HEAD JOINT, EMBOUCHURE HOLE AND FILTERING EFFECTS ON THE INPUT IMPEDANCE OF FLUTES

John Smith, Joe Wolfe and Michael Green

School of Physics
University of New South Wales, Sydney
J.Wolfe@unsw.edu.au

ABSTRACT

A study of **Z**(f), the input impedance of the Boehm flute, measured from 200 Hz to 12.5 kHz shows the expected set of strong resonances in the frequency range that corresponds to fundamental frequencies of the playing regime. These frequencies are below the expected cut-off frequency (due to an array of open tone holes) for propagation along the bore of the flute. Above this frequency, in a range that affects the harmonics rather than the fundamental of played notes, the inertive reactance of the tone holes increases with frequency until the standing wave propagates along the tone hole lattice with little attenuation. Harmonic resonances are again evident, but now correspond to resonances of the whole length of the instrument. However the resonances associated with the bore are strongly attenuated over an intermediate frequency range. This appears to be a consequence of a Helmholtz resonator formed by the air in the embouchure hole and the sealed end of the head joint. Experiments with different head joints confirm this mechanism. The envelope of **Z**(f) shows a broad maximum near 10 kHz that we attribute to the resonance of the embouchure riser tube.

1. INTRODUCTION

Transverse flutes are sealed at one end by a cork or stopper that, in the orchestral flute, is typically positioned about 17 mm from the centre of the embouchure hole. In Figure 1, the volume of air enclosed between the cork and the embouchure hole is labelled *b*. It may, in a first approximation, be considered to act as the compliance for a Helmholtz resonator whose mass is that of the air in the embouchure hole, *a*. This resonator is effectively in parallel with the bore. It is important that the resonances of the entire instrument in its playing configuration have frequencies in nearly harmonic ratios, so that the higher resonances support the higher harmonics of low notes and thus contribute to the brightness of timbre and loudness in the low register. It is also important because the same fingerings are usually used for notes in both the first and second registers. The global intonation of the instrument depends on the frequency dependences of this resonator, of end effects in the bore, of the jet drive mechanism, and of the detailed geometry of the head. Diverse aspects of flute acoustics are described by [1-6].

The moveable stopper gives flutists this important advantage over players of other woodwind instruments: the relative tuning and the absolute tuning may be adjusted by separate mechanisms. Using the tuning slide to shorten the overall length of the instrument of course increases the pitch of all notes (with the complication that the pitch increment or proportional change in frequency is greater for notes played with a shorter effective tube length than those played using a longer effective bore). The position of the cork or stopper in the end of the flute may also be adjusted, using a screw. Pushing the cork in further raises the pitch of all notes, but the pitch increment is greater for notes with higher pitch. Thus the flutist whose octaves are narrow, due to the idiosyncrasies of the embouchure-instrument combination, may push the cork in to widen the octaves, and then pull the tuning slide out to compensate for the average pitch increase.

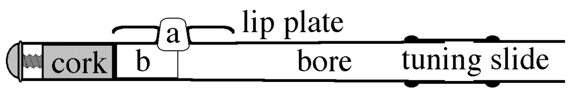

Figure 1: *Schematic of a flute head joint.*

The fundamental frequencies of notes in the range of the flute fall below 3.2 kHz, but the harmonics extend well beyond this range. To treat the air *b* near the stopper as a simple compliance requires that its length be negligible in comparison with the wavelength. This approximation must fail at frequencies of several kHz, where this volume of air may be better approximated by treating it as a waveguide. Similarly, the air *a* in the embouchure hole may not be treated as a compact mass for such frequencies. We therefore consider these complications in this paper.

To study the effect of the stopper position, two simple cylindrical flutes were constructed with long head regions. This allowed the stopper to be moved over a wide range. Because of the timing of conferences and deadlines, this work has already been reported at another conference [7], so we present here only a summary of that paper, from which Figure 3 is reproduced with permission.

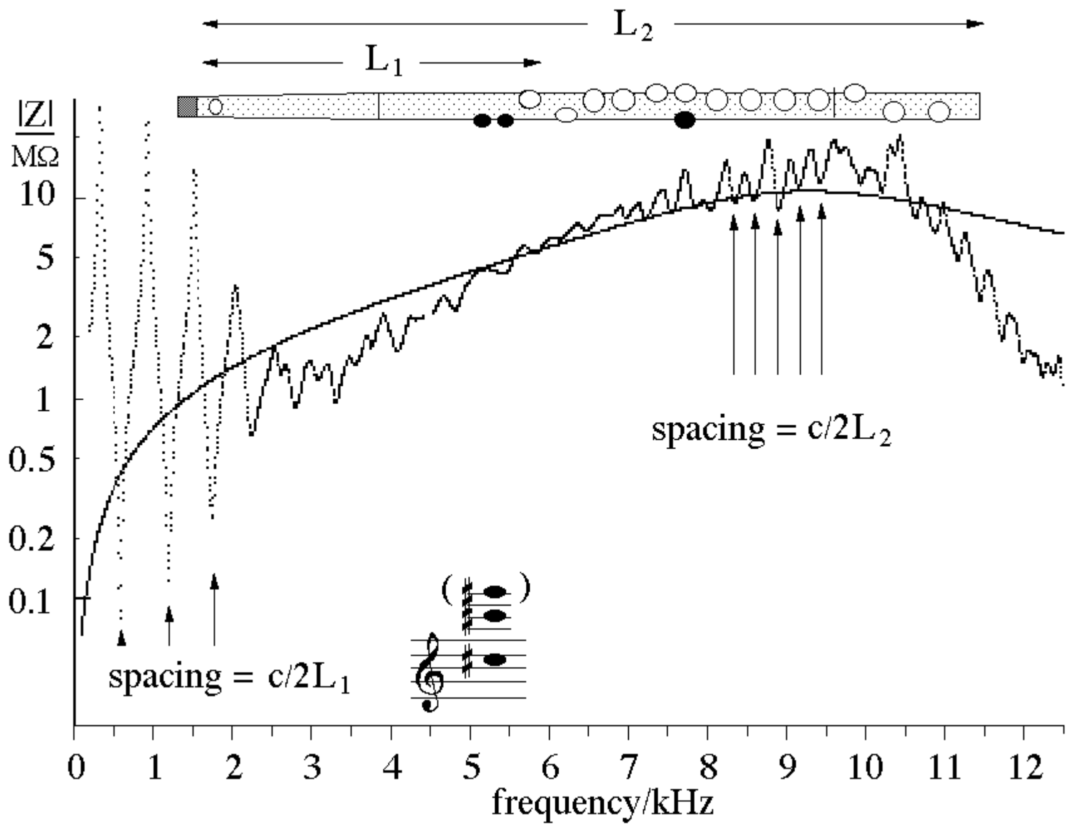

Figure 2: *The impedance spectrum of a normal flute, for the fingering normally used to play C#5 and C#6.*

2. MATERIALS AND METHODS

The cylindrical 'flutes' without tone holes were made from PVC pipe, with internal diameters of 18 and 23 mm. Their lengths were such that they played C4. The normal flute used was a Pearl PF-661: a common, mass-produced instrument. Impedance spectra at the embouchure were measured as described elsewhere [8,9].

3. RESULTS AND DISCUSSION

The impedance spectrum **Z**(f) for a normal, modern flute (Figure 2) shows several interesting features. The fingering shown is that used for the notes C#5 and C#6, which will also play G#6. For this fingering, almost all of the tone holes are open, and the effective length of the tube L_1 is a little less than half the length of the flute, as shown. The fundamental frequencies of these notes correspond to the first three minima in Z(f). Over these three minima and the intervening maxima, the envelope of the curve falls relatively slowly: the resonances become weaker with increasing frequency primarily because of viscothermal losses. Around 2-3 kHz, however, the resonances become suddenly much weaker. This is due to the inertance of the air in the tone holes, which produces a cut off frequency, above which waves are not reflected at open tone holes [10,11]. The effect of the Helmholtz shunt occurs at slightly higher frequencies—about 5 kHz—as we show using the cylindrical flute without tone holes.

At frequencies above about 7 kHz, resonances reappear. However, their spacing is now that of standing waves over L_2, approximately the whole length of the instrument. In this frequency range, the inertance of the air in the open tone holes is sufficiently high that the waves 'hardly notice' that they are open. The relatively high cut off frequency of the modern flute is a result of its relatively large tone holes. Clarinets and baroque flutes have much comparatively smaller tone holes, and their cut off frequencies fall within the normal playing range of the instrument, with the result that highest notes are played using standing waves that use almost the entire length of the instrument [9,11].

The solid line in Figure 2 is the theoretical impedance of a truncated cone having the dimensions of the air in the embouchure hole (*a* in Figure 1) and including the end effects

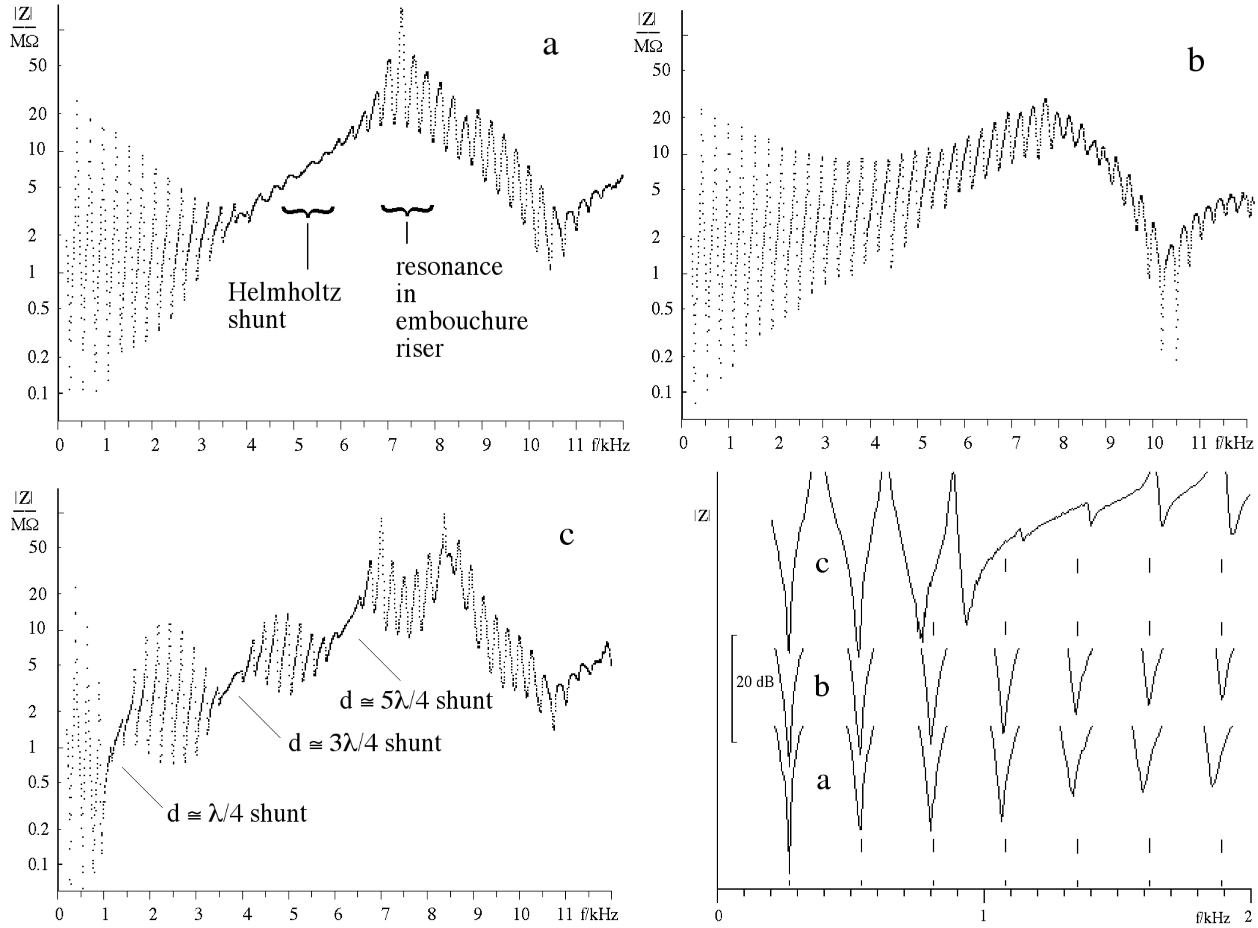

Figure 3: *The impedance spectra of flutes with the cork position at (a) 17.5 mm from the embouchure hole; (b) very close to it and (c) at 70 mm from it. (d) shows, on an expanded scale the minima from (a), (b), and (c). Reprinted, with permission, from [7].*

due to the baffling of the lip plate and the head tube respectively. We offer this as a possible source of the broad maximum at around 10 kHz. However, the influence of this and other high frequency effects on the air jet is not simple to calculate. For instance, non propagating modes in the flute bore may need to be considered [Tsai, this volume].

To separate the effects of the head joint resonance from those of the tone hole lattice, and to demonstrate the waveguide effect of the air near the cork, we measured **Z**(f) on simple cylindrical flutes without tone holes (Figure 3). 3(a) shows the Z(f) for a simple cylindrical flute with the cork in a typical flute playing position, 17.5 mm from the centre of the embouchure hole. With no tone hole effects, the effect of the upstream shunt is more clearly seen.

Figure 3(b) shows the effect of moving the stopper as close as possible to the embouchure hole. The shunt moves to frequencies beyond the range of our spectrometer in this configuration. Players of Cuban *charanga* music often play with the cork pushed in close to the embouchure hole so as to facilitate playing notes in the fourth octave of the instrument (2-4 kHz). The penalty for this is that it upsets the relative tuning of the instrument, as shown below.

For Figure 3(c), the stopper is 70 mm from the embouchure hole. Here its waveguide effects are clearly seen. Treating it as a simple closed pipe, its $\lambda/4$, $3\lambda/4$ and $5\lambda/4$ minima would be expected at 1.2, 3.6 and 6 kHz. These shunts are indeed seen to reduce the envelope of the extrema due to bore resonances.

We note in passing that, at very high frequencies, the extrema are larger than those for the normal flute (Figure 2). We attribute the weaker resonances in the normal flute in part to the finite radiation losses at each tone hole.

Figure 3(d) shows clearly the compression and expansion of the spacing of the resonances due to withdrawal and insertion of the cork. For this simply cylindrical flute, and with the cork at 17.5 mm, the impedance minima are not harmonically spaced: such a flute would be better played with the cork inserted further.

4. CONCLUSIONS

The influence of cork position on the frequencies of impedance minima are in accord with musicians' observations about tuning: greater insertion enlarges intervals. The resonances seen in Z(f) are determined by the effective length of the instrument. Below the cut off frequency for the tone hole array, this is approximately the length from embouchure to the first open tone hole. At sufficiently high frequencies, the effective length is approximately that of the entire instrument. A broad maximum at around 10 kHz is consistent with a resonance in the embouchure hole.

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