Acoustical evaluation of historic wind instruments

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The later decades of the twentieth century saw a remarkable revival in the use of wind instruments of pre-modern design in historically informed performances of Renaissance, Baroque, Classical and Romantic music. In some cases surviving historic instruments have been available, but more frequently museum specimens have been carefully measured and reproduced for performance. This process raises many questions; for example, original reeds and mouthpieces are often missing, and curators are increasingly unwilling to permit playing tests and invasive mechanical measurements of rare and fragile instruments. This paper surveys the use of acoustical techniques to study original instruments, to model their playing behaviour, and to guide manufacturers in the creation of musically excellent reproductions.

1 Introduction

The acoustical study of a musical instrument of any genre or period can yield valuable information about its physical and musical properties. In recent years, signal processing techniques of increasing sophistication have been applied to analyse the sound output of the played instrument, while mechanical and acoustical excitation methods have been used to determine the linear response of the resonators in the instrument. The non-linear sound generation systems which are at the heart of bowed and blown instruments have been investigated using a variety of experimental and numerical modelling approaches.

The study of historic instruments using acoustical techniques raises a number of specific issues. In this context, the term “historic” is used to describe a musical instrument which is either no longer manufactured in the form considered, or is made as a conscious replica of an instrument of a previous time (“period reproduction”). This description thus covers a very wide range of different types of instrument. Some instruments, such as the sixteenth century Phagotum, survive only through illustrations and/or written descriptions, while many prehistoric instruments exist only in broken and fragmentary forms. Musical instrument museums contain numerous examples of instruments from the Renaissance onwards which are more or less complete structurally, but which often lack crucial adjuncts such as woodwind reeds or brass instrument mouthpieces. In addition, the conservation policy of most museums now prohibits the playing of fragile wind instruments because of the danger of cracking or other physical damage.

In the last few decades of the twentieth century, many museum specimens of historic wind instruments were physically measured, and reproductions were made to be played in “historically informed” performances of music ranging from the Middle Ages to the nineteenth century. These reproductions have provided one approach to the acoustical investigation of the original instruments, on the assumption that a carefully made replica should reproduce not only the physical shape but also the acoustical behaviour of the original. Further questions are raised by study of these replicas. Are the originals typical of their period? Should perceived acoustical faults be corrected in reproductions designed for performance, or are they part of the historic character of the instrument concerned?

This paper reviews some of the ways in which the methods of musical acoustics have been adapted to meet the specific challenges of working on historic wind instruments. Rather than attempting a comprehensive coverage of a very extensive field, the review focuses on a number of specific examples. Section 2 outlines various approaches to the problems of understanding the acoustics of prehistoric flutes and horns, Section 3 surveys a number of pioneering studies of Renaissance wind instruments, and Section 4 offers a brief summary of some acoustical studies of the rapid evolution of wind instruments through the Baroque, Classical and Romantic periods.

2 Prehistoric Wind Instruments

2.1 Reindeer phalanx whistles

Among the earliest wind instruments to have been studied acoustically are the whistles made from reindeer phalanx bones by the people of the Palaeolithic era. These have been discussed in detail by Michel Dauvois and Benoit Fabre [1]. One of the principal predators of the reindeer in this era was the wolf, and many reindeer phalanx bones have been found with indentations and irregular holes probably caused by the teeth of wolves. In a number of surviving bones, a hole near the upper end of the phalanx has been carefully extended and made more regular, apparently by human hands (Figure 1, right). When a jet of air is blown across the hole by a player, resting the lower...
lip in the indented end of the phalanx as though it were the embouchure plate on a modern flute, a piercing whistle is produced. Dauvois and Fabre have suggested that this is the earliest evidence of a human sound production device.

The study of these earliest instruments illustrates a technique which has been widely applied to the detailed investigation of historic instruments: the fabrication of an accurate copy (Figure 1, left). The hypothesis that the cavity of the instrument could be treated as a Helmholtz resonator was considered and discounted, since the calculated Helmholtz resonance frequency of the reproduction was 3.4 kHz, and the half wavelength at this frequency (around 5 cm) is comparable to the long dimension of the elongated cavity. Instead the instrument was modelled as a tube closed at the lower end, and the input admittance at the open hole was calculated. The resulting input admittance curve is shown in Figure 2.

The first admittance maximum, at around 2 kHz, is the frequency at which the self-sustained oscillation excited by an air jet would be expected. Sounding the instrument does indeed yield a frequency in the vicinity of 2 kHz, together with some relatively feeble upper harmonics arising from the non-linear nature of the jet excitation mechanism, as can be seen in the spectrogram in Figure 3. In addition, the turbulent nature of the jet generates a broadband noise, which appears in the spectrogram filtered by the (inharmonic) resonances of the cavity.

One further aspect of the spectrogram should be remarked upon. When a historic instrument can be played, either in its original form or as a replica, it is possible for the player to determine by experiment whether specific musical effects can be produced. Figure 3 shows that a wide vibrato can be readily generated on the reindeer phalanx whistle. Whether such a technique was used by Palaeolithic players is of course a matter for conjecture.

2.2 The Isturitz flute

A Palaeolithic bone flute discovered at Isturitz, in the Pyrenees, has also been studied acoustically [2]. The original instrument, which has four finger holes, was judged to be too fragile for playing tests, so the investigation used replicas and numerical modelling of the resonance properties of the instrument. Input admittance curves were calculated for different fingerings corresponding to the successive opening of the side holes. From these, the probable playing frequencies of the flute could be deduced.

The flute, in its present form, is considerably shorter than the bone from which it appears to have been constructed. Is it possible that it was originally longer, and part of it
has been lost? The acoustical study, while not capable of giving a definitive answer to this question, certainly provided some important guidance. It is possible on this type of flute to overblow from a first register (using the first air column modes) to a second register (using the second air column modes). For a model flute with the existing dimensions, it was shown that the highest obtainable first register note (with all holes open) had practically the same frequency as the note obtained in the second register with all holes closed. This continuity of registers, which is also found on modern flutes, has obvious musical advantages. Similar admittance calculations for a model instrument with additional length showed that this advantage was lost, suggesting that the existing length may well have been a deliberate choice.

2.3 Neolithic Chinese flutes

Another important collection of early bone flutes, dating from around 7000 BC, was found in 1999 at Jiahu in Henan Province, China. The collection included instruments with 5, 6, 7 and 8 holes. Playing tests were carried out on the best preserved instrument, with seven holes, and playing frequencies were recorded [3]. Attempts to extend the tests to other seven hole specimens were discontinued when cracking sounds were heard.

This discovery stimulated a team including Patricio de la Cuadra and Chris Chafe at CCRMA, Standford University, to develop a digital waveguide model which would be capable of replicating the sound of the flutes now judged to be too fragile to play, using as input data the measured physical dimensions of the instruments. This is a step further than the calculation of the passive linear frequency response of the instruments, since it is also attempting to model the non-linear air jet sound generator and its coupling to the resonator. The ultimate goal is a time domain model which can generate a sound output equivalent to a playing test of the real instrument.

Development of the model is still in progress; a report of its use in a different context will appear shortly [4].

2.4 Bronze horns

Various types of bronze age horns have been discovered in Celtic and Scandinavian countries, and a number of reconstruction and acoustical evaluation projects have been undertaken [5, 6, 7, 8].

Horns with bells in the form of animal heads appear in numerous illustrations during the period of the Roman Empire. One such instrument was the carnyx, in which the bell took the form of a boar’s head complete with tongue (Figure 4). In the early nineteenth century the upper section of a carnyx was discovered in a bog at Deskford in Scotland. This fragment is now in the National Museum of Scotland, which in 1994 commissioned the reconstruction of a complete carnyx. Since then a further reconstruction has been made for the musician John Kenny, who has played it extensively in concerts and on recordings [9].

A number of acoustical studies were carried out on the replicas in the Musical Acoustics Laboratory of the University of Edinburgh [10, 11]. In an attempt to clarify the acoustical behaviour of the complicated boar’s head bell, a bore reconstruction was performed using the acoustic pulse reflectometry technique [12]. This derived the bore profile of an equivalent tube with cylindrical symmetry, shown in Figure 5; it can be seen that the head is equivalent to an approximately conical final bell section.

Since no complete instruments were known to have survived at the time of the reconstruction of the Deskford carnyx, the gently conical bore, made up of a number of separate sections, was based on pictorial evidence. These images give very little guidance as to the type of mouthpiece (if any) employed. A number of conjectural mouthpieces were constructed, ranging from one with a narrow throat similar to that on a modern trombone mouthpiece to one with effectively no bore constriction. Input impedance curves were measured for the reconstructed carnyx with different mouthpieces, and comparisons were made between the playing frequencies predicted from the impedance curves and the frequencies of the notes actually played by John Kenny. Some tests were also carried out in which notes in the upper part of the instrument’s compass were played by an artificial mouth.
For the higher notes, the playing frequencies could be reliably predicted from the frequencies of the impedance peaks. However, the player found a strong and well-centred low note ($E_2$) which bore no obvious relationship to the impedance curve. This reinforces the desirability of attempting to find a method of modelling the instrument which takes account of the non-linear coupling between the resonator and the lip valve.

In September 2004 an excavation at Tintignac in the Corrèze district of France revealed a buried horde of bronze instruments, including parts of five carnyxes [13], almost certainly dating from the first or second century BC. The acoustical study of replicas and numerical models of these instruments will surely enrich greatly our understanding of these fascinating and mysterious instruments of Celtic civilisation.

3 Renaissance Wind Instruments

3.1 The recorder

In 2000 the Edinburgh University Collection of Historical Musical Instruments acquired a rare ivory tenor recorder dating from the sixteenth or early seventeenth century. Since ivory is a more stable material than wood, it was considered that this instrument provided a particularly valuable record of the constructional practice and musical expectations of recorder makers of the late Renaissance.

Because of the high danger of cracking the ivory by blowing warm moist air through the instrument, the decision was taken that it should not be blown at all by a human player. An accurate reproduction was reconstructed [14] using a material (polymethyl methacrylate enriched with aluminium hydroxide) whose density is similar to that of ivory. The aim of this "research facsimile" was to make an instrument as close as possible to the present state of the original instrument in all acoustically significant aspects. It could then be reasonably expected that playing tests on the facsimile would mirror the current behaviour of the original instrument if it were possible to play it.

In 1981 an exciting discovery was made in Salamanca Cathedral in Spain [15]. A chest underneath one of the benches in the archive room was found to contain an extensive collection of Renaissance double reed instruments: five crumhorns, two shawms, five bombards and a fragment of a sixth bombard. The instruments had lain forgotten and ignored for several centuries.

The collection was catalogued in 1995 by Romà Escales and John Hanchet. The crumhorns are all by the same maker, Jörg Wier of Memmingen in Germany, who was active in the first few decades of the sixteenth century; most of the other instruments are by well known makers from the same period.

This was an important discovery because of the light it shed on religious music practice in sixteenth century Spain. The circumstances of the discovery made it very
plausible that the instruments had been the working tools of the band of instrumentalists known to have been employed in the Cathedral in the sixteenth century. In principle, therefore, many questions could be answered about the relative pitches of the members of a double reed ensemble, and the absolute pitch standard employed by a Spanish wind band at the time.

Unfortunately several crucial elements were missing from the instruments: the double reeds, and the bocals (short metal tubes which connect the reeds to the wooden main bores of the instruments). Smaller shawms normally had an additional wooden flange known as the pirouette between the reed and the bocal, against which the player could press the lips; if these had existed on the Salamanca shawms they had also been lost.

In the course of restoration, some playing tests were done by a musician using modern reproductions of reeds and bocals, but for a combination of practical and conservation reasons the scope of such tests was severely limited. Instead, an acoustical investigation was carried out by Ana Barjau and Vincent Gibiat [16], using the TMTC input impedance measurement technique [17]. It was impossible to move the instruments to an acoustics laboratory, so a portable version of the apparatus was used in the archive room of the Cathedral (Figure 7). A practical advantage of this technique is that an impedance curve for a given fingering of the instrument can be obtained in under 30 seconds. There is also no risk of cracking due to the influx of warm moist air from the breath of a player, or of damage due to wall vibrations induced by the very high internal pressure amplitudes when the instrument is sounded.

Figure 8 shows a set of input impedance curves obtained by successively fingering one of the crumhorns to obtain a diatonic scale as described in playing instructions of the period. Figure 9 shows a corresponding set of input impedance curves for one of the shawms. Several interesting conclusions about the likely playing behaviour of the instruments can immediately be drawn from the information supplied in these figures. For example, the first mode impedance peak is dominant for all the crumhorn fingerings, and is almost the only resonance for the higher notes. This is related to the very low cutoff frequency of the lattice of very small diameter toneholes on the crumhorn; the musical consequence is that the crumhorn will not overblow to a second register. A similar behaviour is found with modern reproduction crumhorns.

The shawms display a much more irregular pattern of resonance peaks. For the lowest fingerings, the second peak dominates over the first, which would allow the shawm to overblow easily to the second register; indeed, it could be difficult to avoid overblowing on the lowest fingering. On the other hand, only the first six fingerings show well developed second mode peaks, so the second register would not extend over much more than a musical fifth. Again, these musical properties are typical of modern reproduction shawms.

In attempting to deduce the relative and absolute playing pitches of the shawms and crumhorns, numerical modelling of the bore was used to add virtual bocals of various
lengths. The goal was to predict the probable dimensions of the best bocal for each instrument, using the criterion that the resulting fundamental mode resonance frequencies should give a well-tuned scale using conventional fingerings. In addition, for the shawms it was desired that the second mode frequency should be close to twice the first, to permit accurate overblowing to the second register.

It was found possible to meet these criteria with reasonable success, and playing tests on one instrument confirmed the musical validity of the approach. The study of the absolute frequencies of the resonances of the virtual instruments also yielded a prediction of the absolute pitch standard to which the instruments were tuned: the relatively high (but not unknown) value of $A = 520$ Hz.

### 3.3 The cornett

![Figure 10: Cornett (Italian 17th century, Edinburgh University Collection of Historic Musical Instruments)](image)

A number of studies have been carried out on the acoustical properties of the cornett, a Renaissance lip reed instrument with finger holes [18, 19, 20, 21, 22, 23]. An example of a seventeenth century cornett is shown in Figure 10.

Figure 11 illustrates the use of data derived from input impedance measurements to determine the absolute playing pitch of the seventeenth century instrument without the intervention of a human player. The equivalent fundamental pitches [19] for the first 8 modes of the early instrument are compared with similar data for a modern reproduction instrument, scaled to play at $A = 440$ Hz and used regularly by a professional performer. Tests were carried out for a number of conventional fingerings; the illustration shows the results for the note $D_4$.

Although the first mode of the early instrument is only around 30 cents higher than that of the modern instrument, the overall form of the curves clearly suggests that the early instrument was built to play at a pitch about 100 cents higher than modern concert pitch. Similar measurements with other fingerings confirmed this conclusion. In fact, the majority of instruments surviving from the seventeenth century are at this high pitch, corresponding roughly to $A = 465$ Hz [24]. In making this type of judgment it is important to take the overall pattern of the impedance peaks into account, rather than relying on the frequency of one (possibly anomalous) peak.

### 4 Baroque, Classical and Romantic Instruments

#### 4.1 Woodwind instruments

In the eighteenth and nineteenth centuries the design of woodwind instruments evolved rapidly, partly because of advances in the understanding of the acoustics of the instruments and partly because of the pressure of changing musical requirements. This process has been reviewed by Benade [25]. The transformation of the flute has been discussed by Castellengo [26] and by Wolfe et al [27]. Acoustical studies of historic clarinets have been published by Jeltsch and collaborators [28, 29]. The acoustical development of the saxophone has been reviewed by Kergomard [30]. Measurements on the tonehole lattice cutoff frequencies of historic oboes have been reported by Benade [31].

#### 4.2 Lip reed instruments

Numerous studies of the historical development of brass instruments have been undertaken, using many of the acoustical techniques previously described [32, 33, 34, 35, 36, 37, 38]. The interesting topic of the evolution of brass instruments in Vienna, with their own distinctive acoustical and musical characteristics, has been studied for some years by the Musical Acoustics Group at the
The serpent is a lip reed instrument with a conical bore. It was invented in the late sixteenth century, and continued in use until the middle of the nineteenth century. Figure 12 shows a typical eighteenth century French serpent. The original serpents had six finger holes irregularly spaced along the sinuous tube; later versions had a number of additional holes closed by pads and keys. The acoustical features of the serpent have been documented in a number of studies [40, 20, 41].

A striking feature of the acoustics of the serpent is that the small diameter of the finger holes in comparison with the bore diameter gives a very low cutoff frequency. Although the mode frequencies with all holes closed form a reasonably harmonic sequence (Figure 13), the opening of several finger holes results in a highly irregular input impedance curve (Figure 14), and a correspondingly complicated fingering scheme in the higher registers.

This problem was addressed in the ophicleide (Figure 15, which supplanted the serpent for orchestral use in the early decades of the nineteenth century. Much larger
holes, covered by pads, raised the typical cutoff frequency from around 100 Hz to around 400 Hz, while the use of keys and levers allowed regular spacing of the toneholes [42]. Input impedance curves measured on a nineteenth century ophicleide show that for most fingerings the first three modes have frequency ratios close to harmonic, which simplifies the relationships between the fingerings of different registers and provides a more stable regime of oscillation in first two registers (Figure 16). Certain notes require venting by much smaller holes, and the corresponding input impedance curves are more irregular (Figure 17).

By the latter part of the nineteenth century the ophicleide was in turn replaced for orchestral use by members of the saxhorn family (Figure 18). The acoustical and musical reasons for the eventual triumph of the valved brass basses over the lip reed instruments with toneholes were reviewed by Myers et al [43].

5 Conclusion

In one sense, the process of development and evolution of musical instruments which we have traced over several millennia has been a process of improvement. Yet the modification or abandonment of an instrument which has been the voice of great players or composers, or which has been a central part of the musical daily life of a society, inevitably involves some loss as well as gain. Acoustical studies can help to bring into focus the precise nature of the differences between historic and modern instruments, and can provide guidance to makers and players of historically accurate reproductions. In this way musical acoustics is deepening our understanding of our musical heritage, and helping to enrich the sound world of the present with the lost voices of the past.

6 Acknowledgements

The author would like to pay tribute to the many colleagues in musical acoustics whose work is described in this review, and to express particular gratitude to Ana Barjau, Chris Chafe, Benoit Fabre, Vincent Gibiat and Arnold Myers for help in its preparation.
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