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THE BAROQUE AND CLASSICAL FLUTES AND THE BOEHM REVOLUTION

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Abstract

The Baroque and early Classical flutes have six finger holes that are small enough to be covered by the unaided fingers, and also positioned so as to allow this. They have a partly conical bore, which is narrower than that of the Boehm flute. We compare these instruments in terms of their sound spectra and intonation, and we explain some of the features of these in terms of their acoustic impedance. Because flutes are open at the air jet, the minima in impedance are of greatest interest. The Classical and Baroque instruments have impedance minima whose depths decrease more rapidly with increasing frequency than those of the Boehm flute. This is attributed to the narrower bore and the consequently greater wall losses, and is one reason for the darker timbre of these instruments. In most fingerings, the effect of a series of open holes is to produce a 'cut off filter', which reduces the depth of higher minima. This occurs at lower frequency for the Classical and Baroque flutes, because of the smaller and fewer tone holes. We also report the effects of cross fingerings, and the effects of the differing hole sizes required by the comfortable placing of tone holes. The frequency dependence of the end effects produced by cross fingering leads to inharmonicities in the impedance minima, which in part explains why notes produced with these fingerings have darker timbre than those produced with simple fingerings.

INTRODUCTION

For nearly all of their long history, flutes consisted of a long, hollow tube of bone, wood, clay or metal, open to the air at both ends, and with a set of holes that, when covered by the fingers in different combinations, allowed a range of notes. Although all wind instruments have evolved gradually over time, the changes in the flute were the most rapid and radical: over several decades the instrument went from a simple, narrow, wooden pipe with several finger holes to a form not very different from the modern flute, with a larger bore and about 17 large holes equipped with keys and mechanisms to allow a fingering system that minimises the need for cross fingering. This transformation is in large part due to the flutist and flute maker Theobald Boehm. It has made the modern flute louder and brighter in timbre and has given it a timbre that changes little from one note to the next, and a greater facility for playing in or near equal temperament. Further, Boehm's key system is arguably the most convenient of all woodwinds [1,2]. The popularity of music played on original instruments and folk music have revived interest in Baroque and Classical instruments. Authentic instruments, however, are not always playable because of leaks and other damage, so a mix of originals and reproductions are played today and studied here.

In an open tube with a length of roughly half a metre, a set of six holes that fall comfortably under the larger fingers of both hands allows something close to the modern diatonic scale (although it is not clear whether this is a happy coincidence or one of the causes of heptatonic scales). This approximately describes the Baroque flute, whose natural scale of D major is played by sequentially lifting fingers, starting at the downstream end, and then overblowing to play the second register. Some remaining notes (F, C and the remaining 'sharps and flats') are played using 'cross fingering', *i.e.* closing one or more holes downstream of the first open hole. Apart from being sometimes more awkward to play, a cross fingered note has a different, 'darker' timbre and less loud sound than does a simply fingered note. The bores of Classical and Baroque flutes are mainly conical (narrowest at the foot), except for a cylindrical head section. The revolution in the flute comprised enlarging the tone holes, the introduction of keys to cover them, coupling mechanisms to avoid cross fingering and finally enlarging the bore and making it cylindrical, with a slightly tapered head. Each of these changes made it louder and

brighter. In this paper we examine the effects of these changes by comparing flutes of different types, and we explain some of the acoustic reasons for the changes produced. Introductions to the acoustics of the flute are given by [3,4].

MATERIALS AND METHODS

The flutes. The modern instrument is a widely used production line model, Pearl PF-661. The others were made by one of the authors (T.McG.). The Classical flute is based on the dimensions of a Rudall and Rose instrument (R&R #655 from the Bate Collection in Oxford), made in about 1828 to play at $A=430$, but scaled to play at $A=440$, while the Baroque flute is an unscaled replica of an instrument made by J.A. Crone in Leipzig in about 1760. It plays at $A=415$. The player was Geoffrey Collins, a leading Australian concert soloist and chamber and orchestral player.

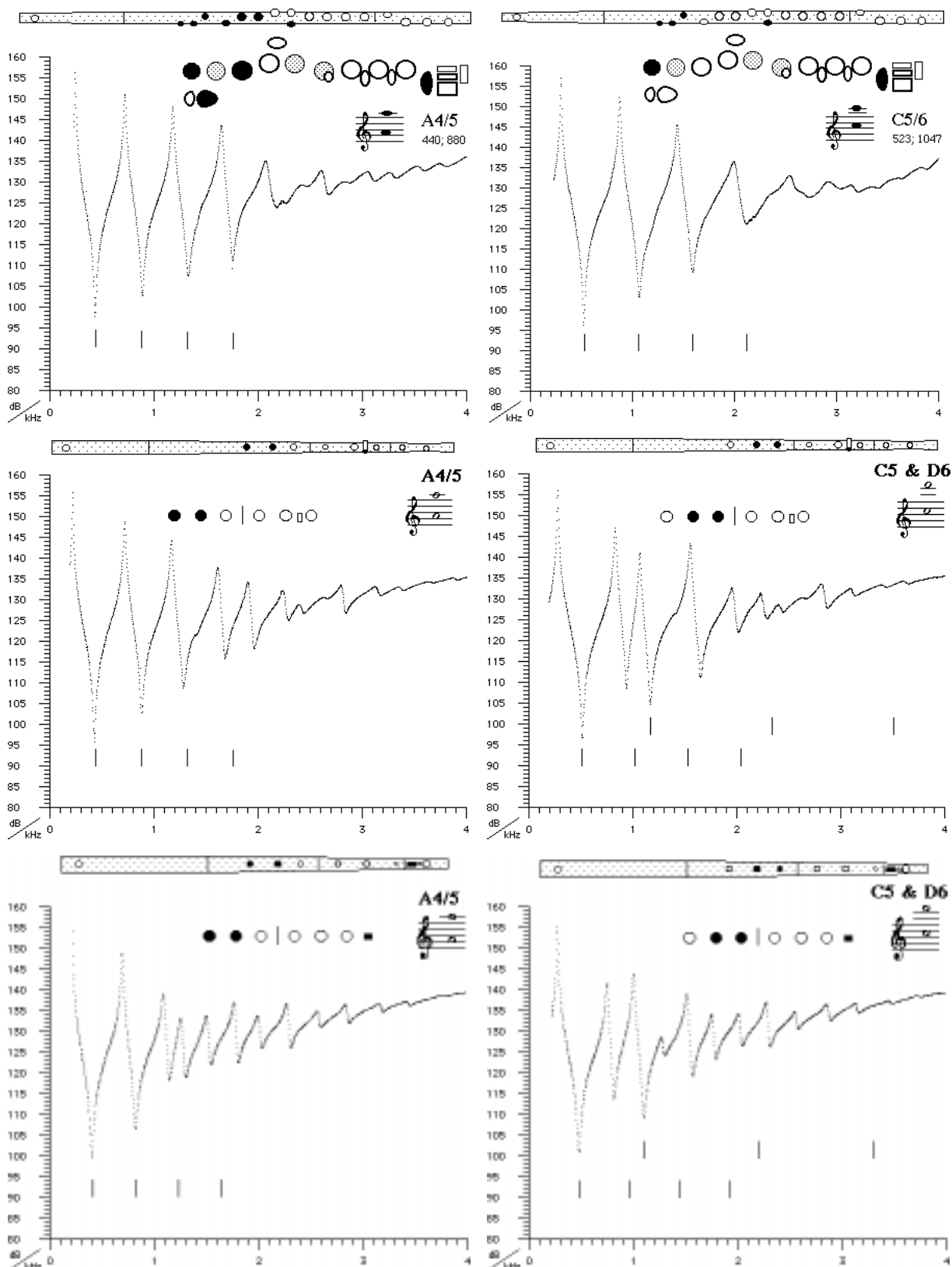
The measurements. The measurements of acoustic impedance spectra at the embouchure and of sound spectra were made as described previously [5]. Briefly, we produce an acoustic current from a high impedance source. Spectral components with equal amplitude and frequencies between 0.2 and 4 kHz with a 2 Hz spacing are produced simultaneously. The system is calibrated using a semi-infinite waveguide as a reference impedance (assumed to be resistive and frequency independent).

RESULTS AND DISCUSSION

We present examples of the measurements of the acoustic impedance for each of the three instruments. The note A4 is played with a simple fingering on all three flutes, and we contrast this with the fingerings for C5, which requires cross fingering on the Classical and Baroque instruments. For Baroque, Classical and modern flutes, over the range from E4 to B4 and E5 to B5, each standard fingering serves for two notes, so for example the flutist uses the same fingering for E4 and E5, but changes the speed, length and shape of the jet. The figures on the left show the impedance spectra for fingerings used to play the notes A4 and A5 on all three instruments. On the two earlier instruments, the hole for the left hand third finger is placed higher than acoustic arguments would recommend, in order to bring it within easy reach of the finger. Consequently, it must be smaller than expected (the second smallest on the instrument). The first observation we make of the impedance spectra $Z(f)$ is that, at low frequencies, the magnitude of the maxima and minima decreases with frequency more slowly for the modern flute than for the Classical, and for the Classical than for the Baroque. This is true even for the lowest notes on the instruments (all holes closed, data in [4]) and is a consequence of the larger bore in the successively more modern designs, which leads to smaller viscous and thermal losses.

The second observation concerns finger holes. Open finger holes provide an inertive shunt to the outside air. The value of the shunt impedance is smaller for larger holes but is never zero, so the standing wave extends past the first open hole—it is this very effect that allows cross fingerings, which are discussed later. According to Benade [6], the effect of a series of open tone holes is like that of a high-pass filter whose cut-off frequency depends on hole size and spacing. Above that frequency, the travelling wave propagates down the bore and so the standing wave is weaker. Thus, on the modern flute, at frequencies less than about 2 kHz, the minima are strong and their frequencies are nearly harmonically related. The first open hole provides a low impedance shunt and, below this frequency, the flute performs approximately as though it were sawn off at a point a little below the first open tone hole. In comparison, the greatly reduced depth of the impedance minima, and increased inharmonicities occur at lower frequencies in the Classical instrument, and at even lower frequencies in the Baroque instrument.

The figures on the right show the fingerings, acoustic schematics and acoustic impedance of modern, Classical and Baroque flutes for the note C5. For the modern flute, the fingering is simple, *i.e.* all tone holes downstream of the first open hole are also open. For the Classical and Baroque flutes, this note is played with a cross fingering, as shown. We note in passing that the modern flute also plays C5 with an alternate fingering, analogous to that shown for the older flutes. This is possible because the hole controlled by the index finger of the left hand is abnormally small, because it serves as both a tone hole and a register hole. In all instruments, this fingering plays C5 as a cross fingering with a dark timbre, a bright timbre D6 using the open hole as a register hole, and a multiphonic, sounding both notes simultaneously. See [4] for details.



The figures at left show the fingering, acoustic schematics and acoustic impedance Z of a modern (top), Classical (middle) and Baroque flute (bottom) for the notes A4 and A5. Z is given in dB, i.e. $20 \log (Z/\text{Pa.s.m}^{-3})$. The figures at right show the fingerings for the note C5 on the same instruments. (These fingerings also play C6, D6 and D6 respectively.) Sound spectra for these notes (given in [4]) show strong peaks for those harmonics that coincide with deep minima. The vertical dashes show harmonic frequencies. Only for the modern flute are the third and subsequent minima nearly harmonic. This, and the different depths, explains in part the darker timbre of the earlier designs, particularly for the cross fingerings.

In the cross fingering, the standing wave extends, with reduced amplitude, past the first open hole into a region with one or more closed tone holes. This gives an end correction presented at the first open hole, which lowers the frequency of the standing wave. However, because the end correction varies with frequency, it affects the harmonicity of the impedance minima. On the modern instrument (top), the note C5 is as bright and as loud as other nearby notes. The same note on the Classical flute is less loud than its neighbours, which are themselves less loud than the same notes on the modern instrument. Further, it has a dark timbre, distinctly different from that of B4 or C#5. The differences are even greater for the Baroque flute. Cross fingering on the modern instrument is possible, but, because of the larger hole size, the pitch shifts are smaller than they are on the older instruments. (Direct measurements of the frequency dependence of the extended standing wave are reported in [7] and details of cross fingerings are discussed in [4].) While the homogeneous timbre of the modern instrument has advantages, the different timbres of different notes were used to advantage by some composers in the Baroque and Classical periods.

For the modern instrument, the first four minima have frequencies in nearly harmonic ratio, which assists the strongly non-linear jet to establish a vibration in which there are strong components at these (and other) harmonic frequencies [8]. For the older designs, the higher order impedance minima are far from harmonic multiples of the primary minimum, and thus lead to a vibration régime that is more sinusoidal, as indicated by the sound spectrum which has relatively weak higher harmonics. The weakness in higher harmonics also contributes to the less loud sound, particularly because most of the higher harmonics fall in the range where the human ear is most sensitive. Sound files for these and many other notes on various flutes are available [4].

To present data for only a few notes on an instrument is hardly adequate, because even trained musicians have difficulty recognizing differences among instruments based on just one or two notes. Further, the musical interest in understanding and rectifying the acoustic properties of instruments often concerns fine details of particular combinations of notes. For that reason, we publish more complete data sets including sound files, spectra and more ample discussion of the details of fingerings and their acoustical effects, on our web site [4].

CONCLUSION

Boehm's revolution—the introduction of larger tone holes, a wider bore and the near elimination of cross fingerings—has changed flute acoustics by producing an input impedance whose minima are deeper and more harmonic for a larger number of notes, and by increasing the cut off frequency. These result in the louder, brighter and more homogeneous tone of the modern instrument. The data base [4] allows detailed comparison for any note, on Baroque, Classical and modern instruments.

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