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THE EFFECTS OF PLACEMENT OF THE HEAD JOINT STOPPER ON THE IMPEDANCE SPECTRA OF TRANSVERSE FLUTES

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ABSTRACT

The stopper that seals one end of a transverse flute is typically set at 17 mm from the embouchure hole. This defines an acoustic volume element between embouchure hole and cork that may be considered to act as the 'spring' or compliance of a Helmholtz resonator at low frequencies. The frequency dependent impedance of this element adjusts the intonation over the range of the instrument. At higher frequencies, variations of pressure within this space become significant and more complicated effects occur. The AC variation of pressure in the embouchure riser (the short pipe connecting the bore to the embouchure plate) also becomes important at high frequencies. We show the effects of a large range of cork placements on the acoustic impedance spectra measured at the embouchure of the flute, over a range from 200 to 13,000 Hz.

KEYWORDS: Flutes, impedance spectra, tuning, head joints

INTRODUCTION

The bores of woodwind instruments are composed from sections that are approximately cylindrical or conical, and therefore have resonances at approximately harmonic ratios. This means that the same fingering (combination of open and closed tone holes) can usually be used to play (at least) two notes, corresponding to the two resonances of lowest frequencies. The series of notes using the first and second resonances are called the first and second registers. In the flute, which is approximately cylindrical and open to the air at both ends, the first and second registers are approximately one octave apart. One of the ways in which this interval is tuned closer to an octave is the placing of the stopper or cork, which seals one end of the flute close to the embouchure hole, and whose position sensitively affects the instrument's intonation. The geometry is shown in Fig. 1.

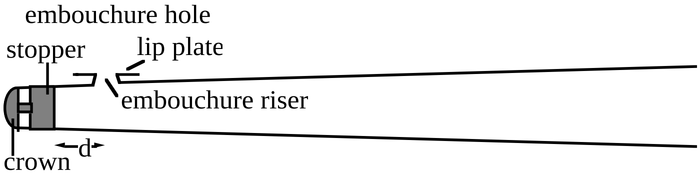

Fig 1. A sketch of the head joint of the Boehm flute. The slight taper is exaggerated in this illustration. The stopper is position by a screw in the crown. The embouchure riser is approximately a truncated cone, flanged by a plate, which rests against the player's lower lip.

A simple, cylindrical pipe, open at the end and having a diameter much smaller than its length, has harmonic resonances. To be more explicit, the acoustic impedance (the ratio of acoustic pressure to volume flow) measured at one end has minima which are equally spaced in frequency.

The flute is not a simple cylinder. Apart from the geometry of the head, it has tone holes that can provide low impedance shunts to the external sound field. In the lowest registers, the first open hole may be considered approximately to terminate the bore, reducing its effective length.

A number of effects complicate this simple model. First, the end effects are frequency dependent. The shunts provided by both the open end and by the open tone holes are inertive and introduce a frequency-dependent end correction. Second, the acoustical impedance presented to the bore by the embouchure hole may have a different (inertive) impedance in the different registers, because, in order to select the desired register, players may change both the jet speed and its length. Changing the latter requires reducing the distance between the lips and the edge of the embouchure hole, which reduces both the area and the solid angle available for radiation in the external field. Third, the impedance of the jet itself is a function of its speed and length. Introductions to the theory of the flute are given by [1,2,3]. Detailed measurements of the impedance spectra [4,5].

The relative intonation of the first two registers is corrected by the taper in the head joint and the position of the stopper, and it is the latter that concerns us here. For frequencies less than several kilohertz, the air in the embouchure riser may be considered as a compact mass, and the air between the embouchure hole and the stopper as a compliance: together they are usually considered to comprise a Helmholtz oscillator (hereafter called the upstream resonator), whose capacitative impedance is effectively in parallel with the inertive radiation impedance at the embouchure hole. Together the two terminate the bore at the embouchure end.

MATERIALS AND METHODS

The method for measuring the impedance spectrum at the embouchure is described by [4,5]. The standard flute used was a Pearl PF-661, closed hole, C foot model: a common, production line instrument. The other 'flutes' used were specially constructed from PVC pipe, with internal diameters of 18 and 23 mm and lengths chosen so that they played C4. They had a long head to allow a large range of stopper positions.

RESULTS AND DISCUSSION

Fig.2 is the acoustic impedance spectrum Z(f) measured at the embouchure hole of a modern flute set up for normal playing. The fingering (key configuration), which has most of the tone holes open, is the one usually used to play C#5 and C#6 (the player chooses between these two harmonics by blowing differently). The first two minima in Z(f) correspond to these notes. The third minimum corresponds to the note G#6, which may also be played with this fingering. These minima occur at almost exactly harmonic ratios of frequency.

The magnitude of the extrema decreases with increasing frequency for two reasons. One is that viscous losses at the wall become more important at high frequency (See [4] for data and a discussion). But another is the effect of the upstream resonator: the mass of the air in the embouchure riser oscillating on the 'spring' or compliance of the air between the embouchure hole and the stopper. Considered as a Helmholtz resonator, this would have a resonant frequency of a few kilohertz (the exact value depends upon how the geometry is approximated) at which its admittance becomes large, and it would 'short out' the admittance of the bore, with which it is effectively in parallel. (It is interesting to note that, when the resonances reappear at higher frequencies—above about 7 kHz, their spacing is reduced to about 250 Hz. This is because, at these frequencies, the inertive impedances of the open tone holes become high, and the standing waves are those of the entire length of the bore: the standing waves 'don't notice' that the tone holes are open (more details in [6]). The broad peak at around 10 kHz we attribute to a resonance within in the embouchure riser itself.

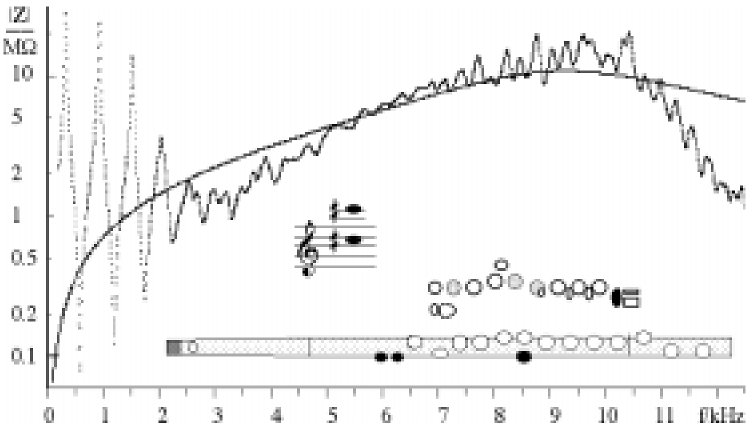

Fig.2 The points are measurements of the impedance spectrum of a modern flute. The continuous curve is the theoretical impedance of a truncated, flanged cone having the measured dimensions of the embouchure hole riser: length 5 mm and radii 5.8 mm outside and 6.4 mm inside the instrument. In the inset diagram, a filled circle represents a closed tone hole. In [4,5], results are shown with the external radiation impedance included as a series inertive element. Because of the large frequency range of this study, that is not done here.

In Fig.2, the amplitude of the extrema due to the resonances of the bore becomes successively weaker with increasing frequency up to about 5 or 6 kHz, suggesting that this is the effective resonance frequency of the upstream oscillator. At this frequency, the quarter wavelength is 15 mm long, so the Helmholtz resonator approximation is invalid: the pressure within the compliance does not have uniform phase. This observation suggested the present study, in which the stopper position was varied over a large range in specially constructed, cylindrical flutes.

Fig.3 shows the results of measurements of Z(f) on a cylindrical flute with the stopper at a range of different positions. The flutes have no tone holes and their lengths give a lowest note of C4, so in these curves the extrema are spaced at about 250 Hz over the whole frequency range. With the stopper in a 'normal' position of 17.5 mm from the centre of the embouchure hole (a), the global features of Z(f) are similar to those of the modern flute, though of course simplified by the absence of tone holes. With the stopper positioned level with the edge of the embouchure hole (b), the 'shorting out' of the extrema is almost removed. Treating the upstream resonator as a Helmholtz resonance, the compliance is very small and the resonant frequency is above the range studied. Players of the Cuban *charanga* style of music push the stopper in closer to the embouchure hole to facilitate playing in the fourth octave of the instrument, ie above ~ 2 kHz. Comparison of the depth of the minima in (b) with those in (a) explains the effectiveness of this. It also shows the disadvantage: the minima are no longer harmonically related.

With the stopper 70 mm from the embouchure hole (c), the upstream resonator would be expected to act like a simple closed pipe, with impedance minima at the odd harmonics, ie at approximately 1.2, 3.6 and 6 kHz. These frequencies indeed correspond approximately with the 'shorted' bands in the figure. (At the seventh harmonic, near 8 kHz, the resonances in the embouchure riser itself may dominate.) Note that, below 1.2 kHz, the impedance of this close tube is expected to be compliant, but between 1.2 and 2.4 kHz it is expected to be inertive. Their effects on the effective length of the flute are therefore in opposite directions, as well as being frequency dependent. The inset shows the predicted effect: the spacing of the impedance minima is compressed in the first (compliant) regime and expanded in the second (inertive) regime.

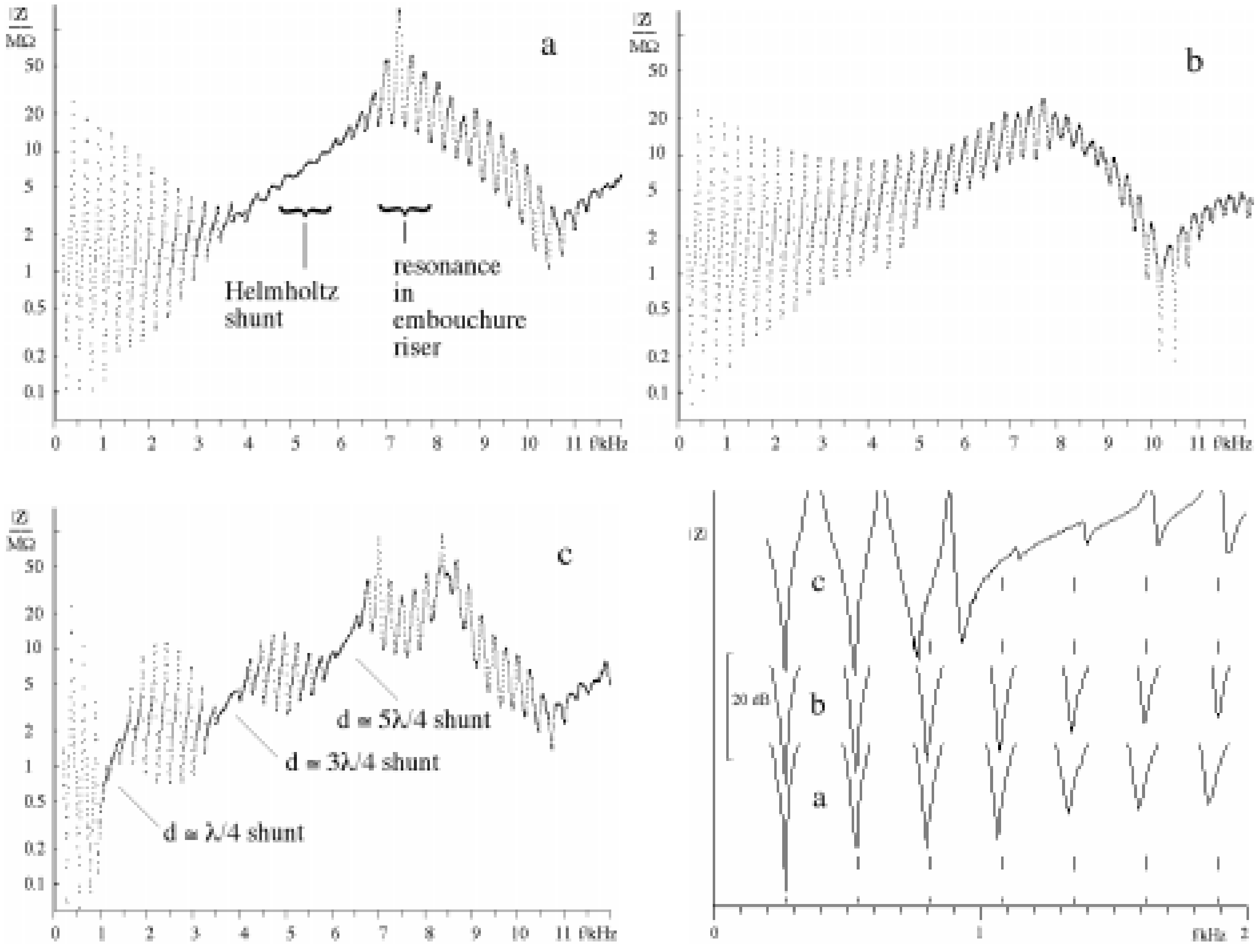

Fig.3 The input impedance of a cylindrical flute with the stopper (a) at a 'normal' position of 17.5 mm from the centre of the embouchure hole; (b) at 5 mm, ie right next to the edge of the hole; (c) at 70 mm. The inset shows the minima from the three curves on an expanded abscissa. The dashes are equally (ie harmonically) spaced. Note that for this flute (without a tapered head), 17.5 mm stopper position does not produce harmonic minima.

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