ASSESSING THE SOUND OF A WOODWIND INSTRUMENT THAT CANNOT BE PLAYED

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ABSTRACT

Historical woodwind instruments in museums or private collections often cannot be played, by virtue of their poor condition or the risk of damage. Acoustic impedance measurements may usually be performed on instruments in good condition, but only if they are in playable condition. Many museum specimens are not. However, If the bore shape and tone holes are measured accurately, we are able to compute the acoustic impedance of the instrument for all fingerings. Conclusions may then be drawn about the instrument's pitch, intonation, temperament, fingerings, effects of bore shrinkage and even the timbre of the notes. A simple linear, plane- and spherical-wave computational model, originally developed for calculating the acoustic impedance of conical-bore woodwinds, is here applied to bass clarinets for the first time. The results are assessed by experimental impedance measurements and by playing tests on an historical Heckel bass clarinet in A of 1910 that has been continuously maintained in playing condition but relatively lightly used. In all cases the lowest two to five frequency impedance peaks agreed well with the calculations. The method is shown to be a viable method for the examination of historical woodwind instruments.

1. INTRODUCTION

The aim of the investigations in this paper is to test the idea that it is possible to model the input impedance of a woodwind instrument sufficiently accurately that one may draw reliable conclusions about its behaviour purely from geometrical measurements of its bore, tone holes and keypads. This will enable the vast collections of woodwind instruments in museums to be used for primary evidence of their sounds without risk of damage.

There is a very large number of musical instruments in museum collections. However, many institutions preclude playing the instruments because of the risk of damage [1]. This is especially true for woodwind instruments where the act of playing rapidly introduces air at a much higher humidity and temperature, triggering potentially damaging reactions in the wood. Moreover, even if playing is permitted, it is fairly unlikely that a wind instrument 150 – 200 years old will be usefully playable without restoration that goes well beyond normal conservation.

However, museums will normally permit the handling and careful measurement of instruments that are not too fragile, to an accredited researcher under supervision and the guidleines of ICOM/CIMCIM [2]. This has been used to study the development of types of musical instrument and their keywork (see, for example, [3, 4, 5] for clarinets), but their sounds have so far been mostly inaccessible, apart from the small number of restored instruments.

The principle upon which the main methodology of this paper is based is that the sound of a wind instrument is largely dominated by the shape of its air column, as indicated by its resonance or 'input impedance' spectrum [6, 7]. This is not to say that the mouthpiece/reed is unimportant, but that, at least up to the middle of the clarion register, it has a much smaller effect on the intonation of each note than does the air column [8, 9].

A well-preserved instrument from 1910 was used for this trial. Standard acoustic computational methods were used to calculate the impedance spectra for each note of the instrument, and two tests of the accuracy were performed: one by measuring the input impedance directly in the laboratory, and the other by playing tests on the instrument, measuring the frequency of the note emitted at each fingering and looking at the predicted intonations produced by both 'normal' and 'alternative' fingerings.

2. COMPUTER MODELLING OF WOOD-WIND INSTRUMENTS

The development of methods of modelling woodwind instruments has taken place over more than a century, beginning with the analytical ideas of Hemholtz [10]. Major contributions were made by Bouasse [11] and especially by Benade and his collaborators [7]. The understanding of woodwind acoustics progressed through analytical expressions for lossless and then lossy systems [12, 13, 14], linear system calculations [15], analysis of the reed/mouthpiece system [e.g. 10, 16, 17, 18], impedance of the bell [19, 20] and non-linear treatment of the reed generator [21, 22]; an excellent recent treatment appears in Chaigne and Kergomard [23]. In 1979, Plitnick and Strong [24] first applied the computer modelling method to the whole instrument. They split the bore (of an oboe in this case) into short cylindrical segments approximating the conical shape of the bore (the staircase approximation), 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 acoustic theory and strictly only apply to small amplitudes. This suffices for the calculation of resonance peaks, but the effects of large amplitudes are critical in the understanding of the peaks actually selected, as discussed below.

This is essentially the method used today. Differences are in the expressions for tone hole impedances, for wall losses and the radiation impedance of the bell, and in the matrix formulation analogous to transmission line theory which significantly speeds up the calculation [25]. Nederveen [26] has added some valuable insight into the elements of the modelling equations. Research on simulating clarinet sound dynamically using digital formulations of the air column and reed/mouthpiece system are also reaching an interesting stage [27, 28].

The program used here was written in MatLab™ and depends largely on the equations given by Keefe [25]. This contains the main advances made in theoretical modelling since Plitnik and Strong, though we added the treatment of reed and embouchure impedance from Dalmont *et al.* [29]. We were able to use the program IMPEDPS written by Robert Cronin [30, 31] to test our program, since its source code was kindly provided to us and we could configure our program to use identical algorithms. The methodology is generally applicable to reed-driven instruments, which all share a similar non-linear generation and feedback mechanism at the reed, while the cylindrical sections of clarinets are simply cones of infinite length. We have tested the basic assertion by comparing calculated impedances to experimental measurements of impedance and to audio playing tests as described below.

Many of the investigations involving the concept of acoustic impedance so far have been to test the acoustic theory and modelling [32, 33, 34] and to control manufacture [35, 36, 37, 38, 39, 40, 41] rather than to learn about the musical behaviour of historical instruments. The main exception is the work on bassoons by Cronin and Keefe [30, 25], Dart [42] and Hichwa and Rachor [43], in which the viability of alternate fingerings, the intonation and temperament, the quality of alternate wing-joint and boot-joint designs were examined. 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) [44]. The set was in very good condition, so they could compare impedance measurements with playing frequencies, and also make comparisons with a modern (Noblet) clarinet. Jean-Xavier Lefévre refers to this maker's clarinets in his famous tutor [45] and gives particular fingerings to exploit or overcome their characteristics. In their data analysis they concentrated on the harmonicity relations produced by the fingerings of the clarinets. They showed, for example, that the first register was not well tuned. Lefévre remarked on this feature in his tutor and also composed his sonatas mainly in the second register of the instrument. The modern clarinet showed much better alignment of the harmonics. Jeltsch and Shackleton have performed a similar study on early nineteenth century clarinets by Alexis Bernard et Jacques Francois Simiot [46]. Bass clarinets do not appear to have been studied so far.

The impedance spectrum shows the resonances in the tube that are capable of sustaining an oscillation in combination with the reed/mouthpiece generator. They will only make a good musical instrument if the harmonics of an oscillation based on one resonance coincide with other resonances, thus forming a 'regime of oscillation', when the non-linear generator combines with two or more resonances to form a stable tone [21, 21, 22].

3. COMPUTATIONAL METHODOLOGY

The program is an implementation of the well-established linear, small-signal plane- and spherical-wave acoustic impedance modelling equations. We shall cite sources for the key parameters and the necessary equations: the radiation impedance of a bell, the impedance of a conic segment, the impedances of tone holes and the impedance of the reed/embouchure.

3.1. Input parameters and equations

The following parameters were used: 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 C_p/C_v = 1.4; thermal conductivity of air =2.63 10^{-02} $Wm^{-1}K^{-1}$; specific heat at constant pressure C_p = 1.006 J $kg^{-1}K^{-1}$ These were chosen for appropriate playing conditions, that is, a somewhat elevated temperature and humidity and a substantially elevated CO_2 content of the exhaled air [26]. 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 these two conditions agree to better than 0.2 cents, below the limits of intonation discrimination by human ears.

The computation starts from the radiation impedance of the bell, and works up in segments to the mouthpiece. The bell formula was taken from experimental data from Benade and Murday [47], who give explicit formulae for the equivalent-length end correction due to the radiating aperture, dependent on the geometry of the aperture. This is converted into impedance by the standard formula for a lossless cylinder (e.g. [25]), since there are no walls to cause losses. As noted by Chaigne and Kergomard [2323, p. 684], there are no known formulas for the radiation impedance of a cone or flared bell, hence at present the semi-empirical formulas must suffice; however the choice does not strongly influence the end result.

The impedance of a conic section, in terms of the exit impedance of the previous section, is given in Keefe's 1990 paper on the modelling of woodwind air columns [2525]. This is a spherical wave solution, and includes viscous and thermal losses at a smooth wall. Segments end either at a tone hole, or at an output diameter within 10% of the input diameter, so that the wall losses (which depend on diameter) are calculated reasonably accurately.

Keefe's paper was also used for the tone hole corrections, with series and shunt length corrections to the segment impedance as given in his equations 5-9. Separate equations are needed for closed tone holes, open tone holes and open keyholes with a pad at a certain distance above the hole. These depend on both Keefe's theoretical models and on experiments by Benade and Murday [47] and by Cronin and Keefe [unpublished].

The reed impedance should be accounted for [48, 26]. In the initial calculations the column was terminated with an infinite impedance in order to compare closely with the experimental measurements (see below). To model the actual playing frequency, we should need the impedance as seen from the mouthpiece looking at the reed; the imaginary part of the "embouchure impedance" should be equal and opposite to that of the appropriate resonance peak to ensure no phase shift around the feedback loop to the reed; It therefore includes contributions from the reed, mouth and oral cavities. Thus the frequencies selected by the instrument will be slightly below impedance peaks of the tube alone. We have used the model of Dalmont et al [29], who show that the mouthpiece/reed combination can be taken into account by adding a small equivalent-length segment on to the top of the mouthpiece segment of the model. For soprano clarinets they found 7 ±2 mm for this correction and by considering the scaling of the equation we would expect 14 ±4 mm for bass clarinets.

4. MATERIALS AND METHODS

4.1. Description of the instrument and measurements

The instrument used for the tests was a Heckel bass clarinet in A from 1910 shown in Figure 1, owned by the author. It is a 21-key system including 5 plateau keys, and is German system with a so-called patent C#. Dated at 1910 from Heckel records [49] and formerly owned by the Kiev Symphony Orchestra, this has been kept in playing condition all its life, but lightly played (there are relatively few orchestral parts for the bass clarinet in A [50]. It is therefore a good experimental instrument for this project.

Figure 1. The Heckel bass clarinet in A used for the trials.

Bore diameters were measured with a set of graduated circular discs on the end of aluminium tubes. The bore is 23.2 mm for all its length, with a largely-conical flare beginning 153 mm from the bell. The mouthpiece was made by E. Pillinger to the dimensions of an original Heckel Bb bass clarinet mouthpiece in Nuremberg (D.N.gnm.MIR480), published by Bär [51].

Tone hole positions were measured with a calibrated tape measure to ±0.25 mm; tone hole diameters and depths and bore disc diameters were measured with a polymer caliper with accuracy ±0.1 mm. In addition to the tone hole centres and diameters, the chimney depth, diameter of the body at the tone hole position, the diameter of the tone hole keypad (where fitted) and its opening height were measured. The radius of curvature of the outer tone hole edges was estimated at 1.0 mm. These parameters all enter into the expression for the tone hole impedance when opened. Approximately 300 measurements in all were used to describe the instrument. We estimate that the parameters affecting the tuning (tone hole positions) are measured to 0.5%, corresponding to an average tuning accuracy of better than 5 cents. Since each length measurement is independent, this error applies separately to each note, and is not cumulative. The mouthpiece and crook were measured by filling with water and weighing the water, taking the average of ten measurements.

4.2. Experimental impedance measurement systems

Two systems were used to measure impedances in the laboratory: an Open University built-in-house single-microphone capillary system that has been extensively calibrated [52] (courtesy Prof. D. Sharp), and the commercial BIAS (Brass Instrument Analysis System) modified for woodwind [53, 54, 55]. One measurement (note G3) was made with the in-house system, which verified that the agreement between the methods was good. For all subsequent meas-urements 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 recording 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 which may be made constant using some active control). Provided the wavelength is sufficiently above that of the instrument's bore, the ratio of pressure over flow rate gives the plane wave component of the impedance. Phase information can also be obtained from the system through the use of a phase meter connected to the two microphones.

An adaptor was made from nylon to fit the BIAS system at one end and the mouthpiece 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.

4.3. Audio frequency measurements

In order to compare the measured and calculated impedances with the pitches actually produced, the instrument was played, and the sounds recorded over full chromatic scales. Each note was played for several seconds, without looking at a tuner and while attempting to play in the natural 'centre' of each note. The frequency was estimated by chopping the transients at the beginnings and ends of each note, and using the YIN algorithm to determine the frequency [56]. The accuracy of this method is estimated by its authors to be approximately ±1 cent.

5. RESULTS

5.1. Comparison of calculations and acoustic measurements

Waves with frequencies beyond the tone-hole cut-off limit are not reflected at the first open tone hole but transmit through to and out of the bell (which is usually designed to have a similar cut-off frequency). Such waves do not contribute to the standing waves in the instrument nor to the feedback that stabilises the oscillations of the reed, though they can contribute weakly to the sound spectrum. The tone-hole cut-off frequency for this instrument is about 1000 Hz, calculated from Benade's approximate formula [7] for an open tone-hole lattice

$$f_c = 0.11c\left(\frac{b}{a}\right)\left(\frac{1}{sl}\right)^{1/2}$$

where f_c is the cut-off 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. The result is confirmed by visual inspection of the impedance spectra. It is worth noting this value, since for bass clarinets, and also by scaling from soprano clarinets, one would normally expect a cut-off around 750 Hz [77]. This is a significant parameter to evaluate in the study of historical instruments, since it affects the musical sound and playing qualities. This is discussed by Benade [77], who notes that woodwind instruments have actually 'evolved' over the centuries so that their cut-off frequencies became approximately constant over the whole range of the instrument. We thus chose the frequency range 20 – 2000 Hz for both the measurement and calculations. The range on the instrument for analysis was chosen to be from written E2 to D5 (69.3 to 494 Hz fundamental peaks), corresponding to C#2 to B4 concert pitches). Whilst information could be obtained from higher note fingerings, it is less significant. Only one harmonic is available for generating pitches above about G4, and this 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.

We first show a few notes from (written) E2 to C5 (in SPN) with experimental and calculated impedances superimposed (

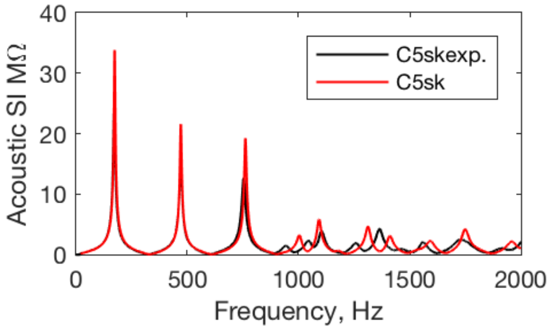
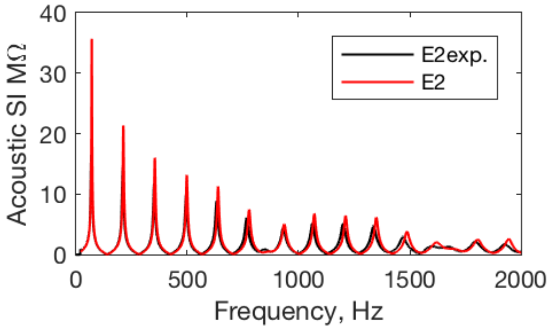
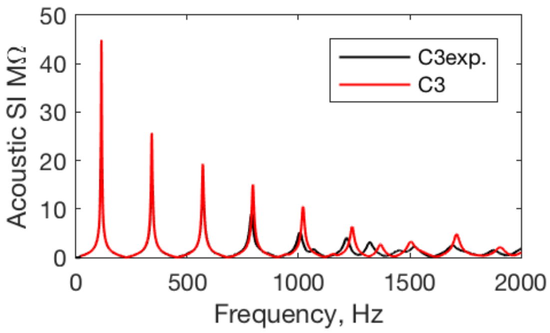
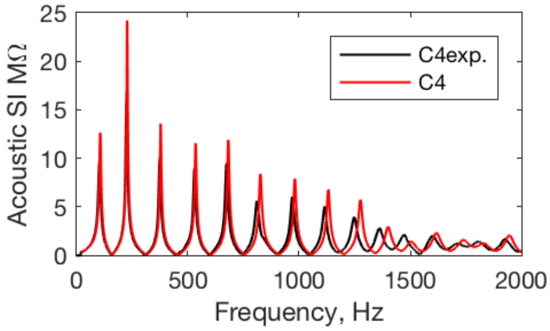


Figure 2). The experimental absolute values of the impedance peak amplitudes agree well in frequency but are up to 2× lower in amplitude. This is consistent with the results of Plitnik and Strong [24], indicating that some losses in the tube, such as fingers, pads, edges, or porosity are not taken into account.







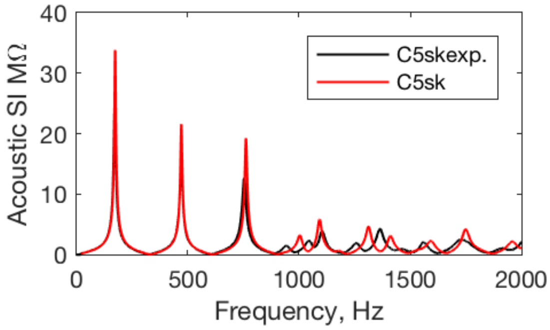


Figure 2. Four comparisons of experimental and computed results, from low written E2 up to C5.

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 and above, 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.

The overall picture is shown by Figure 3, which shows the departures from equal temperament for the calculated and measured impedance values and for the frequencies shown by the playing tests. As expected, the playing frequencies are slightly below the impedance peak values. It is seen that the instrument is playing somewhat sharp, relative to equal temperament at A4=440 Hz, and becomes sharper at higher notes.

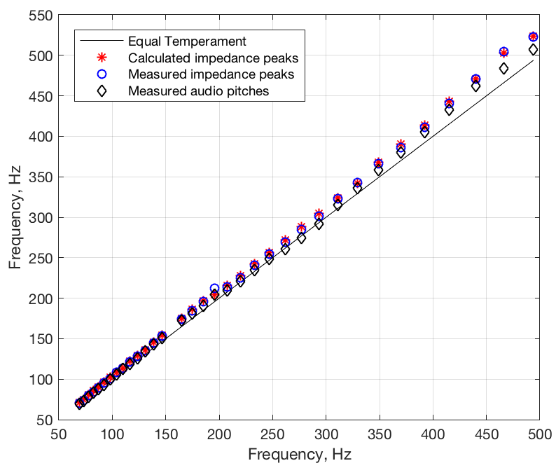


Figure 3. Graphs of calculated impedance peaks, measured impedance peaks and measured audio pitches for notes from E2 to D5. The 'break' in the instrument ranges between written Bb3 and B3 occurs at about 200 Hz and

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.

It is useful to express the frequency differences in cents. This gives a deviation from a target pitch by an amount that is comparable over the whole range. Figure 4 shows the measured and calculated impedance peaks, and the measured audio pitches, relative to equal temperament.

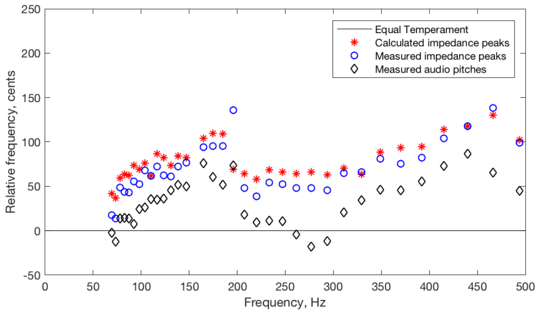
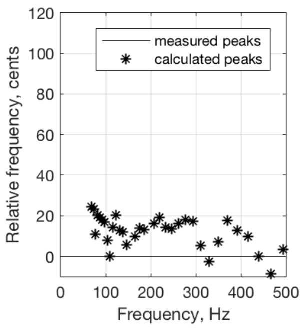


Figure 4: Deviation in cents for each note. The horizontal line at y=0 represents equal temperament at A4=440 Hz.

Whilst there is scatter, the variations in each function appear to track one another. Figure 5 therefore shows the differences between calculated and measured impedance peaks. The calculated peaks average 10 ±8 cents higher than measured peaks. Figure 6b shows the difference between the measured impedance peaks and the playing frequencies. These average at 37 ± 8 cents.



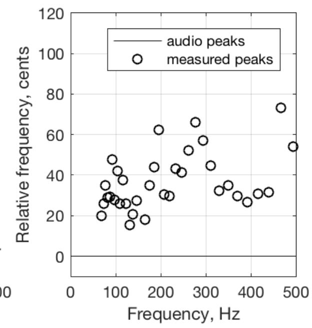


Figure 5 (left): differences between calculated and measured impedance peaks.

Figure 6 (right): differences between measured impedance peaks and audio playing frequencies at *mf* levels.

Since the impedance peak differences between calculation and experiment are reasonably consistent, they appear to be systematic and might be reduced by further development of the computation, for example to take account of other losses such as wall porosity. However, an agreement within 10 cents, which may be corrected empirically as shown below, 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 are similar to those of Dalmont *et al.* [29] though there is more scatter, possibly because the latter used a blowing machine not a player. We therefore recalculated the impedances with a number of embouchure equivalent lengths added to the top of the column, just before the terminating impedance, simply by extending the length of the segment representing the mouthpiece volume. Our best estimate is that the equivalent length required for compensation of the small differences between calculated and experimental impedances is 3 ±1 mm and that the equivalent length of the embouchure correction should be 17 ±4 mm. The latter is consistent with the results of Dalmont *et al.* [29]. These are simply added onto the mouthpiece segment. We do not know how closely the copy of the Bb mouthpiece is to the original supplied with the A clarinet. However, its volume was accurately measured, so the results should be consistent between calculation and playing. Figure 7 shows the differences between the calculated impedance peaks and the audio frequencies for two cases, first with the mouthpiece pushed fully in and then with it pulled out by 10.8 mm. It is seen that the same correction gives consistent results in the two cases.

5.2. Investigation of alternative fingerings

Most of the application of modelling to understanding historical instruments will be comparative, for example, how in tune are the alternative fingerings? We tested this by calculating and playing several notes that have, or may have, alternative fingerings: (written) Bb2, Eb3, F3, C#4 and C5. These are referred to as 'normal' or 'fork' and are shown in Table 1. Only the calculated results are shown.

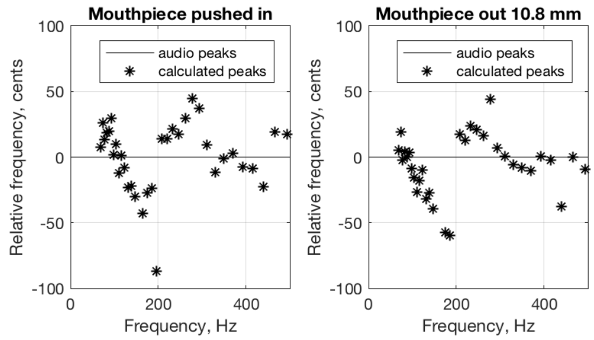


Figure 7. Comparison between calculated impedance peaks and audio playing frequencies when the overall end correction was 20 mm. (a) with mouthpiece pushed in, (b) with mouthpiece pulled out.

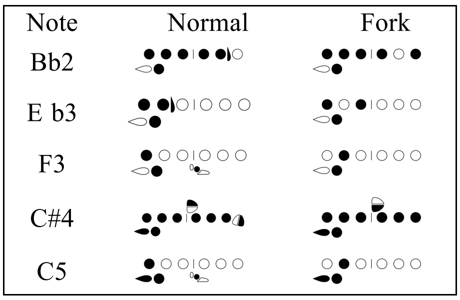


Table 1. Alternative fingerings investigated. [57].

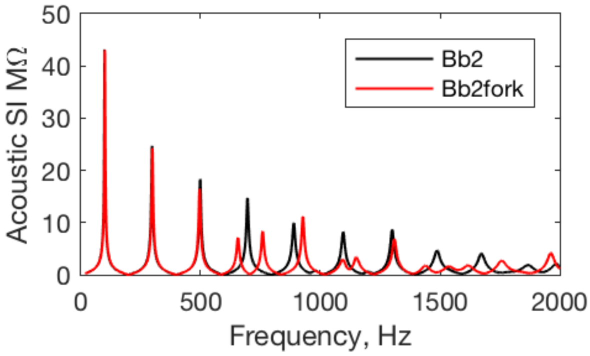


Figure 8. Calculated impedance spectra for two fingerings for the note Bb2.

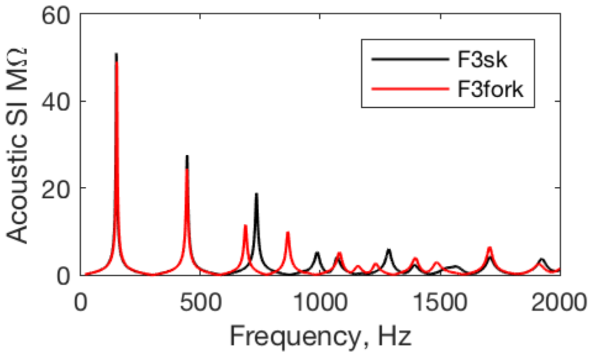


Figure 9. (right). Calculated impedance spectra for two fingerings for the note F3.

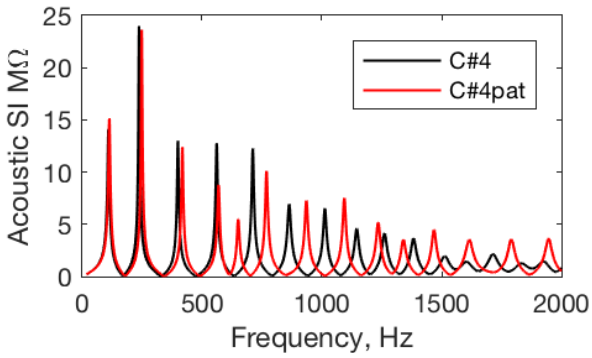


Figure 10. Calculated impedance spectra for two fingerings for the note C#4.

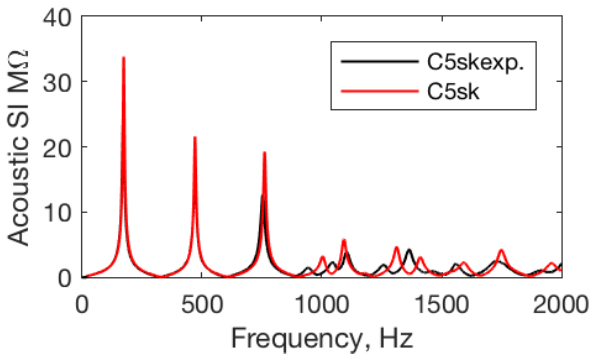


Figure 11. Calculated impedance spectra for two fingerings for the note C5.

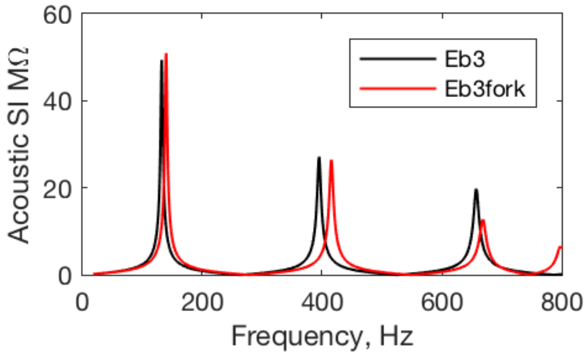


Figure 12. Calculated impedance spectra for two fingerings for the note Eb3.

The calculated impedance spectra for the notes are shown in Figure 8 Figure 12. In all except Figure 12 the fundamental and at least one other resonance aligns well between the two fingerings and these also align with fundamental and third harmonic of the designed note (not shown). For some notes, especially the "patent" C#4, the resonances are a good fit for the 5th and 7th harmonics also. The observation on playing was that a two-resonance match was sufficient to produce good intonation match of the fingerings, but that the timbre of the tone was better matched if more resonances were aligned.

However, the forked D#/Eb3 (Figure 12) showed no such match, and played almost a semitone sharp, just as predicted from the impedance curves. Whilst the fork fingering is often acceptable for this note on earlier German system clarinets it is clearly not the case here, and is in fact generally not the case for Albert system clarinets.

6. CONCLUSIONS AND FUTURE WORK

We recall that the model used is based on small-signal, linear, plane- and spherical-wave acoustics, with viscous and thermal wall losses. It does not take account of some loss mechanisms such as wall porosity, internal tone-hole edge turbulence and finger and pad absorption. Nevertheless, it is remarkably accurate for the absolute values of resonance frequencies and the relative heights of resonance peaks. We conclude that the method is certainly accurate enough for the purpose of reconstructing the acoustic impedance (resonance) spectra of instruments of bass clarinets. This extends the conclusion of Dalmont *et al.* [**Error! Bookmark not defined.**] from soprano clarinets, oboes and alto saxophones to bass clarinets, and provides a measurement of the embouchure equivalent length in the instrument studied.

We believe that we achieve tuning accuracy 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 we may, for example, compare the tuning of alternative fingerings for notes, determine the temperament in which the instrument was constructed or compare the overall acoustic behaviour of two different instruments. This will be performed for a number of bassoon-form bass clarinets as part of a historical and acoustic study.

The implementation in MatLab™ gives the ability to calculate a complete instrument (50 notes including alternatives) and to analyse its resonances in about one minute (on a MacBook Pro with 3 GHz Intel Core i7), and also gives the facility to introduce different models. For example, it was straightforward to introduce an embouchure equivalent length. The mouthpiece, reed and oral cavity impedances have received much theoretical and some experimental attention since IMPEDPS was written in 1994-6: for example in the second edition of Nederveen [26], Fletcher and Rossing [58] and notably Chaigne and Kegomard [23]. Some improvement could therefore eventually be made in the model by implementation of new results.

As pointed out by many others [77, 26, **Error! Bookmark not defined.**, 25, 42, 32] the knowledge of resonance peaks has utility in instrument design, restoration and modification. The effect of drilling or moving a hole, or of reaming the bore (for example, for removing the tenon compression induced by tenon lapping before cork came into use [59]) can be checked before material is removed. Playing problems with a particular instrument may also be diagnosed. Thus, it is clear that this Heckel instrument would play more in tune with a longer neck, or at a higher orchestra pitch. Examination of the neck does indicate that it might be a later replacement and not an original. 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. We believe, therefore, that we have quantitatively validated the computational method of acoustic impedance as a research tool for investigating and restoring both modern and historical bass clarinets and other woodwind instruments. A fuller and more detailed publication of these results is in preparation [60].

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7. REFERENCES

[1] Karp, Cary. 'Restoration, Conservation, Repair and Maintenance: Some Considerations on the Care of Musical Instruments.' *Early Music* 79-84 (1979).

[2] *ICOM/CIMCIM: recommendations for regulating the access to musical instruments in public collections: 1985.* http://bit.ly/2ADcQfz

[3] Rice, Albert R. (1992). *The Baroque Clarinet*. Oxford: Clarendon Press.

[4] Rice (2003). *The Clarinet in the Classical Period*. Oxford: Oxford University Press.

[5] Rice (2009). *From the Clarinet D'amour to the Contra Bass: A History of the Large Size Clarinets, 1740-1860*. OUP USA.

[6] Campbell, Murray and Clive Greated, *The musician's guide to acoustics*. New York: Schirmer (1987) p259

[7] Benade, A.H. *Fundamentals of Musical Acoustics. New York*: Dover. Corrected reprint of 1976 edition, New York: Oxford University Press (1990).

[8] Smith, R.A. and Mercer, D.M.A., 'Possible causes of woodwind tone colour'. *Journal of sound and vibration*, 32, 347-358.

[9] Benade, Arthur H. *Horns, strings and harmony*. New York: Anchor (1960).

[10] Helmholtz, Hermann von. *Tonempfindungen.* (1863).Tr. Alexander J. Ellis. *On the sensations of tone*. (1954) New York: Dover reprint.

[11] Bouasse, H. *Instruments à Vent (Vol. I and II)*. Paris: Libraire Delagrove (1929).

[12] Lamb H., *Dynamical theory of sound*. London: Armold (1931).

[13] Olson, H.F. *Acoustical engineering*. Princeton: Van Nostrand (1957).

[14] Caussé, R., Kergomard, J. and Lurton, X. 'Input impedances of brass musical instruments'. J. Acoust. Soc. Am. 75, 241-254 (1984).

[15] Backus, J. *Small vibration theory of the clarinet*. J. Acoustic. Soc. Am. 35 305-313 (1963)

[16] Strutt, J.W. (2nd Baron Rayleigh) (1877). *The theory of sound*. London: Macmillan and Co.

[17] McGinnis, C.S and C. Gallagher. 'The mode of vibration of a clarinet reed'. . *Journal of the Acoustical Society of America*, 12, 529-531 (1941).

[18] Taillard, Pierre-André and Jean Kegomard. '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).

[19] Levine, Harold and Julian Schwinger. 'On the radiation of sound from an unflanged circular pipe'. *Phys. Rev.* 73, 383-406 (1948).

[20] 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).

[21] Benade, A. H. and D. J. Gans 'Sound Production in Wind Instruments', *Annals of the New York Academy of Scienc*e 155, 247-263 (1968).

[22] Worman, Walter E. *Self-Sustained Nonlinear Oscillations in Clarinet-Like Systems*. Ph.D. diss., Case Western Reserve University, Cleveland, Ohio (1971).

[23] Chaigne, Antoine and Jean Kergomard. *Acoustics of musical instruments (1st English edition)*. New York: Springer-Verlag (2016).

[24] Plitnick G.R. and W.J. Strong, `Numerical method for calculating input impedances of the oboe'. *Journal of the Acoustical Society of America*, 65, 816-825 (1979).

[25] Keefe, D.H. ‘Woodwind air column models’. *Journal of the Acoustical Society of America*, 88, 35-51 (1990).

[26] Nederveen, C.J. *Acoustical aspects of woodwind instruments* (revised edition). Dekalb, IL: Northern University Illinois Press (1998).

[27] Guillemain, P., J. Kergomard, and T. Voinier, “Real-time synthesis of clarinet-like instruments using digital impedance models,” *J. Acoust. Soc. Am.*, 118, 483–494, (2005).

[28] 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.

[29] Dalmont, J.P., Gazengel, B., Gilbert, J., Kergomard, J.: ‘Some aspects of tuning and clean intonation in reed instruments’. *Appl. Acoust.* 46, 19–60 (1995)

[30] Cronin, Robert H. (1996). ‘Understanding the operation of auxiliary fingerings on the modern bassoon'. *Journal of the International Double Reed Society*, 24, 13-30

[31] Cronin, Robert and Douglas Keefe (1996). `Understanding the operation of auxiliary fingerings on conical doublereed instruments'. Notes for a talk presented at the 131st meeting of the Acoustical Society of America, Indianapolis, Indiana, 13-17 May 1996.

[32] Schumacher, R.T., ‘*Ab Initio* calculations of the oscillations of a clarinet’, *Acustica* 48 71- 85 (1981).

[33] Backus, J. ‘Input impedance for reed woodwind instruments’. *J. Acoust. Soc. Am.*, 56 1266-1279 (1974).

[34] Benade, A.H. and Kouzoupis, S.N. ‘The clarinet spectrum: Theory and experiment’. J. Acoust. Soc. Am., 83, 292-304 (1988).

[35] Benade, Arthur H. and Douglas H. Keefe, *The Galpin Society Journal* 49 113-142 (1996)

[36] Benade, A.H. ‘Benade's NX clarinet: Its genesis’ (written in 1987 and published posthumously), *The Clarinet* , pp. 46-48 Jan/Feb (1994).

[37] Jameson, George. ‘Benade’s clarinet: Mechanical and other considerations. The Clarinet, pp. 32–33 May/June 1994

[38] Stephen Fox Clarinets. http://www.sfoxclarinets.com/Benade.html. Consulted 8 March 2018.

[39] 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, 668-674 (2010).

[40] 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(1), Pt 2*, 728-736 (2012).

[41] Kowal, Paulina; Sharp, David and Taherzadeh, Shahram (2013). ‘Analysing differences between the in- put impedances of five clarinets of different makes’. In: *Institute of Acoustics Annual Spring Conference 2013: Acoustics 2013*, 13 May 2013, Nottingham, UK.

[42] Dart, Mathew. *The Baroque Bassoon*: *form, construction, acoustics, and playing qualities.* London: London Metropolitan University. PhD thesis (2011).

[43] 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’. *Société Francaise d’Acoustique. Acoustics 2012*, Apr 2012, Nantes, France. 2012. Online: <hal-00810841>

[44] Jeltsch, Jean, 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.

[45] Jean-Xavier Lefevre, *Méthode de Clarinette. Adopté Par Le Conservatoire Pur Servir Àl’étude Dans Cet Établissement* (Paris: Impr. du Conservatoire de Musique, 1802).

[46] Jeltsch, Jean and Nicholas Shackleton, “Caractéristation Acoustique de Trois Clarinettes de Facteurs Lyonnais,” in *Colloque Acoustique et Instruments Anciens: Factures, Musiques et Science* (Colloque Acoustique et Instruments Anciens: Factures, Musiques et Science, Paris: Cité de la Musique, 1999), 103–24.

[47] Benade, A.H. and J.S. Murday. ‘Measured end corrections for woodwind tone holes”. *J. Acoust. Soc. Am.* 41, 1609 (abstract only; 1967).

[48] Thompson, Stephen C. ‘The effect of the reed resonance on woodwind tone production’, J. Acoust. Soc. Am. 66,1299-1307 (1979).

[49] Reiter, Edith. Wilhelm Heckel, six generations dedicated to music. Wiesbaden: Marixverlag (2014).

[50] Bowen, D. Keith. ‘The Rise and Fall of the Bass Clarinet in A’, *The Clarinet,* September 2011 44-51 (2011).

[51] Bär, Frank P. (2006). *Verzeichnis der Europäischen Musikinstrumente in Gemanischen Nationalmuseum Nürnberg. Band 6: Liebesklarinetten, Bassetthörner, Bassklarinetten, Metallklarinetten*. Wilmhelmshaven: Florian Noetzel.

[52] 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 Acust united Ac*, 97:819-829(5) (2011).

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

[54] 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, 560–565 (1994).

[55] 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, pp. 517–520 (1995).

[56] de Cheveigne, Alain and Hideki Kawahara, 'YIN, a fundamental frequency estimator for speech and music', *J. Acoust. Soc. Am.* 111 1917 – 1930 (2002).

[57] Pimentel, Brett, *Fingering Diagram Builder*, https://fingering.bretpimentel.com/#!/clarinet-german/albert/ . Consulted 11 March 2018.

[58] Fletcher, N.H. and Rossing, T.D. *The physics of musical instruments (2nd. Edition).* New York: Springer (2010).

[59] McGee, Terry. *'Effect of thread wrapping on flute tenons'* http://www.mcgee-flutes.com/effects_of_thread_wrapping.htm (2011). Consulted 20/11/2017.

[60] Bowen, D. Keith, David Sharp, Kurijn Buys and Mathew Dart, *Applied Acoustics,* in preparation (2018).