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ACOUSTICS OF THE AIR-JET FAMILY OF INSTRUMENTS

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ABSTRACT

The air-jet family of instruments includes the European transverse flute and the recorder and also the shakuhachi, the syrinx and a range of other flutes from the Pacific region. The acoustics of the resonators of the air-jet instruments have been less studied than have those of the reed instruments. Reed instruments are closed by a narrow aperture in the player's mouth, so they operate near maxima in the acoustic impedance of the bore. At these maxima, the pressure signal is large and readily measured. Members of the air-jet family are open to the air and so operate near impedance minima, where pressure signals are smaller. Their acoustic impedance varies over some 70 dB. Our laboratory has specialised in rapid, precise measurements of impedance spectra with large dynamic range. We report and compare measurements of the input impedance spectra of members of this family and discuss the relation between the various impedance minima for a given fingering, the vibration régime(s) which can be supported and the sound(s) produced.
KEYWORDS: Acoustics, flute, shakuhachi, acoustic impedance.

INTRODUCTION

The use of the air-jet in musical instruments is widespread in time and space. Such instruments have been made since at least the paleolithic [1], and have given rise to a wide range of variants in different parts of the world, including the transverse flute, the recorder, the shakuhachi, the quena, the syrinx, the ocarina and the organ pipe. In this paper we report a technique for measuring the acoustic impedance spectra of air jet instruments, and we compare some measurements on a transverse flute (hereafter called flute) and a shakuhachi.

In these instruments, the spontaneous wave produced by the air-jet striking an edge excites a column of air in a long, thin bore. Under appropriate conditions of jet speed and length, the jet can be deflected alternately into and out of the embouchure hole so as to excite large oscillations at one or more of the resonant frequencies of the bore. The air jet is open to the radiation field, so at the mouth end of the instrument, the boundary condition imposed on the standing waves is a large acoustic flow with relatively little variation in the acoustic pressure. This contrasts with reed or lip-reed instruments, in which the players mouth covers the input aperture, and in which the mouthpiece boundary condition is a high acoustic pressure and low flow. The ratio of acoustic pressure to volume flow is called the acoustic impedance **Z**(f), which is complex and a function of frequency. Many of the acoustic properties of wind instruments depend on the particular form of **Z**(f). For air-jet instruments, stable oscillation régimes (the ordinary notes of the instruments) occur at frequencies for which **Z**(f) is a minimum. Further, since the jet is not sinusoidal, such regimes usually depend upon minima in **Z**(f) occuring at or near harmonics of the fundamental frequency of oscillation. This contrasts with reed instruments, for which the vibratory regimes depend upon the maxima in **Z**(f). For an introduction to the operation of wind instruments in general, see Fletcher (this volume [2]). More detail is given by [3].

In the shakuhachi and flute, the resonant frequencies of the bore are changed by opening and closing tone holes that are bored through the wall. Beginning with all the tone holes closed, successive opening of the holes from the end remote from the mouthpiece shortens the effective length of the tube. The standing wave, however, does not fall to zero at the first open hole, but penetrates considerably further down the tube. Thus a tone hole must be drilled at a position rather closer to the embouchure than the point at which the tube would need to be cut [4]. If the tone holes are small relative to the bore, this extension of the standing wave past the first open tone hole may be substantially affected by subsequent toneholes. The closing of such subsequent tone holes in order to flatten the note is called a cross fingering. A combination of open, closed or part closed holes is called a fingering. Each one gives a set of minima in **Z**(f) and thus a set of notes that may be played. Players must know several dozen of these and be able to produce them sequentially with great precision and agility. The acoustic performance of the instrument depends (among other things) on the spectra of **Z**(f), and that is the main motivation for the present study.

Detailed studies of **Z**(f) for reed and lip reed instruments have been published decades ago [5-7]. Despite the popularity and musical importance of the flutes, few studies of their impedance spectra have been published. The reason is one of limitations on measurement technique: acoustic flows are virtually impossible to measure accurately, but pressures may be measured with a microphone. Thus it is easier to measure maxima in **Z**(f) than minima. **Z**(f) can vary over 60-70 dB or more, so a large dynamic range is required to measure the minima accurately. (In most measurements of **Z**(f) for reed and lip-reed instruments, a linear Z scale is used, so that most of the curve lies on the Z = 0 axis.)

Measurements of Impedance. Our measurement technique uses a source of acoustic current containing thousands of frequency components simultaneously. The frequency dependence of the amplitude of the components is chosen by the experimenter, and for the experiments reported here they are independent of frequency. As in virtually all measurements of acoustic impedance, we compare unknown impedances with known impedances, because of the difficulty of measuring acoustic current directly. In our case, the reference impedance is a 'semi-infinite' cylindrical waveguide, which has the advantage that its impedance is resistive: *ie* real and independent of frequency. For practical and economic reasons, the semi-infinite waveguide is approximated by a finite, stainless steel pipe, of diameter 7.8 mm and length 42 m (the latter being determined by the size of the building). For frequencies above 200 Hz, attenuation is over 1 $dB.m^{-1}$ in such a pipe, so waves reflected from the far end return attenuated by at least 80 dB. This is very much smaller than all of the components generated during calibration, so that the pipe is effectively semi-infinite.

Flute and Shakuhachi. The shakuhachi is an approximately cylindrical instrument, traditionally made of bamboo, with five tone holes for four fingers and one thumb. Its name derives from its most common length, which is one *shaku* plus eight *sun* or tenths, *ie* about 540 mm. (A *shaku* is about 300 mm.) It is blown at the end: the player's chin seals most of the open end and s/he directs the air-jet at a sharp edge of horn or ivory (or a synthetic substitute) which is set into a notch bevelled into the cylindrical side. This geometry allows the player to change the length and angle of the jet by movements of the arms and head, which leads to great control of the timbre, loudness and pitch. This flexibility, plus the relative prominence of the broadband sound of the jet in the timbre of the instrument, give it great expressive range, and it is often used to suggest natural sounds including those of birds, wind and water. The five holes suggest a pentatonic scale, but cross fingerings, partial closing of the holes and the adjustment of the embouchure permit not only a Western chromatic scale over two octaves, but microtonal divisions as well. The shakuhachi studied here was a Bei Shu model (Nagano Ken, Japan) of standard length. It has a bamboo body, but the bore itself is synthetic. This is an advantage for scientific purposes, as it allows a greater degree of reproducibility.

The modern transverse flute is well known in most countries, and we have already reported studies of **Z**(f) for this instrument [8,9]. In this paper, we compare the shakuhachi with the conical or classical flute: an instrument such as was used for European music in 18th and early 19th centuries. Unlike the modern flute, both the classical flute and the shakuhachi have rather fewer than the twelve tone holes required for a Western chromatic scale, and therefore use cross fingerings extensively. In both instruments, opening the lowest tone hole produces a similar change in pitch (about a whole tone, in Western language). A major difference is that the classical flute has a body in the shape of a truncated cone, with the smaller end remote from the mouth, which abuts a cylindrical head. The instrument reported here was made by Terry McGee of Canberra, Australia. Its dimensions are based on those of a large-hole Rudall and Rose flute (Rudall and Rose #655 from the Bate Collection in Oxford) but the scale has been adjusted to play at A = 440 Hz.

MATERIALS AND METHODS

The spectrometer used here is a development of a version originally designed to operate very rapidly for measurements of the human vocal tract [9-11], which we describe only briefly here. A waveform with the desired spectrum is synthesized by a computer and output via a 16 bit AD card and an amplifier to a concentric pair of loudspeakers. These are matched via an exponential horn to an attenuator, whose cross section is a narrow annulus, which attenuates standing waves in the attenuator below measurable levels, and which gives it a high output impedance

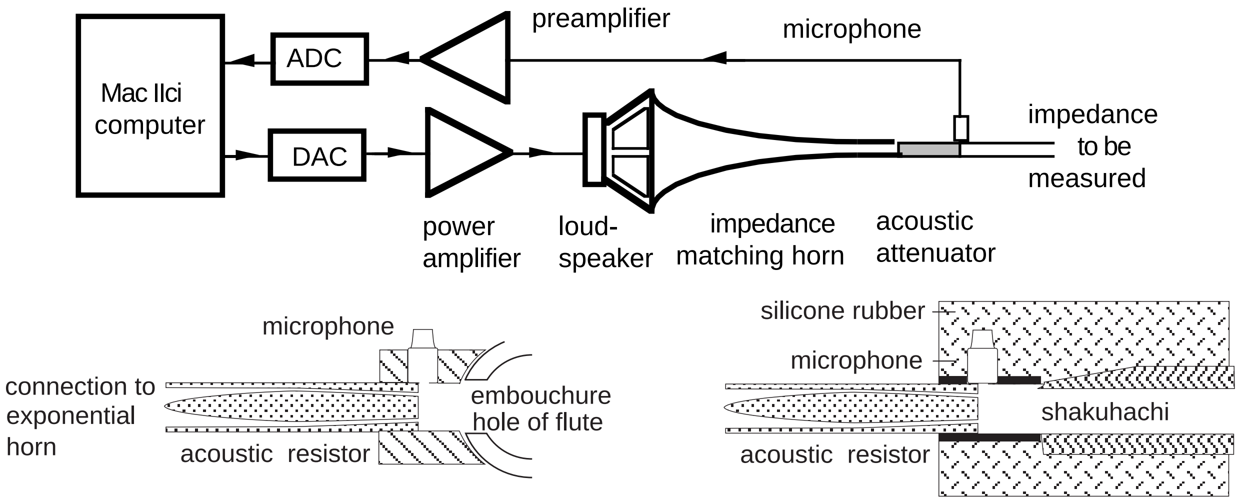

Fig. 1 Schematic of the acoustic impedance spectrometer (top) and measurement geometries for the flute (bottom left) and shakuhachi (bottom right). Figure is not to scale.

(Z_a = 155 MPa.s.m^{-3} or 155 MΩ) and thus provides a nearly ideal source of accoustic current. For calibration, the microphone at the output measures the impedance of the semi-infinite waveguide (R_{ref} = 8.5 MΩ). in parallel with Z_a. The microphone signal is digitised and the spectral components **p**(f) are calculated. This spectrum includes the frequency dependence of amplifiers, speakers, horn, attenuator and microphone. A new electrical spectrum V_{cal}(f), with

Fourier components proportional to 1/**p**(f), is synthesized and output to the calibration load. This now produces a signal $\mathbf{p}_{cal}$(f) which, to the precision of the 16 bit card, is independent of frequency. (Because the semi-infinite waveguide and the attenuator are both resistive, it is therefore also a frequency-independent acoustic current.) When measurements are made, the waveguide is replaced with an adaptor (Fig 1), which both fixes the impedance head to the instrument and compensates for the radiation impedance of the embouchure, as is explained below. V_{cal}(f) is output, and the spectrum $\mathbf{p}_{meas}$(f) measured is now that of the measured load in parallel with the attenuator. The conductance of the latter is subtracted from the measured admittance to give **Z**(f).

For measurements, the instrument and impedance head were placed inside a rigid box lined with acoustically absorbent materials to minimise resonances of the box. The stainless steel coupling from the source passed through a small hole. Larger holes with cylindrical sleeves surrounded the arms of the operator whose hands fingered the instrument. Measurements were triggered by a foot control. These precautions were considered necessary because background noise could otherwise affect measurement of the weak pressure signals at the impedance minima.

RESULTS AND DISCUSSION

Sample plots of Z(f) are shown in Fig 2. The upper curves are for the lowest notes (named D4 and *ro*) on the two instruments, which are quite similar in pitch. In this configuration, with all tone holes closed, the instruments most closely resemble a simple pipe, and their impedance spectra qualitatively resemble those of an open pipe. The first several minima in Z(f) are very nearly harmonic. When the lowest note is sounded, harmonics of the note coincide with each of these minima. Further, the notes corresponding to the first several minima can be sounded on their own by changing the length and speed of the jet. There are many similarities between these plots and the analogous plots for the modern Boehm flute. Impedance spectra, sound spectra and sound recordings on that instrument are available at http://www.phys.unsw.edu.au/music/flute/.

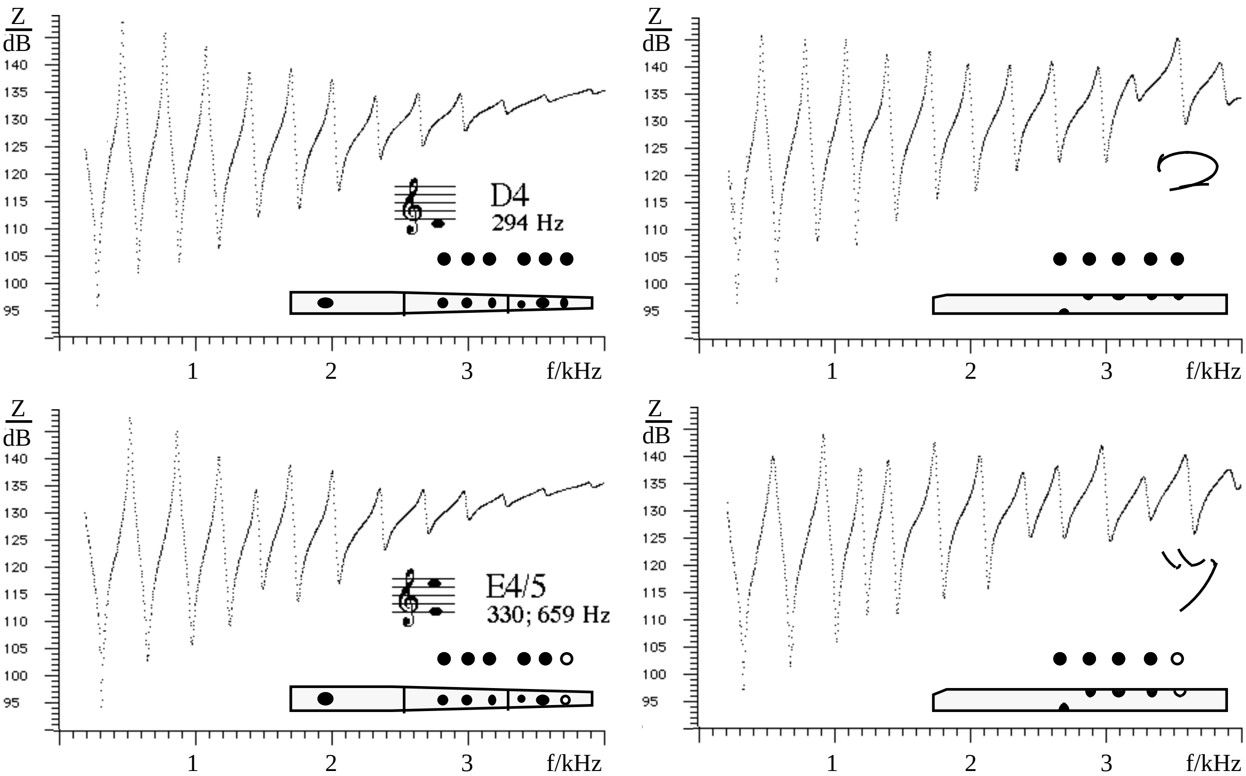

Fig. 2 Impedance spectra for the two lowest notes on the flute (left) and the shakuhachi (right)

The lower figures show the effect of opening the most distant tone hole (to achieve the notes E4 and *tsu*). The shorter effective length of the pipe produces the first few minima at frequencies increased by approximately 12%, and so the corresponding note rises by about a tone. Notice that only the first few impedance minima are now harmonic. The section of the tube downstream from the first open hole has its own resonances, and so imposes on the upper tube an acoustic load more complicated than that of an open pipe, hence the more complicated series of resonances. The opening of further holes yields successively more complications, which appear at successively lower frequencies as the downstream length increases [8]. For these fingerings, fewer of the notes corresponding to minima are playable. An array of such holes (fingerings for the higher notes) produces a filter which transmits higher frequencies. This reduces the standing waves and thus the playability of higher notes [12].

The impedance spectra of flute and shakuhachi differ at high frequencies for two reasons. In the flute, the closed tube upstream from the embouchure hole is in parallel with the rest of the bore, which adds approximately 6 dB per octave at high frequencies. Further, the embouchure hole itself is a relatively narrow chimney whose larger impedance reduces the magnitude of both the maxima and minima in Z(f) at high frequencies.

'Lipping up or down'—the effect of the radiation impedance at the embouchure. Players of the flute must adjust the embouchure to play in tune for different notes and different dynamic levels. Rolling the embouchure hole towards the face has (at least) three effects: it shortens the length of the jet, it partially occludes the embouchure hole with the lower lip, and it reduces the solid angle for radiation due to the face acting as a baffle. The latter two increase the radiation impedance, which lowers the frequencies of the minima in **Z**(f). In classical Western flute performance, the resulting control of pitch is primarily used to compensate for imperfect tunings in the instrument (which result from the compromises made when each tone hole serves more than one purpose) or to compensate for the pitch change that would otherwise result from playing more loudly or softly.

In shakuhachi performance, pitch control by embouchure is sometimes a more prominent feature of performance. The fact that the chin closes the pipe means that the area which links the bore to the radiation field, and the solid angle available, can be controlled by movements of the head and arms. Although these parameters are difficult to measure directly, we expect that have a substantial effect on the impedance minima and thus on the pitch and timbre of notes played.

In our measurements, the impedance head is connected to the instrument via a coupling pipe with a diameter of 7.8 mm (Fig 1). For the flute, the length between the measurement plane and the plane of the embouchure hole was 6 mm (the load tube). This was chosen to simulate a typical value of the radiation impedance at the embouchure hole. (For these dimensions and the frequencies of interest, the radiation impedance and the impedance of a short tube are both inductive.) Thus the measurement already simulates the impedance of a flute in a playing configuration. When the flute is rolled towards the face (to shorten the jet) the covering of the hole by the lower lip reduces the size of the hole and the baffling of the face reduces the solid angle for radition. Both increase the radiation impedance. To calculate the Z(f) for such differences, the length of the load tube can be increased or decreased either in the experiment (which is time consuming) or by recalculation of the spectrum using the transfer matrix for a cylindrical pipe [3]. For the shakuhachi, the coupling pipe used was 9 mm long, however this choice was made partly for mechanical reasons, and we use the transfer matrix to 'remove' part of it.

For a baffled pipe of radius a, the radiation impedance nearly equals that of an ideal tube with a length about 0.85a. Without the effect of the player's face, the radiation load at the embouchure would thus approximate that of a pipe with the same area and length. In practice, the player's lower lip covers part of the hole and his face reduces the solid angle for radiation, so the effective length is increased. For the flute, the value of 6 mm is chosen empirically so that, at the corresponding temperatures and humidities, the impedance minima correspond to the played notes.

Let the open fraction of the hole be g, and the radiation angle be $h2\pi$ steradians. The radiation impedance is thus

$$Z_{rad} = \frac{0.85a\, j\omega\rho}{\sqrt{g}\, hS_{emb}}$$

where S_{emb} is the area of the embouchure hole, ρ is the density of air, and ω the angular frequency. To simulate this impedance with a coupling pipe,

$$Z_{couple} = \frac{j\omega\rho L}{S} = Z_{rad} = \frac{0.85a\, j\omega\rho}{\sqrt{g}\, hS_{emb}}$$

Using 6 mm for the flute and 90 mm^2 for S_{emb}, $h\sqrt{g} = 0.3$, which is a little less than the value when g = h = 0.5.

For the shakuhachi, the geometry at the embouchure is more complicated, and the area through which the bore radiates is more difficult to define. For typical playing positions, the values are probably rather similar to those for the flute. For this reason, we plot the measurements in Fig 2 for a load equivalent to 6 mm of our coupling tube. Adjusting this length affects the tuning, but it also affects the overall features of the impedance spectra. A smaller acoustic impedance at the input gives a spectrum whose variation between minima and maxima diminishes less with frequency (data not shown). This, along with necessary changes in the jet to accommodate the altered geometry, are presumably responsible for some of the timbre changes associated with head and body movements on this instrument.

CONCLUSIONS

There are several similarities in the acoustic impedance spectra of these two members of the air-jet family. The details of their spectra can be used to explain many of the characteristic performance features of the instrument. The impedance spectrometer described here is well suited for measuring wind instruments, including those which are open at the mouthpiece.

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