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Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Improving the quality of a simple plastic 'didjeridu'

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ABSTRACT

Traditional didjeridus have an irregular bore produced largely by termites eating the interiors of small eucalypt trees. The recent popularity of the instrument, both in Australia and abroad, creates demands upon the number of suitable eucalypts available for harvest, and also the number of indigenous craftsmen who can produce an authentic traditional instrument. Cylindrical plastic tubes are often used as cheap, widely available and easily tuned substitutes. However, their quality as musical instruments is generally perceived by players as being substantially inferior.

In this paper we report methods that might improve the playing quality of these plastic instruments. We found in an earlier study that the ranked 'overall quality' of a didjeridu was correlated negatively with the magnitude of its acoustic input impedance, particularly in the frequency range from 1 to 2 kHz. This is consistent with our observations that players used peaks in the impedance of their vocal tracts to modify the spectral envelope to produce the changes in timbre that are characteristic of didjeridu performance. Instruments with lower impedance in the critical band 1 to 2 kHz are therefore favoured. We consequently report on three modifications that reduce the acoustic impedance of a plastic instrument in the 1 to 2 kHz frequency range. The first involved increasing the internal damping in the instrument bore. The second involved adding multiple, suitably tuned, Helmholtz resonators along the instrument. The third involved the addition of a flared section or horn at the far end of the instrument. All modifications successfully reduced the impedance in the required range, but the addition of a final flared section had the additional advantage of increasing the output sound level in this range.

INTRODUCTION

Traditional didjeridus, to use a generic term, are unusual and ancient lip-valve instruments with an irregular and somewhat flared bore that is largely constructed by termites eating the wood from the core of small eucalypt trees. They are made from a length of a suitable tree, using a stick to clean out the internal structures made by the termites. The narrow end of the instrument is placed at the lips and usually played at a single pitch using cyclic breathing, although higher harmonics are occasionally used for emphasis. Simultaneous vocalisations are also commonly employed, particularly in imitation of native animals (Fletcher 1983, 1986; Fletcher et al., 2006).

Originally developed in some regions of Northern Australia, these instruments would only be played by initiated males of that area (Moyle, 1981). However the didjeridu has now become highly popular not only throughout the indigenous peoples of Australia, but also throughout the world. However, there are severe environmental constraints upon the number of suitable eucalypts available for harvest, and also the number of indigenous craftsmen who can produce an authentic traditional instrument. Furthermore, some didjeridus carry a secret spiritual significance, which cannot be known by the uninitiated.

Consquently the majority of ‘didjeridus’ are not made, and indeed cannot be made, by traditional custodians from traditional materials.

Often, cylindrical plastic tubes are used as cheap, robust, widely available and easily tuned substitutes. However, their quality as musical instruments is generally perceived by players as being substantially inferior (e.g. Neuenfeld, 1997, Amir, 2004).

The overall quality of traditional didjeridus

A previous study from this lab involved seven experienced players who assessed the overall quality of 38 traditional instruments on a scale from 1 to 10. The acoustic impedance spectrum $Z(f)$ at the mouth or input of each instrument was also measured. The best indicator of overall playing quality of an instrument was found to be a low magnitude of $Z(f)$ over the frequency range of 1 to 2 kHz (Smith *et al.* 2007). This can be understood in terms of recent work that has explained the coupling of the vocal tract to the instrument and the mechanism whereby the strong formants in the output sound are produced by the configuration of the player's tract. (Tarnopolsky *et al.* 2005, 2006). Vocal tract resonances can more readily dominate the spectral envelope in this frequency range when the resonances of the instrument are less strong (Fletcher *et al.* 2006,). Figure 1 shows $Z\{f)$ for four traditional instruments covering a range of assessed overall quality. The importance of the magnitude of $Z\{f)$ at frequencies above 1 kHz is clearly evident.

The overall quality of cylindrical plastic tubes

The study on traditional instruments also considered the overall quality of 11 cylindrical PVC pipes (Smith *et al.* 2007). The average score out of 10 awarded for overall quality of nine PVC pipes with the same diameter (38 mm), but different lengths, was found to be only around 3.0/10. Examination of Figure 2, which shows the calculated $Z(f)$ for cylinders of different diameters, shows a high magnitude for $Z(f)$ is expected for a 38 mm diameter pipe, including the crucial 1 to 2 kHz region. Indeed, the magnitude of $Z(f)$ is similar to that shown for traditional instruments that received similar low scores for overall quality (3.7/10 and 3.1/10) – see Fig. 1.

Figure 2 also shows the expected reduction in $Z(f)$ as the diameter increases. To test the influence of diameter on quality, PVC pipes of 3 different diameters and the same playing pitch (i.e. approximately the same length) were assessed by five players. As might be expected, the players showed distinct preference for the wider bore with the average scores for overall quality being 2.0/10, 3.2/10 and 4.0/10 for 25, 38 and 50 mm diameters respectively. A similar preference was found with traditional instruments. Although the details of the complicated internal bore of such instruments are unknown, the study showed a positive correlation between ranked quality and the bore diameter measured at the input of 35 traditional instruments.

In this study we investigated the following simple methods that might reduce the magnitude of maxima in $Z(f)$, particularly in the crucial 1 to 2 kHz region.

(i) Increase internal damping and wall losses. This modification seems obvious because traditional instruments have a very complicated and rough internal bore profile.

(ii) The addition of tuned resonators along the bore. These are not generally present in traditional instruments, although instruments made from forked sections of trees can have an additional bore that lowers $Z(f)$ in the 1 to 2 kHz range (Schneider, Smith and Wolfe, 2007). However, resonators with appropriate frequencies, suitably positioned, may selectively diminish the peaks in $Z(f)$ in a required range.

The consistently poor ranking of cylindrical PVC pipes as a 'didjeridu' is thus consistent with their high values of maxima in $Z(f)$. Can we make a better didjeridu using PVC pipes as a starting point?

(iii) The addition of a flared section or horn at the far end. The bell of a brass instrument radiates high frequencies. If a wave is radiated rather than reflected, standing waves will be weaker and so the extrema in $Z(f)$ will be weaker. The shape of trees often produces a bore with a flared lower section. Earlier studies found a positive correlation between the assessed quality of traditional instruments and their overall flare ratio (i.e the ratio of diameter measured at the output to that at measured at the input).

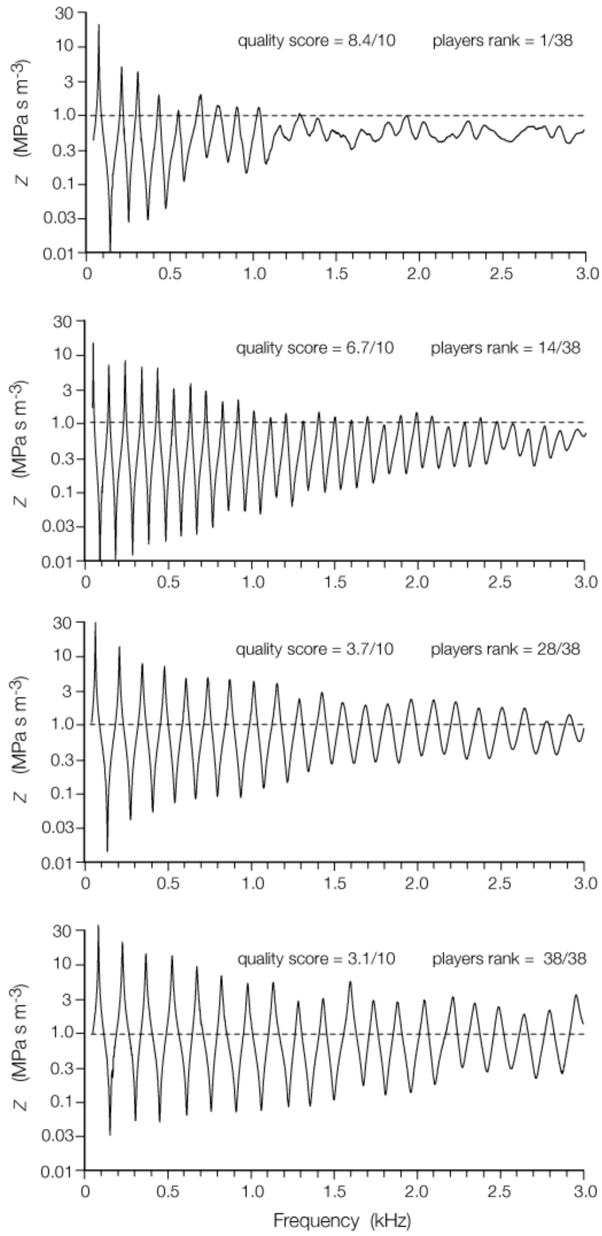

Figure 1. Semilogarithmic plots of the magnitude of the measured acoustic impedance $Z(f)$ as a function of frequency f for 4 different traditional didjeridus of different quality. The horizontal dashed lines indicate Z(f) = 1 MPa s m-3. The highest rank (best instrument) is denoted by 1 and the lowest by 38.

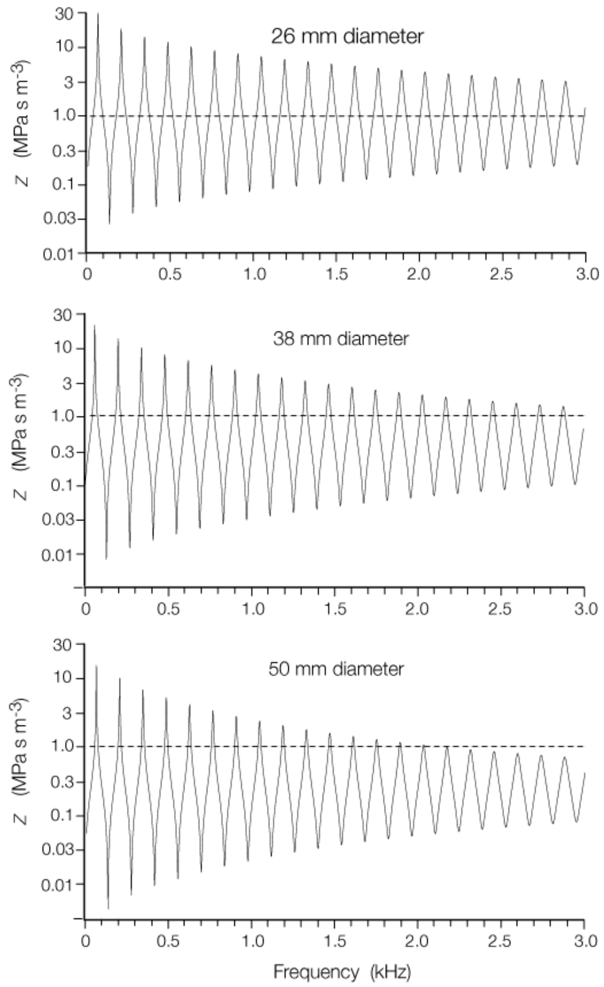

Figure 2. Semilogarithmic plots of the magnitude of the calculated acoustic impedance Z(*f*) as a function of frequency *f* for PVC pipes of different diameters and length = 1.2 m. The horizontal dashed lines indicate $Z(f)$ = 1 MPa s m^{-3}.

A fourth method would be to increase the internal diameter of the cylinder, but 50 mm appears to be a practical upper limit for players with conventional facial geometry.

In order to make any improvements more noticeable, this study used a narrow cylindrical pipe (26 mm diameter) as the starting point. Such an instrument is rated very poorly by players (average score = 2.0/10) and so leaves substantial room for improvement.

MATERIALS AND METHODS

Impedance measurements

The acoustic input impedance impedance $Z(f)$ and transpedance $T(f)$ (acoustic pressure outside instrument / acoustic volume flow at mouth) were measured using an acoustic current source (e.g. Smith, Henrich and Wolfe, 1997; Wolfe *et al*., 2001). In some cases a three–microphone technique was used with two non-resonant calibrations – see Dickens, Smith and Wolfe (2007). Ideally the pressure response used for our transpedance measurements would be measured in the far sound field, however only a small suitable room was available and so the microphone was placed in the near field, about one radius from the end of the instrument.

Numerical modelling

Simple one–dimensional models were used and impedances calculated in the standard manner (e.g. see Fletcher and Rossing, 1998).

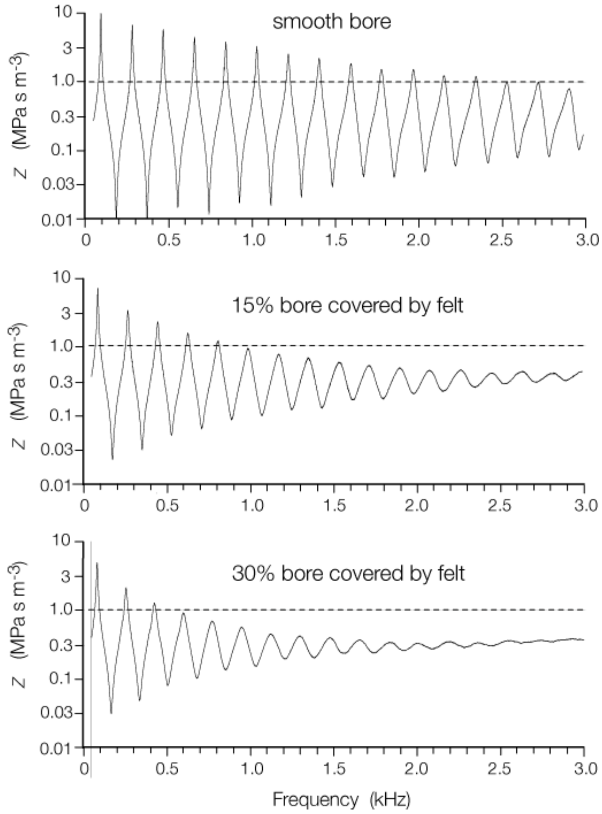

Figure 3. Semilogarithmic plots of the magnitude of the measured acoustic impedance Z(*f*) as a function of frequency *f* for cylindrical PVC pipes with different internal damping caused by the insertion of felt strips into the bore.). The horizontal dashed lines indicate $Z(f)$ = 1 MPa s m^{-3}.

RESULTS AND DISCUSSION

Increased internal damping and wall losses.

The internal damping of two PVC tubes was increased by the addition of felt strips to the internal bore – see figure 3. The resonance frequencies of the instrument were also lowered by the increased damping, lowering the playing pitch of the instrument. The increased damping also had a dramatic effect on $Z(f)$ above 1 kHz. However, the score for overall quality awarded to these instruments was significantly lower. This may be because these instruments were noticeably less loud than the undamped pipe. Further, the increased internal damping also decreased the strength of the fundamental resonance, which is responsible for determing the vibration regime, although didjeridu players are less sensitive to this than most wind musicians (Smith *et al.,* 2007).

The addition of tuned resonators

Another possibility is to reduce the impedance in certain frequency bands by the addition of resonators along the bore.

The open end of a Helmholtz resonator has low impedance at its resonant frequency. Thus a minimum in Z at a particular frequency could be produced by putting a suitably tuned Helmholtz resonator very near the input, or at an integral number of half wavelengths distant from the input. (The impedance and transpedance will not be significantly affected if the resonator is located at a pressure minimum, i.e. at an odd number of integral quarter wavelengths from the input).

To this end we used disposable plastic 10 ml syringes as tunable resonators. Figure 4 shows the effect of adding a single 2.4 kHz Helmholtz resonator at a distance equal to half a wavelength of its resonant frequency away from the input. The ‘hole’ it produces in both the impedance spectrum and transfer function can be clearly seen.

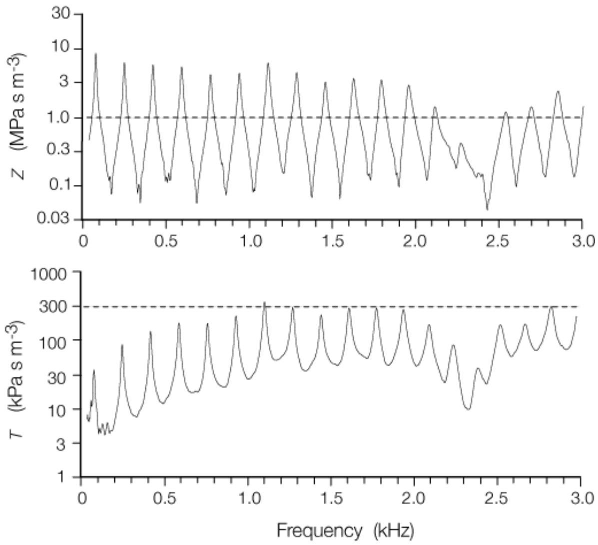

Figure 4. Semilogarithmic plots of the magnitude of the measured acoustic impedance Z(*f*) and transfer function *T*(*f*) as a function of frequency *f* for a PVC pipe (length = 1 m) with a 2.4 kHz resonator added at a distance of 70 mm from the input. Volume of resonator cavity was 1.6 ml with throat diameter and length both equal to 7 mm. The horizontal dashed lines indicate *Z*(*f*) = 1 MPa s m^{-3} and *T*(*f*) = 0.3 MPa s m^{-3}.

Figure 5 shows the result of attaching five differently tuned Helmholtz resonators to the instrument bore. They were tuned to the following harmonics of the fundamental frequency; 14, 16, 18, 20, 22. A substantial decrease in the envelope of *Z*(*f*) in the range 1 to 2 Khz. is thus produced.

An interesting, but slightly different approach, involves the addition of an extra section of bore to produce an instrument with a branched duct, i.e. a ‘didjeriduo’. Additional sections of suitable length and attachment position can help lower the *Z*(*f*) in the crucial 1 to 2 kHz region (Schneider, Smith and Wolfe, 2007).

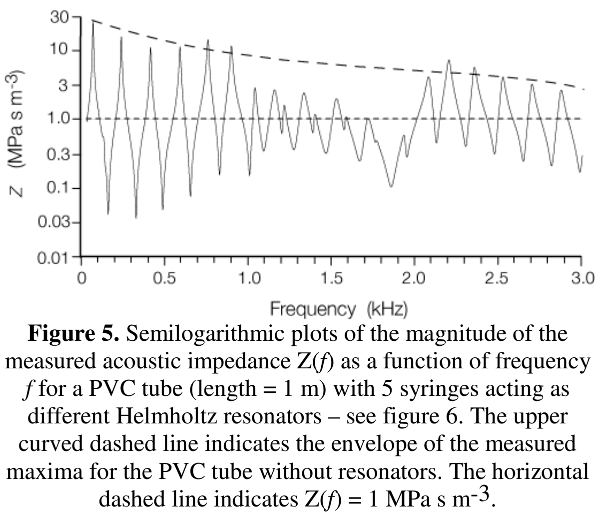

Figure 5. Semilogarithmic plots of the magnitude of the measured acoustic impedance Z(*f*) as a function of frequency *f* for a PVC tube (length = 1 m) with 5 syringes acting as different Helmholtz resonators – see figure 6. The upper curved dashed line indicates the envelope of the measured maxima for the PVC tube without resonators. The horizontal dashed line indicates Z(*f*) = 1 MPa s m^{-3}.

The addition of a flared section or horn

Acoustical horns often exhibit a cutoff frequency: a frequency above which they radiate rather than reflect most of the power of an incident wave. (The bells of brass instruments, for instance, radiate high frequencies and give those instruments their characteristic bright timbre.) A horn that radiates frequencies above 1 kHz would reduce reflections and thus reduce the size of the impedance extrema in that frequency range. A further advantage is the enhanced output of sound in the frequency range (1-2 kHz) in which the interesting and varied timbres of the didjeridu are most prominent.

To test this the following horns were used. See figure 7 for two examples.

- Clarinet bell. This was chosen because it was available and had appropriate input diameter.

- A long conical horn. This horn flared from 26 mm diameter to 80 mm diameer over 800 mm in length. This overall degree of flare corresponds to what is found in some didjeridus, although traditional instruments are unlikely to exhibit such a uniform degree of flaring.

- A set of relatively short, but wide, horns available as part of a previous investigation. 3 different profiles (conical, exponential and tractrix) were available with approximately the same throat diameter (approx 80 mm) and similar mouth dimensions (360 – 420 mm). (The tractrix profile is the involute of the catenary, and is also known as the equitangential curve or hundkurve. It has the property that the length of the tangent from any point to the asymptote is constant).

These horns were attached to an appropriate length of cylindrical pipe (26 mm) so their fundamental pitch was close to that of a one metre cylindrical pipe. (The wide horns were attached via the long conical horn).

Fig 8 shows that all the horns reduced the impedance peaks at high frequency. (The wide horns with exponential and tractrix profiles gave similar results to the conical horn and are not shown). The efficiency of the large horns at radiating small wavelengths is clear in the nearly complete lack of resonances for wavelengths less than about 0.5 m.

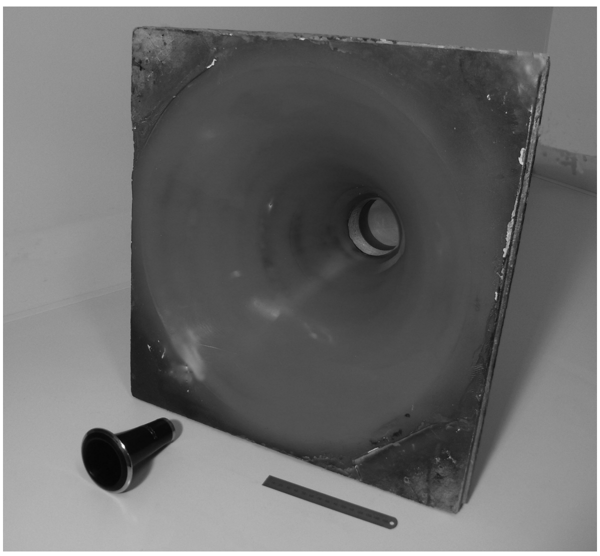

Figure 7. Photograph showing the relative size of the clarinet bell and exponential horn used for measurements. Scale is indicated by a 150 mm metal ruler.

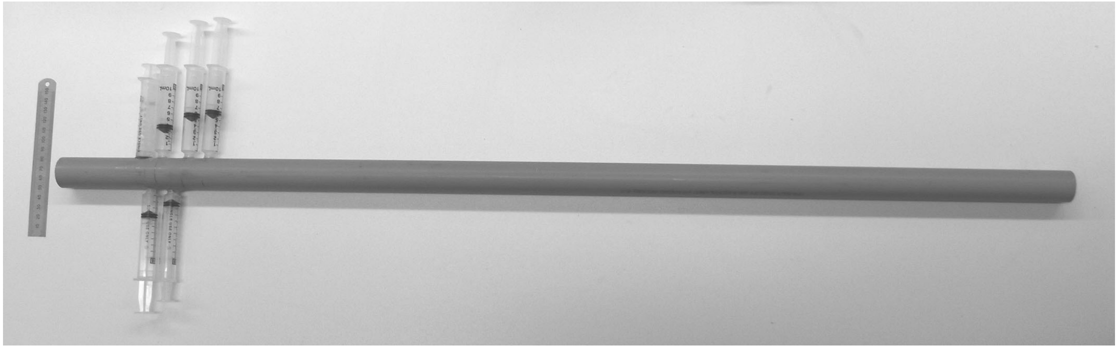

Figure 6. Photograph showing an example of how syringes were attached to a 26 mm diameter pipe and used as tunable Helmholtz resonators. Scale is indicated by a 150 mm metal ruler

The frequency-dependent reflections from a horn have the further effect on the input impedance of reducing the harmonicity of the peaks: the effective length of the horn is longer for a higher frequency wave, so the impedance peaks occur at frequency ratios that are contracted compared to those of a simple pipe without the horn.

The larger horns and the cone both reduced substantially the first resonance, making it weaker than the second. (This is common in conical musical instruments such as saxophones.) The first resonance is responsible for the stability of the playing regime and, because of the inharmonicity of the impedance peaks, is almost solely responsible. Players do prefer a strong first resonance, but this preference is relatively weak and is easily overcome by the preference for a low overall impedance (Smith *et al*., 2007).

The lowering by the horns of the transfer function at high frequencies deserves comment. The transfer function was measured in the near field of the horn and, the larger the horn diameter, the larger the area over which the radiated energy was distributed. In practice, the loudness increased with horn size.

Large horns were judged to be an 'overkill'; the instrument was satisfyingly loud and bright, but awkward to play and impractical to transport.

CONCLUSIONS

The three methods we tried were all successful in reducing in the impedance of a PVC cylindrical pipe at frequencies above 1 kHz. Deciding which method is best would ideally require ranking in blind tests by a panel of players. However, MS (an experienced player) thought the addition of a long conical horn gave the best result.

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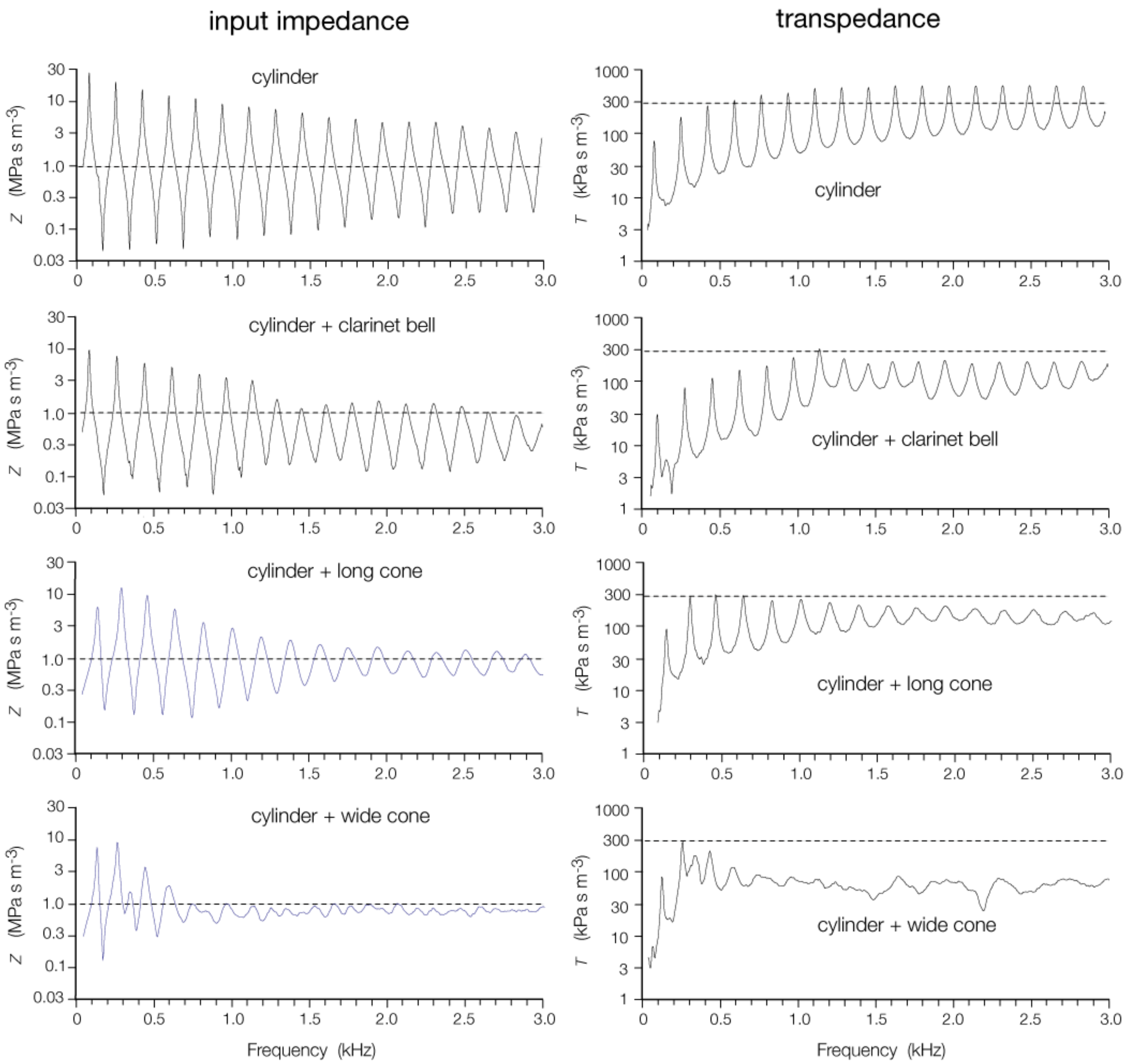

Figure 8. Semilogarithmic plots of the magnitude of the measured input impedance $Z(f)$ and transpedance $T(f)$ as a function of frequency f for a PVC tube with different horns attached to its end (see text). The horizontal dashed line for input impedance and transpedance indicate $Z(f) = 1$ MPa s m^{-3} and $T(f) = 0.3$ MPa s m^{-3} respectively.