-37	B-F	C	n.k.	17	n.k.	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	NL.DH.gm	840390	1828-37	B-F	B♭	n.k.	19	n.k.	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	D.M.dm	68079	1833	B-F	C	B♭1	19	n.k.	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	D.N.gnm	MIR477	1835	B-F	B♭	B♭1	19	24.2	
Streitwolf, J.H.B.	Bass	Göttingen	Hanover	D.LE.u	1539	1835	B-F	B♭	B♭1	18	25.2	6 INF. RT.
Streitwolf, J.H.B. attr.	Bass	Göttingen	Hanover	DK.K.m	E11	1828-37	B-F	n.k.	n.k.	n.k.	n.k.	
Tomschik. Martin	Sop.	Brno	Austrian Empire	I.R.ms	3069	1857	B-F	B♭	C3	11	n.k.	

Tuerlinckx	Alto	Mechelen	Belgium	B.B.mim	933	1800-30	H-B	F	E2	6	15.46	
Uhlmann, Jos.	Bass	Vienna	Austrian Empire	D.M.dm	43337	1850	O-F	C	C	20	n.k.	
Widemann	Bass	Paris	France	D.Bochum.m	SGK 47	1847	O-F	n.k.	n.k.	n.k.	n.k.	
Widemann	Bass	Paris	France	D.B.im	2902	1837-50	B-F	n.k.	n.k.	20	n.k.	
Widemann attr.	Bass	Paris	France	GB.L.hm	14.5.47/301b	1836-50	O-F	B♭	C2	n.k.	n.k.	
Wiepricht & Skorra	Contra.	Berlin	Prussia	D.B.im	2904	1839-	O-F	C	E1	n.k.	39	