International Congress on Acoustics, Rome, Session 8.09, pp 14-15.

Tone holes and cross fingering in wood wind instruments.

John Smith and Joe Wolfe

School of Physics, University of New South Wales, Sydney NSW 2052, Australia, jrs@newt.phys.unsw.edu.au

Opening successive tone holes in woodwind instruments shortens the standing wave in the bore. However, the standing wave propagates past the first open hole, so its frequency can be affected by closing other tone holes further downstream. This is called cross fingering and, in some instruments, it is used to produce the 'sharps and flats' missing from their natural scales. The extent of propagation of the standing wave depends on frequency, so that different modes of the bore are affected to different degrees, giving different timbres to cross fingered and simply fingered notes. We measure the frequency dependence of the transmission of waves in the bores of flutes in both the regions where tone holes are closed and open, and of the radiation from open holes of different sizes. We use these results to explain the different effects of cross fingering in modern and traditional instruments, and the differences in timbre between cross fingered and normally fingered notes.

INTRODUCTION

On modern woodwind instruments such as the flute, oboe, clarinet and saxophone, a chromatic scale may be played over at least one octave simply by opening tone holes, one at a time, starting at the downstream end. Mechanisms that couple the keys allow the player to cover more tone holes than s/he has fingers. On the recorder, and on the ancestors of the modern flute, oboe and clarinet, opening successive finger holes produces a diatonic scale. The missing notes in the chromatic scale are achieved by cross fingering. In both old and new instruments, a second register is obtained by overblowing, using nearly the same fingerings. Third and higher registers involve cross fingering.

Opening a tone hole provides a low inertance shunt from the bore to the external radiation field. If the hole has a large diameter and if the frequency is sufficiently low, the shunt approximates an acoustic short circuit. So, for instruments with large holes (flute and saxophone) cross fingering has relatively little effect in the lowest register. Various authors have modelled tone holes with a range of complications[1-5].

Although the standing wave is attenuated by the tone hole, it still extends past it along the bore, giving an extra length or end effect that varies with frequency. The end effect decreases as the size of the tone hole increases, and depends (to a lesser degree) on the height of its chimney, the extent of covering by keys, and the degree of undercutting (i.e. chamfering of the junction between the tone hole and the bore).

In this study we measure the frequency dependence of the propagation of the standing wave beyond the first open tone hole for simple and cross fingerings.

MATERIALS AND METHODS

The instruments studied are similar but not identical to those studied previously [6]. An acoustic current was synthesized having frequency components from 0.2 to 3 kHz with 2 Hz increments, and input to the embouchure hole via a short pipe whose impedance approximates the radiation impedance that normally loads the instrument at this point when it is played. To measure the frequency dependence of propagation of the standing wave, a probe microphone was inserted at the embouchure, and also at the open or closed tone holes The technique for the measurement of transfer functions is described elsewhere [6], except that a probe microphone (external diameter 1.0 mm) was used for all measurements.

RESULTS AND DISCUSSION

The first plot shows the input impedance spectrum of a reproduction of a 19th century flute (chosen because of its relatively small tone holes) for the fingering used to play E4 or E5. At low frequencies, the spectrum is not very different from that of a shorter version of the bore, as if it were terminated a little beyond the first open hole. The flute, being played with the embouchure open to the radiation field, operates at minima in impedance. For most fingerings, the first few impedance minima are harmonically spaced. (See [6-9] for detailed discussions.) At higher frequencies, the minima are weaker (due to wall losses) and, in the example shown here, they also occur at frequencies lower than harmonic multiples of the fundamental, due to the greater propagation of the wave beyond the first open tone hole.

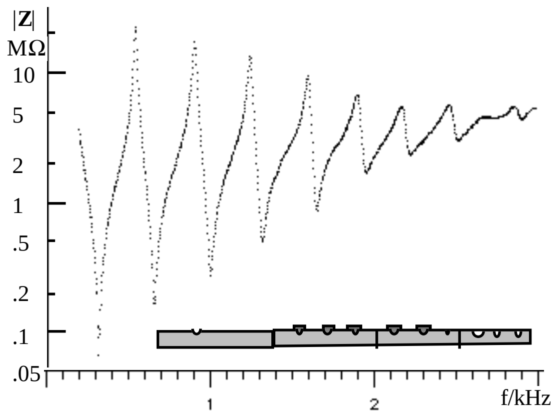

FIGURE 1. The acoustic impedance spectrum, in $MPa.s.m^{-3}$, for a simple fingering that plays E4/5.

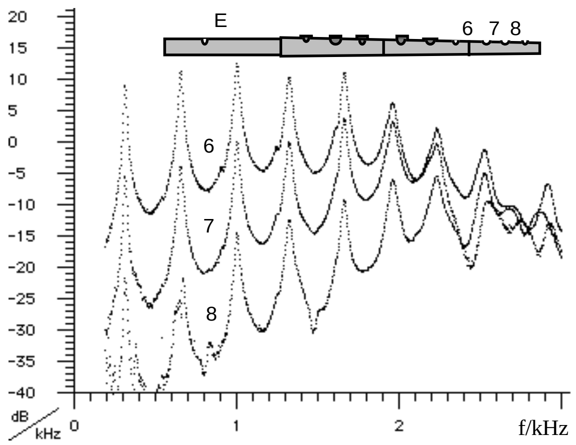

FIGURE 2. The ratio of the pressure at the open tone holes to the pressure at the embouchure.

Figure 2 shows the frequency dependence of propagation of the standing wave into the region of open holes, expressed as the ratio of the acoustic pressure at the 6th, 7th and 8th tone holes to that at the embouchure for the same acoustic current at the embouchure. The sharp peaks coincide with the minima in Z: other frequencies do not generate a strong standing wave for this fingering.

At the first open hole (hole 6), the first several peaks (those corresponding to the harmonic minima in Z) have similar magnitudes, but they become weaker at higher frequencies. Further down the bore (holes 7 & 8), the penetration increases with frequency, up to the cut off frequency for the array of open tone holes (for this instrument around 2 kHz), above which there is little difference with position, and the standing wave propagates freely [8]. In modern instruments with larger tone holes, (data not shown), the penetration increases less rapidly with frequency and the cut off frequency is higher.

When cross fingerings are used, the analogous curves are more complicated. The wave propagates strongly down the bore, and for most frequencies, the acoustic pressure increases with length past the first closed hole. This increases the effective length of the bore with frequency, and so the first minimum is flattened, and the second a little more. This allows the production of flattened notes, but it also produces inharmonic minima, which do not support the high harmonics in a strongly non-linear vibration régime, and hence contribute to the darker timbre of cross fingered notes.

Musically useful discussion requires much greater detail. Discussions of fingering effects and a much larger set of results are given on our web site [9].

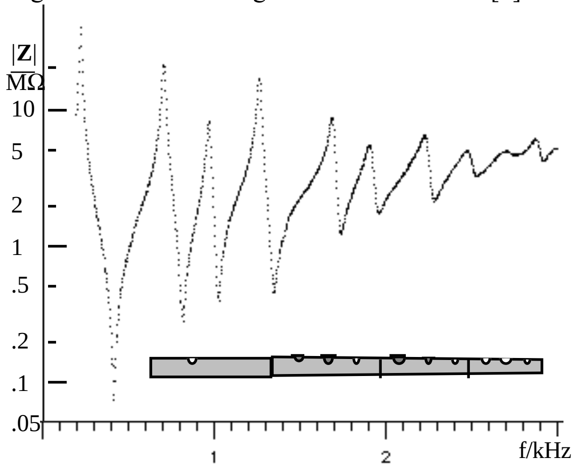

FIGURE 3. The impedance for a cross fingering.

ACKNOWLEDGMENTS

We thank John Tann and Terry McGee. This work was supported by the Australian Research Council.

REFERENCES

1. J.W. Coltmann, *J.Acoust. Soc. Amer.,* **65**, pp. 499-506 (1979).
2. W.J. Strong, N.H. Fletcher and R.K. Silk, *J. Acoust. Soc. Amer.,* **77**, pp. 2166-2172, (1985)
3. D.H. Keefe, *J. Acoust. Soc. Amer.,* **72**, pp. 676-687, 1982.
4. C J. Nederveen, J.K.M. Jansen and R.R. van Hassel, Acustica **84,** pp. 957-966, (1998).
5. V. Dubos, J. Kergomard, A. Khettabi, J-P. Dalmont, D.H. Keefe, C.J. Nederveen, *Acustica* **85,** pp. 153-169 (1999).
6. J. Wolfe, J. Smith, J. Tann, and N.H. Fletcher, *J. Sound & Vibration*, **243**, 127-144 (2001).
7. N.H. Fletcher and T.D. Rossing, *The Physics of Musical Instruments.* New York, Springer-Verlag, 1998
8. A.H. Benade *J. Acoust. Soc. Amer.* **32**, 1591-1608 (1960).
9. J. Wolfe, J. Smith and J. Tann. *Flute acoustics* www.phys.unsw.edu.au/music/flute