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A NEW TECHNIQUE FOR THE RAPID MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF WIND INSTRUMENTS

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Abstract

The input acoustic impedance of musical wind instruments necessarily has a dramatic variation with frequency. Our technique uses an acoustic current source whose output is calibrated on a purely resistive load, provided by a 'semi-infinite' cylindrical pipe. The frequencies, amplitudes and phases of the sinusoidal components in the stimulus are chosen explicitly to provide the desired frequency resolution and range, and also to optimise the signal to noise ratio. A stimulus waveform is then synthesized from this set of frequency components. The acoustic current is produced using a loudspeaker coupled to the system under study via an exponential horn and an acoustic attentuator with a large acoustic impedance. This allows rapid, high precision measurements over a wide dynamic range. This permits us to investigate the air-jet family of instruments, which operate at the minima in impedance, and which require therefore a large dynamic range in measurement. We have conducted a detailed study of some members of this family. Aspects of the sound and playing behaviour of the instrument in any particular configuration or fingering can often be explained by the frequency dependence of the impedance, in particular the frequencies, depths, bandwidths and harmonicities of the impedance minima which together determine a playing régime.

INTRODUCTION

Acoustic impedance **Z**(f) is the (complex) ratio of acoustic pressure to acoustic volume flow. The importance of the impedance spectrum of the bore of a wind instrument upon the intonation, timbre and stability of its notes has been known for decades. Until recently, detailed comparative studies have often been complicated by the either the time taken for time domain or swept frequency methods (e.g. Gibiat and Laloë, 1990; Keefe et al, 1992) or inadequate dynamic range. The requirement to measure such a spectrum for every useful combination of keys (several dozens for woodwinds) makes rapid measurements desirable.

The air jet family of instruments (flutes, recorders, ocarinas, shakuhachi, quena etc) poses a particular problem for the measurement of acoustic impedance, which may explain why there is very little published material about **Z**(f) for this family. These instruments are driven by an air jet, so the bore of the instrument is open to the air at the input. Consequently, the minima of **Z**(f) are of acoustic importance. The variation in **Z**(f) in a musical instrument is quite large (typically 60-70 dB) and so a large dynamic range is needed. The situation for 'closed' instruments such as the reeds (the other woodwinds) and the lip-reeds (brass) is quite different. These instruments operate at impedance maxima, for which the sound pressure is of course large. In the substantial literature on such instruments (eg Backus, 1974, 1976), the impedance spectrum is usually plotted on a linear scale. Although this gives the required detailed information about impedance maxima, it would be completely inappropriate for air jet instruments, because no information about the impedance minima is visible: in such a plot; the curve appears to lie parallel to the axis over much of the range.

THE IMPEDANCE SPECTROMETER

The synthesized broad band signal.
A waveform is synthesised that only contains equally spaced frequency components over the frequency range of interest. For the results presented in this paper, the waveform was the sum of 1040 frequency components equally spaced at 2.69 Hz intervals between 200 and 3000 Hz. The relative phases of the components were adjusted to optimise the measured signal to noise ratio - see Smith 1995.

The acoustic current source.
The synthesized broad band electrical signal is amplified and connected to a 130 mm loudspeaker that incorporates a separate coaxial piezoelectric tweeter. The loudspeaker is sealed in a chamber that is connected to the larger end of reverse exponential horn with a cut-off frequency around 200 Hz. An acoustic attenuator is connected to the smaller end of the horn - see Figure 1.

The acoustic attenuator
This attenuator is constructed from two conical sections spaced by 3 wires each 120 µm in diameter. The pressure on either side of the acoustic attenuater is measured using two miniature electret microphones and is amplified by 2 low noise pre-amplifiers with computer-controlled gain. This version of the spectrometer uses a Macintosh IIci computer with a 16-bit Analogue/Digital card (National Instruments NB-A2100).

Calibration.
The first step in calibration involves deciding upon the desired variation of the acoustic current $u_{REF}(f)$ with frequency. The signal to noise ratio in an experiment can often be improved by increasing the relative amount of acoustic current at frequencies where the impedance of the sample is low or where noise is high. However an acoustic current that was independent of frequency was used for the experiments described in this paper. An electrical waveform with a

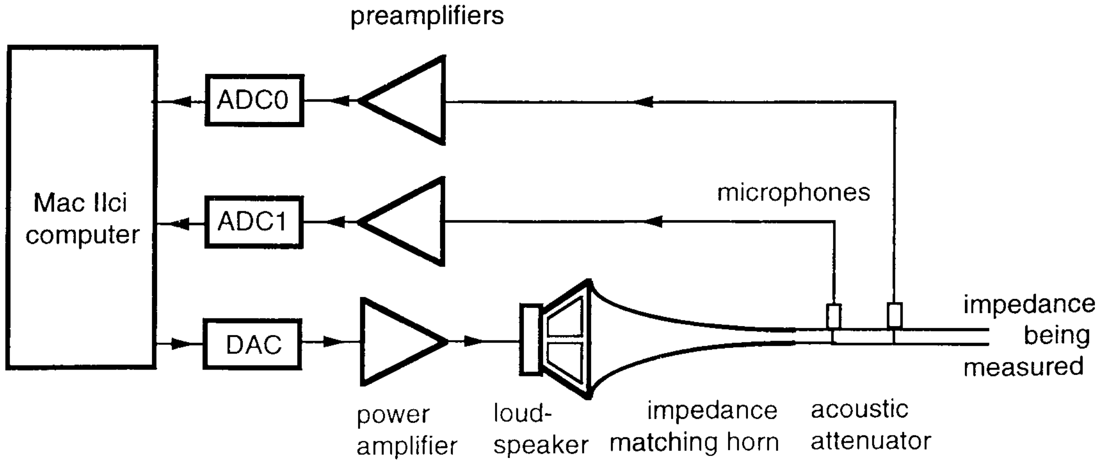

Figure 1. Schematic diagram of the acoustic impedance spectrometer.

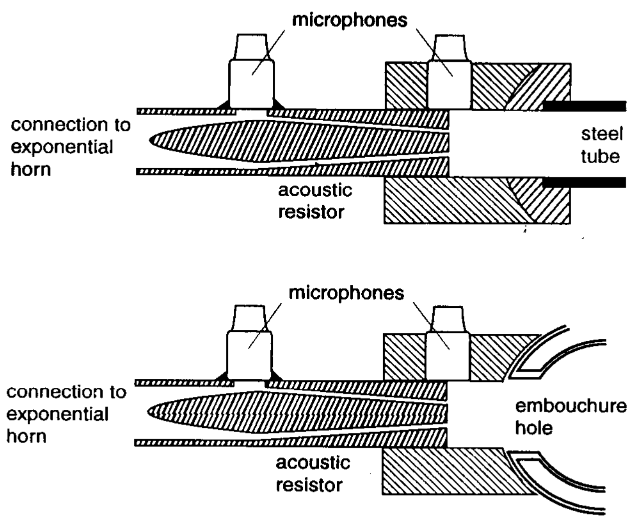

Figure 2. Schematic diagrams (not to scale) indicating how the acoustic impedance spectrometer is connected to a cylindrical pipe or the embouchure hole of the flute. For simplicity the various threads and Swagelock fittings used to interconnect the elements are not shown

frequency independent power spectrum denoted by $V_{REF}(f)$ is synthesized and converted by the loudspeaker, exponential horn and acoustic attenuator into an acoustic current $u_{REF}(f)$, which is coupled to a resistive reference load $Z_{REF}(f)$. The acoustic pressure is measured via the microphone and the pressure spectrum $p_{REF}(f)$ calculated. A new waveform with Fourier components proportional to $V_{REF}(f)/p_{REF}(f)$ is then synthesized. This produces an acoustic current spectrum that is flat (i.e. frequency independent to ± 0.03 dB) when $p_{REF}(f)$ is measured.

A resistive load Z_{REF} was used for calibration This was a 'semi-infinite' pipe - a 42 m stainless-steel pipe with an internal diameter of 7.8 mm, i.e. slightly smaller than the embouchure hole of a flute - see Figure 2. The attenuation in a tube of this diameter is approx. 0.11 m^{-1} at 200 Hz (Fletcher and Rossing 1998), so the echo returned with a loss of 80 dB and thus made negligible change in the amplitude measured in the calibration signal. (The dynamic range of the instrument is actually a little greater than 80 dB, but the precision is less than this. Any echo coincides with a frequency component of the input which is 80 dB greater, and so can be ignored.)

Correction for reflection at the attenuator

The output end of the attenuator is effectively in parallel with the measured or reference load. The measured admittance in both calibration and measurement must therefore be corrected by subtraction of the attenuator conductance. Assuming that the thickness of the annular cone in the attenuator is equal to the diameter of the spacing wires, we calculate a characteristic impedance of 170 MRayl. This calculation is only approximate, however, as the wires are not perfectly straight. We therefore determine this value accurately to be 155 MRayl by measuring the impedance of a known load at a frequency where its impedance is large. The microphone on the input side of the attenuator is used to determine whether the signal at that point depends on the load being measured. No measurable difference is detected between calibration (load with 8.5 MRayl, independent of frequency) and measurement on systems with strong resonances (Z(f) varying from 200 MRayl to 20 kRayl). Thus the wave that is reflected at the load end, then at the source end, and which then appears at this microphone, has negligible effect on the measurement. This justifies treating the parallel impedance of the attenuator as purely resistive.

This shunt impedance ultimately imposes an upper limit on the impedance that can be measured using this technique. With the system described here, the upper limit for precise measurement is therefore of order 100 MRayl. This exceeds the impedance maxima of the air jet instruments measured to date and, in any case, it is the minima in Z(f) that are of importance. (The upper limit is a design compromise in the attenuator. For higher impedances, a thinner annular space may be used, but this also reduces the signal transmitted. This either reduces the sensitivity for measuring a low impedance by increasing the signal to noise ratio, or else requires lengthy measurements involving signal averaging.

Measuring Z(f) for wind instruments

The important **Z**(f) for understanding the behaviour of instruments in the flute family is the impedance which provides the acoustic load for the air jet. With the flute in the playing position, its embouchure hole is partially occluded by the lower lip. Furthermore the face of the player acts as a baffle over a fraction of the solid angle available for radiation. The spectrometer was thus coupled to the embouchure hole of the flute using the measurement head shown in figure 2. It is designed to measure the impedance at the embouchure hole when it is loaded with an impedance approximately equal to the radiation impedance of the hole with the player's lips and face acting as a baffle (see Smith, Henrich and Wolfe 1997 for more details).

RESULTS AND DISCUSSION

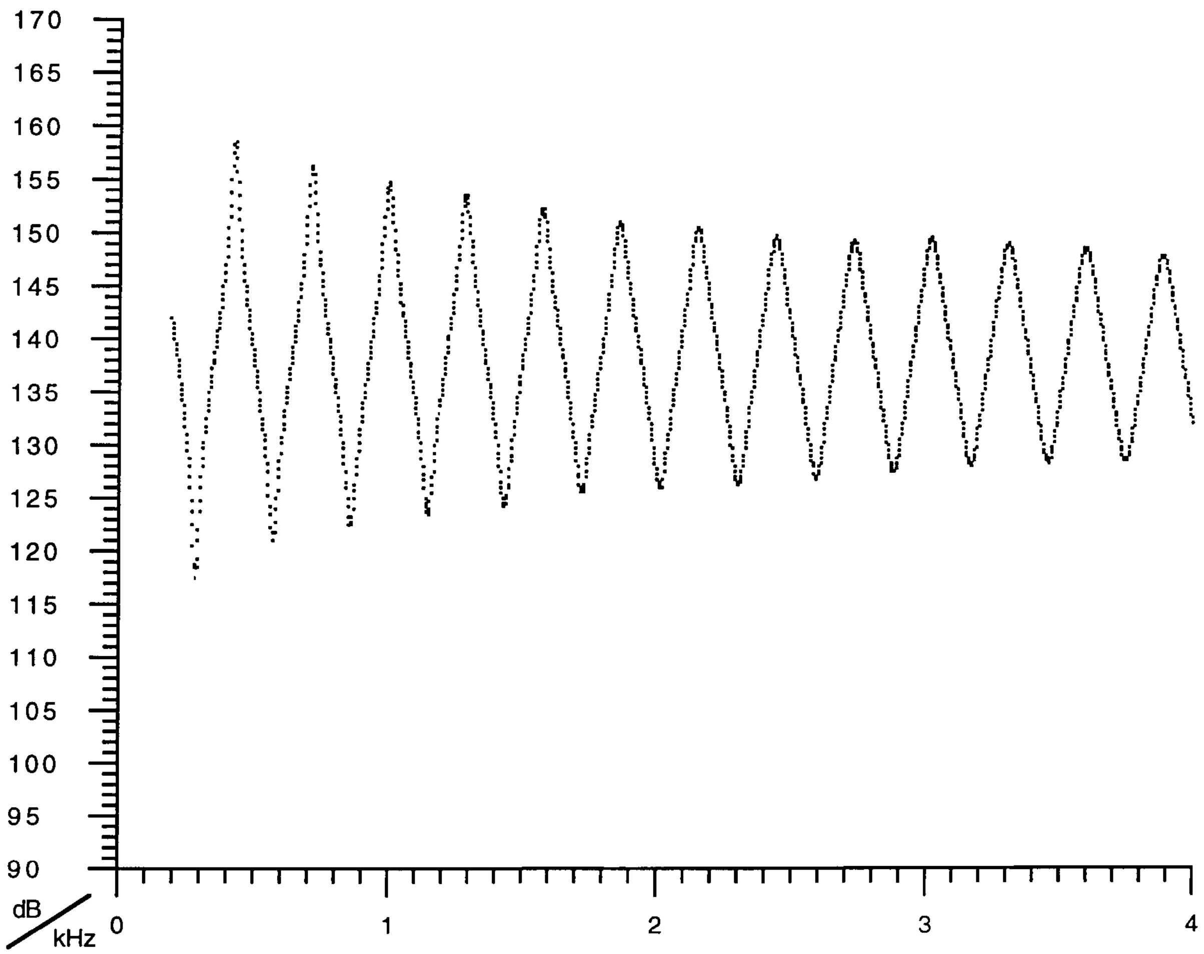

Figure 3. The magnitude of the measured acoustic impedance of an open ended stainless steel cylindrical tube of length = 596.7 mm. These data were compared with the theoretical Z(f) for a finite tube gave a value of $\chi^2 = 0.00007$, using standard tables of the speed of sound (Kaye and Laby, 1973).

Impedance measurements on cylindrical tubes.
The theoretical **Z**(f) of finite cylindrical tubes can be calculated with some precision (see Fletcher and Rossing 1998) and consequently measurements of their impedance can provide a good test of the performance of the spectrometer. The first test was to measure the 'semi-infinite' tube used for calibration. Z(f) was found to be independent of frequency as expected with any variations less than ± 0.03 dB. This test was usually repeated after each set of measurements: the instrument measuring adaptor was dismantled and the measurement head was reconnected to the semi-infinite load.

The second test was to measure a set of stainless steel, cylindrical tubes of different lengths. Excellent agreement was found between theory and experiment. Once the impedance of the acoustic attenuator has been determined during the calibration procedure described above, there are no adjustable parameters. One example is given in figure 3.

Impedance measurements on the flute
To allow easy replication by others, all measurements were made on a basic production line flute (Pearl PF-661, closed hole, C foor or B foot) rather than the finer instruments of our industry collaborator. This mass produced instrument uses the same 'scale' (*ie* positioning of tone holes) in both the open and closed hole variations. Measurements were made at T = 25±0.5°C and relative humidity 58±1%. Like all modern flutes, it is of the Böhm style with a cylindrical body, a head that tapers towards the embouchure, and tone holes whose diameter is not very much smaller than the diameter of the bore. The stopper in the head was positioned at 17.5 mm from the centre of the embouchure hole, and the tuning slide was set at 4 mm — both chosen as standard values used by flutists playing at standard pitch. (These and other parameters were also varied to determine their effect on relative and absolute tuning, and on harmonicity. These results will be published elsewhere.)

The time taken to acquire the data to calculate each plot of Z(f) was several seconds, depending on the background noise at the time, and calculation of the Fourier components from the data sampled at 44.1 kHz took a comparable time. Sixty fingerings were measured on the B foot flute, and then the series was repeated on the C foot (most data not shown).

Figures 4 and 5 show Z(f) for a flute in two different configurations, called 'fingerings' by players. On the diagram of a flute above each figure, the keys shaded black are those depressed by the player's fingers (some keys open holes, others shut them). Below the sketch is a schematic cross-section of the instrument showing the location of the open holes. The long series of open holes has two effects. At low frequencies, the pipe behaves rather like a simple cylinder truncated a little beyond the first open hole, hence the series of harmonic minima. (The almost regular lattice of holes gives rise to the structure above about 2 kHz). Above the diagram is a 'fingering diagram' showing how this configuration would be achieved by a player. (Black means depressed, white means not depressed, and grey means a part of the instrument not normally touched.)

Both fingerings play the note B4, at about f = 490 Hz, which is the frequency of the first minimum in Z(f). The first of these is the 'standard' fingering used for the notes B4 and B5. Z(f) has a series of harmonically spaced minima (at f, 2f, 3f and 4f). With this fingering, the first 3 or 4 notes in that series can be played by adjusting the speed and geometry of the air jet. (Schematic pressure mode diagrams are shown.) When this fingering is used to play B4, the sound has a strong harmonic series, with the first four harmonics especially pronounced.

The second fingering, which also has a first minimum at about f = 490 Hz, is an unusual fingering for B4, which is used to play the note softly and with a 'dark' or 'covered' timbre. Its second minimum is at a frequency a little greater than 2f, and the third is considerably higher than 3f. This fingering will play B4. It will also play a note a little sharper than B5, and another about halfway between F#6 and G6. When B4 is played, there is a prominent fundamental, a rather weaker second harmonic, and only very weak higher harmonics. The subsidiary minima in Z(f) may be considered as the standing wave whose pressure mode diagram is shown in parentheses, and its second harmonic. The open hole is displaced from the pressure node, so the resonance is weak, and these notes cannot (to our knowledge) be played.

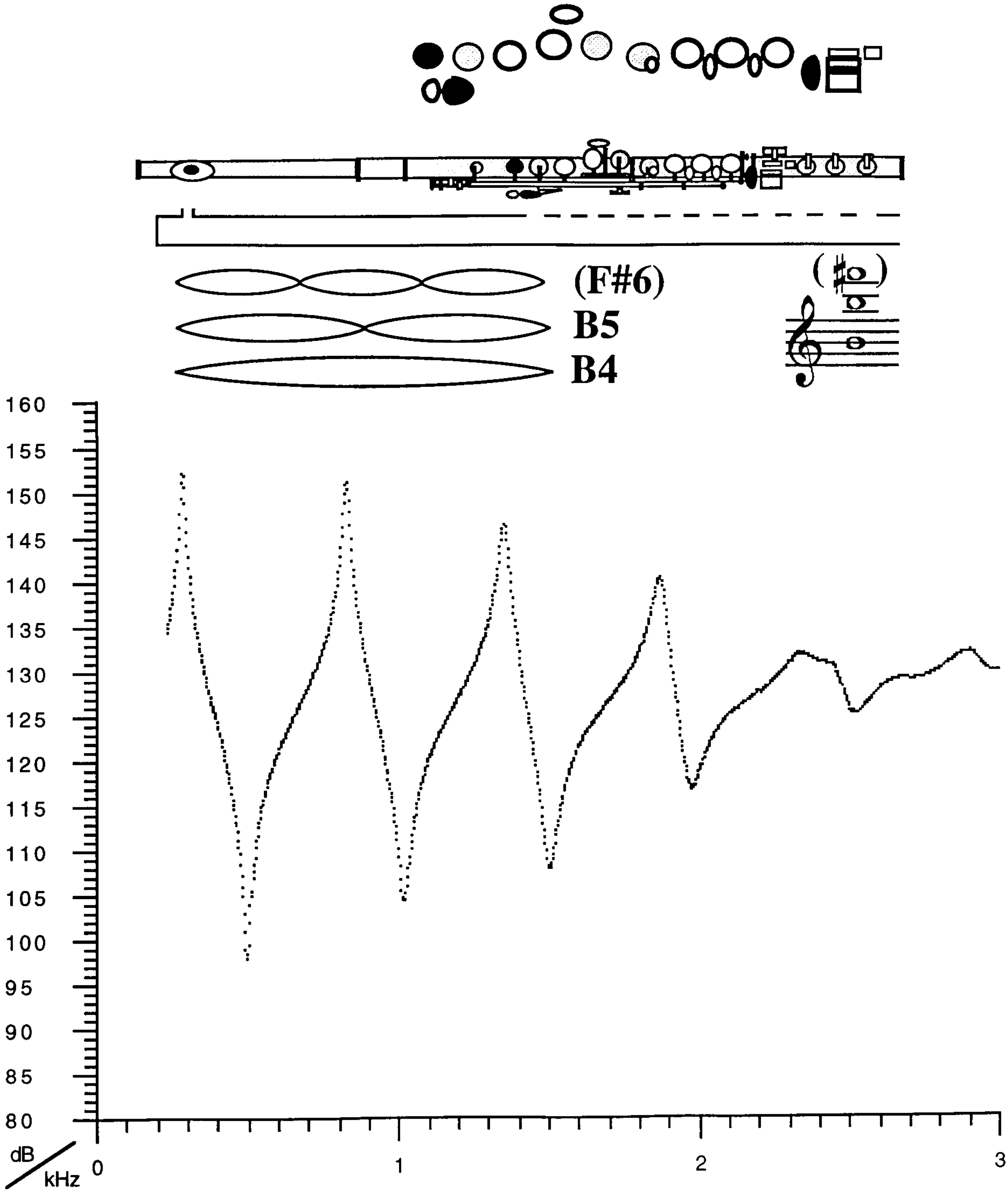

Figure 4. The lower graph shows Z(f) of a flute (Pearl PF-661, closed hole, B foot) measured at the embouchure hole with the conventional fingering for B4 or B5. The plot is a set of points representing measurements at 1040 different frequencies. The upper figures are explained in the text. (The phase of the impedance was also measured, but is not shown here.)

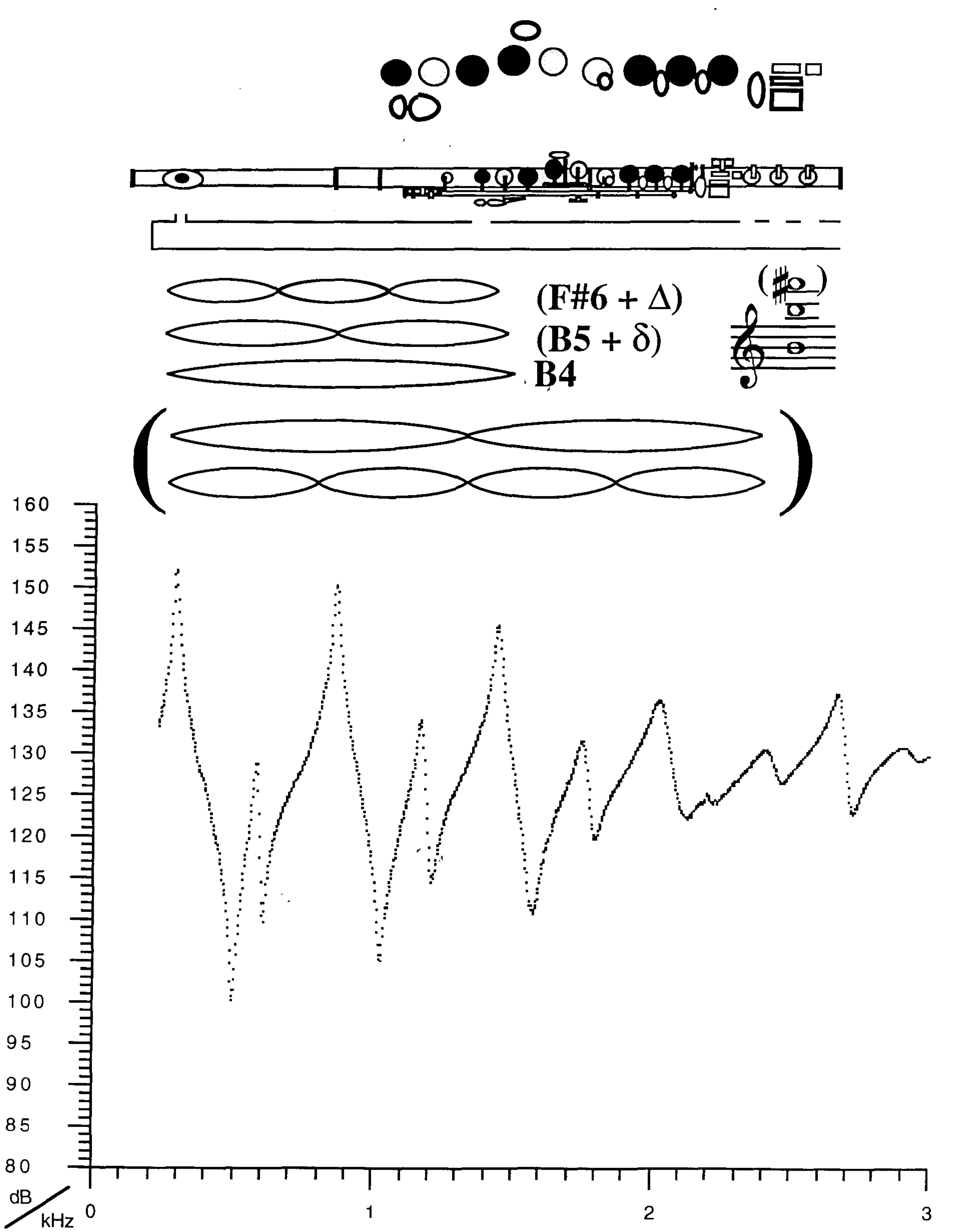

Figure 5. The lower graph shows Z(f) of a flute measured at the embouchure hole with an unusual fingering for B4. For details see the text or the caption to Fig 4.

We have now measured the impedance spectra for the several dozen standard fingerings B3 to F#7 for both the standard (approximately cylindrical) Böhm flute and the classical flute (which approximates a truncated cone, and which has relatively small tone holes). These, and selected non-standard and multiphonic fingerings, are available at our website - **http://www.phys.unsw.edu.au/music/flute.** The site also has the sound spectra of notes played with these fingerings, so the relationship between the impedance curves and the sound spectra may be inspected directly.

CONCLUSIONS

The method of measuring acoustic impedance described herein offers several advantages. The combination of a high impedance attenuator (a current source), a purely resistive reference load and a calibration loop which adjusts the input current spectrum provides a system which can measure acoustic impedance precisely, rapidly and conveniently over a large dynamic range. This speed and precision have also proved useful in measurements of the vocal tract (Dowd *et al*, 1997; Epps *et al*, 1997).

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