Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Improved method of measuring reflection or impedance spectra using adapted signal spectra and resonance-free calibrations

Paul Dickens (1,2), John Smith (1) and Joe Wolfe (1)

(1) School of Physics, The University of New South Wales, Sydney 2052, Australia
(2) ResMed, Bella Vista, New South Wales 2153, Australia

PACS: 43,58.BH, 43.20.YE, 43.20.MV, 43.20.EL

ABSTRACT

Standing waves, resonances and/or singularities during measurement and calibration often limit the precision of measurements of acoustic reflection spectra and acoustic impedance spectra. This paper reviews and compares several established techniques, and then describes techniques that incorporate some or all of three features that together considerably improve precision and signal:noise ratio. The first feature is to minimise problems due to resonances by calibrating the apparatus using up to three different acoustic reference impedances that do not themselves exhibit resonances [1,2]. The second involves using multiple pressure transducers to reduce the effects of measurement singularities [1,3,4]. The third involves shaping the spectral envelope of the stimulus signal [1,2]. Here, the envelope is adjusted iteratively to control the distribution of errors across the particular measured impedance spectrum [1]. The most useful non-resonant load is the acoustically infinite waveguide, whose impedance is real and independent of frequency. We describe the performance of different approximations to the infinite waveguide including 'infinity in a box', a portable calibration load.

INTRODUCTION

Reflection and absorption spectra of acoustic products are often measured using the impedance tube arrangement. Ducts of various sorts, including musical wind instruments, are often characterised by their impedance spectrum.

Because of the importance of reflection and impedance spectra, the instrumentation techniques for their measurement are sufficiently well advanced and investigated as to have their own PACS number.

For both reflection and impedance spectra, measurements at many frequencies are made, often simultaneously. Often, the measurement consists of determining a boundary condition in the measurement plane, which is calculated for each frequency from the signals measured by two or more microphones distributed along the impedance tube or impedance head.

The present authors have contributed some improvements to this measurement technology. One of these was distributing energy among the different frequencies of measurement in such a way as to compensate for the frequency response of the transducers and ducts involved so as to achieve a flat excitation spectrum [2] or to produce an excitation spectrum designed iteratively to compensate for the frequency distribution of noise and to maximise the singal:noise ratio over the whole range [1]. Another was only using calibration loads that have no resonances in the frequency range of interest. Of these, perhaps the most useful is the semi-infinite acoustical waveguide [1,2].

While the flat spectrum of excitation has since been adopted by other researchers [5], the semi-infinite acoustical waveguide is not widely used, in part because of the perceived difficulty in making one and in verifying its performance.

The present paper very briefly reviews the different measurement techniques, listing their advantages. It also reports the properties and performance of several different approximations to the infinite waveguide.

CALIBRATION LOADS

Open and closed circuits

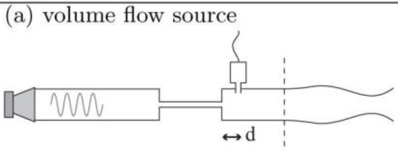
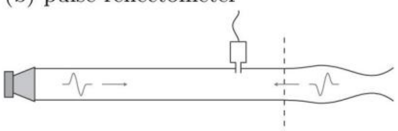
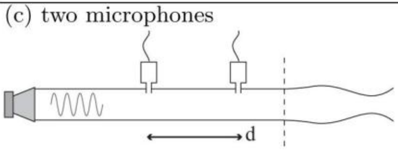
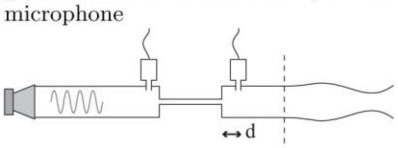
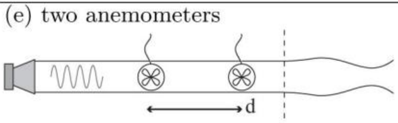
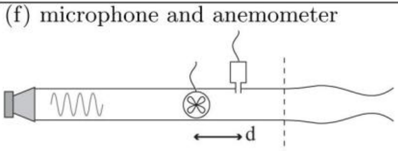
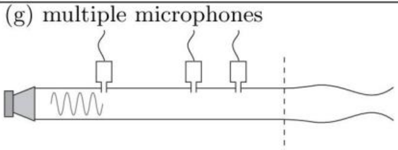
To use the familiar analogy, the acoustical open circuit ($U = 0$) is well approximated, for a sound wave in air, by a rigid block of dense material. It has very large impedance, which is often taken as infinite for the purpose of calibration.

The closed circuit ($p = 0$) is not so readily approximated. The impedance of the radiation field terminating a flanged tube, however, has been measured and modelled [6]. Its impedance is largely imaginary and, at low frequencies, has small amplitude.

Finite waveguides

Models of the impedance of a waveguide of constant cross-section and terminated by one of the impedances just mentioned are well known and may be calculated readily [7].

For short waveguides, the resonances give rise to an impedance whose amplitude varies, with frequency, over several orders of magnitude and whose phase varies over almost 180°.

Impedance Head	Singularities	Refs.	Notes
(a) volume flow source 	$kd = (2n-1)\frac{\pi}{2}$	1, 5–7	• computationally simple • requires calibration of the source • prone to errors at high $\lvert Z \rvert$
(b) pulse reflectometer 	f-range limited by pulse width	3, 4	• uses same microphone for incident and reflected wave; calibration unnecessary • accuracy limited by length of measurement duct
(c) two microphones 	$kd = (n-1)\pi$	8–15	• fewer simplifying assumptions required • computationally intensive
(d) volume flow source with upstream microphone 	$kd = (2n-1)\frac{\pi}{2}$	16–18	• signal from upstream microphone proportional to flow (for an attenuator with high impedance compared to the unknown load)
(e) two anemometers 	$kd = (n-1)\pi$	19	• computationally similar to (c) • several particle velocity sensors can be made simply with similar characteristics
(f) microphone and anemometer 	$kd = (2n-1)\frac{\pi}{2}$	20–22	• direct measurement of both pressure and flow • correction required to obtain volume flow from particle velocity
(g) multiple microphones 	vary with microphone spacings	23	• wide frequency range • increased precision

Legend: sound source; attenuator; microphone; flow sensor

Table 1: Several of the more common impedance spectrometers. (From [1]. Numbers refer to references in that paper.)

A semi-infinite waveguide

Continuing the electrical analogy, one could say that measuring acoustic impedance is harder than measuring electrical impedance for several reasons. One reason is the electrical resistor: a simple, cheap component whose impedance is predominantly real, independent of frequency and easily measured. Pass the same current through an unknown impedance and a known resistance and the (complex) ratio of voltages gives the ratio of impedances.

In a straight waveguide of constant cross-section and lateral dimension small compared to a wavelength, the acoustic pressure p and flow U in a travelling wave are related by the characteristic impedance $Z_0 = p/U$. The wave is one-dimensional, p and U are in phase, and Z_0 is purely resistive and is given by $\rho c/A$, where ρ is the density of air, c the speed of sound and A the cross-sectional area.

Unless the waveguide is terminated with an identical impedance at the frequency of the wave, there will be a reflection of the incident wave. For short waveguides, of course, the echo returns quickly, the waves in the two directions interfere constructively and destructively at different frequencies, giving impedances that vary with frequency by several orders of magnitude. If the guide is sufficiently long however, the echo is not only delayed, but is also greatly attenuated by wall losses.

So using a semi-infinite waveguide as a calibration reference offers very considerable advantages: it has no resonances, its impedance is real and independent of frequency, and no model is needed to calculate its value. Its length, however, is a significant disadvantage. So, how long need it be? And does it need to be straight? As we show below, the answers to both these questions are encouraging.

MEASUREMENT TECHNIQUES

The principal techniques have been reviewed elsewhere [8,9,1]. Here we reproduce two tables from the most recent of these (Tables 1 and 2).

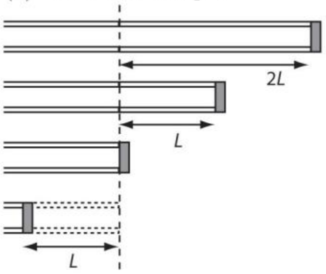
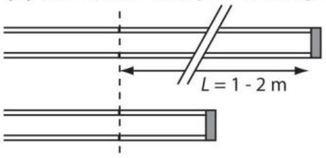
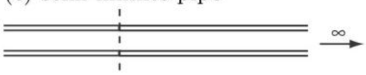
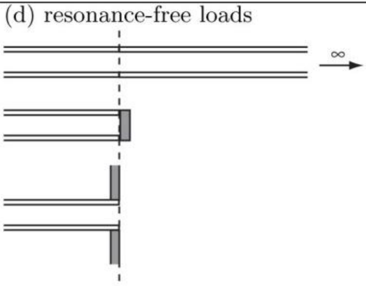
Calibration Loads	Refs.	Notes
(a) TMTC technique 	13, 15	• 'complete' calibration with three known loads • several sets of calibration loads needed to cover wide f-range • complex wavenumber need not be known if a fourth 'negative length' load is used
(b) resonance analysis of long tube 	7, 25	• after initial measurement of Z for long tube, calibration parameters determined from oscillations in α and k • complex wavenumber need not be known if an extra short tube is used • data obtained only at resonances and antiresonances of long tube—low frequency limit determined by length of tube
(c) semi-infinite pipe 	6	• almost purely resistive load—impedance insensitive to complex wavenumber • used for calibration of volume flow sources
(d) resonance-free loads 		• complete calibration as in (a) • valid for all frequencies, due to lack of resonances • the flange calibration may be omitted if a model of the impedance head is available

Table 2: Selected techniques for calibration of impedance heads. (From [1]. Numbers refer to references in that paper.)

HOW LONG IS INFINITE?

One of our first calibration standards was a straight, stainless steel pipe, 42 m in length and 7.8 mm internal diameter [2]. It was constructed from 6 m sections, the ends machined flat and joined in external sleeves. The pipe was located in the ceiling space and its length was determined by the width of the building. It is sealed at the remote end to prevent ingress by insects, and a wad of acoustic wool is inserted inside the cap.

In principle, one could make a measurement in the 250 ms before the echo returns, but this would limit the frequency precision to 4 Hz. So an echo at this frequency returns attenuated by more than 80 dB, which is an acceptable signal:noise ratio for many measurements.

At frequencies below 50 Hz however, the 4 Hz resonances of the 42 m pipe become visible as periodic artifacts with an amplitude as much as 10% in impedance magnitude. When we began a research project on the contrabassoon, whose lowest note lies below 30 Hz, a 'more infinite' reference was required.

Using the 42 m stright pipe as a reference, we measured the impedance of a 100 m rigid plastic pipe, with inner diameter 7.5 mm, arranged in a coil of diameter 470 mm with the loops in contact and a sealed termination as before. As expected, this showed weak features spaced at 4 Hz in the range below 40 Hz, due to the resonances in the 42 m calibration. It also showed weak features (about 1.5 dB in amplitude) at about 110 Hz, which we attributed to coupling between adjacent loops, with circumference = λ/2. Our solution was to add the 100 m coil to the end of the 42 m straight pipe: we expected that any reflections due to the junction between the two and to the curvature in the coils would be attenuated along the straight pipe.

To determine the effectiveness of this system, we used it for calibration, then measured the impedance spectrum of an open, cylindrical pipe, also with 7.8 mm inner diameter, but with length 300 mm, and consequently having resonances well above the frequency range of interest. Examination of the impedance spectrum over the range showed no discontinuity at 110 Hz, any features spaced at 4 Hz (reflections returning from the junction) or at 0.8 Hz had amplitudes no more than about 1%.

Our impedance heads are usually made to match exactly an 'infinite' waveguide reference load. For measurements of ducts whose apertures do not match that of the impedance head, corrections may be made. However, these corrections become less accurate with increasing mismatch [10]. For that reason, additional 'infinite' references have been installed, with different internal diameters (and lengths): 3.0 mm (42 m), 15.0 mm (97 m) and 26.2 mm (197 m). The 3.0 mm pipe is completely straight. The longer pipes are straight for the first 35 m and then have bends with a 5 m radius that allow them to follow the corridors of the building. They are placed inside a larger tube and completely hidden in the ceiling space above the corridors of the building – see figure. The inputs to the pipes project through one of the laboratory walls with their values at 25 °C indicated by the resistor colour code.

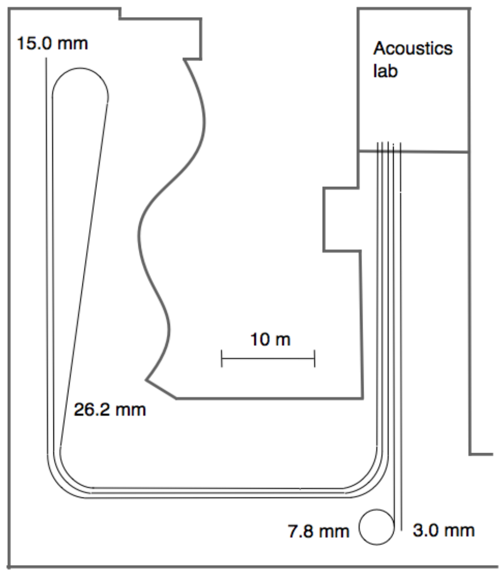


Figure 1: A plan of the physics building at UNSW, showing the acoustics laboratory and the 'infinite' waveguides installed in the ceiling space. The 7.8 mm guide is terminated with a 100 m coil. The 26.2 mm guide has both ends accessible in the laboratory.

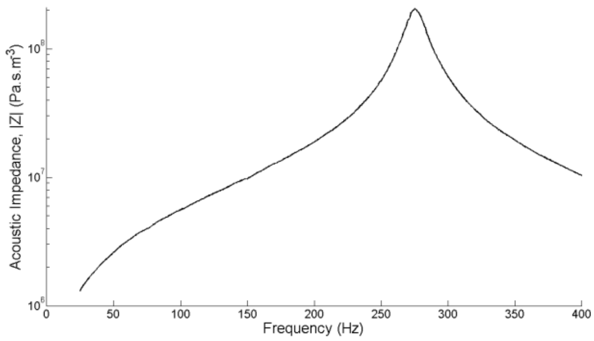


Figure 2: The low frequency impedance spectrum of an open pipe, 300 mm long and 7.8 mm inner diameter, measured using a head calibrated on a reference comprising 42 m straight pipe and a coiled 100 m hose of inner diameters 7.8 and 7.5 mm respectively. The measurement was made from 25 to 4000 Hz, but only the low frequency range is shown here, to exhibit the absence of features spaced at 4 Hz, such as might be produced by reflections at the junction. Points on this graph are spaced at 44.1 kHz/2^{16} = 0.6 Hz, giving the impression of a continuous curve.

Further measurements of simple pipes using this technique are given elsewhere [1]. We have also used the technique for measuring the impedance spectra of musical instruments [2,11-13] and that of the vocal tract of musicians playing them [14-17].

Of the methods reviewed in Table 1, we usually use method g (the three microphone technique) for precision measurements of passive systems, because of its high signal:noise ratio. For the measurements of the impedance spectra of the vocal tracts of wind instrument players, however, the relatively low output impedance of the impedance head perturbs the measurement. Players cannot produce some notes and effects when the impedance of their vocal tracts is shunted by an impedance head made from a waveguide. For these applications we used the current source method (a in Table 1), which of course has a high output impedance. For this method, the infinite waveguide is a particularly useful calibration, and the only one required. To first order, the unknown impedance spectrum is just the ratio of the measured pressure spectrum to the calibration pressure spectrum. (Improved results are obtained if the output admittance of the source is subtracted [2].)

A practical infinite waveguide: Infinity in a box

A portable infinite waveguide (PIW) was also built and calibrated against our standards. The PIW was intended to serve as a portable calibration reference for acoustical measurements of medical devices made by the sleep and respiratory medicine company ResMed. It was also intended to accommodate mean flow with a calibrated flow resistance. The PIW (Figure 3) consists of a 50 m length of PVC irrigation hose with circular cross-section of 19 mm internal diameter. The hose was coiled and placed inside a vented timber box and was mechanically isolated from the internal walls of the box with acoustic damping materials. The hose was terminated with a plug of foam, which serves the purposes of regulating the DC flow resistance, reducing acoustic reflections and preventing the ingress of foreign materials and insects.

Figure 3: The portable infinite waveguide built by ResMed for calibration of and verification of acoustic testing procedures. The timber box is 800 mm square and 210 mm deep.

The input impedance of the PIW was measured on a system as described in [1] that was calibrated against the 15.0 mm (97 m) calibration pipe at UNSW. Measured between 200 Hz and 4 kHz, the input impedance was found equal to $\rho c/A$ with a precision better than 5% in magnitude.

CONCLUSIONS

The infinite waveguide provides a useful, resonance-free calibration load for current source measurements [1,2]. Along with an acoustic open circuit, it provides a well characterised calibration for multiple microphone techniques [1]. A practical, portable waveguide that is acoustically infinite over all but very low frequencies may be built cheaply and easily. The signal:noise ratios of measurements of acoustic impedance and reflection spectra can be much improved by shaping the signal spectrum to concentrate energy at frequencies where the gain of the system is weak or where singularities appear [1,2].

REFERENCES

1 P. Dickens, J. Smith and J. Wolfe, "Improved precision measurements of acoustic impedance spectra using resonance-free calibration loads and controlled error distribution", *J. Acoust. Soc. America*, **121**, 1471-1481 (2007)

2 J.R. Smith, N. Henrich and J. Wolfe, "The acoustic impedance of the Boehm flute: standard and some non-standard fingerings" *Proc. Inst. Acoustics* **19**, 315-330 (1997)

3 V. Gibiat and F. Laloë, "Acoustical impedance measurements by the two- microphone-three-calibration TMTC method", *J. Acoust. Soc. Am*. **88**, 2533–2545 (1990)

4 S.H. Jang, S.H. and J-G. Ih, "On the multiple microphone method for measuring in-duct acoustic properties in the presence of mean flow", *J. Acoust. Soc. Am*. **103**, 1520-1526 (1998)

5 X. Jing and X. Sun "Flat-response sound source technique for using the two-microphone method in an impedance tube (L)" *J. Acoust. Soc. Am*. **122**, 2519-2521 (2007)

6 J.-P. Dalmont, C. J. Nederveen, and N. Joly, "Radiation impedance of tubes with different flanges: Numerical and experimental investigations," *J. Sound Vib*., **244**, 505–534 (2001)

7 N.H. Fletcher and T.D. Rossing, *The Physics of Musical Instruments*, (Springer-Verlag, New York, 1998)

8 A. H. Benade and M. I. Ibisi, "Survey of impedance methods and a new piezo-disk-driven impedance head for air columns," *J. Acoust. Soc. Am*., **81**, 1152–1167 (1987)

9 J.-P. Dalmont, "Acoustic impedance measurement. I. A review," *J. Sound Vib*. **243**, 427–439 (2001)

10 N.H. Fletcher, J. Smith, A.Z. Tarnopolsky and J. Wolfe "Acoustic impedance measurements – correction for probe geometry mismatch" *J. Acoust. Soc. Am.* **117**, 2889-2895 (2005)

11 P. Dickens, R. France, J. Smith, and J. Wolfe, "Clarinet acoustics: introducing a compendium of impedance and sound spectra". *Acoustics Australia*, **35**, 17-24 (2007)

12 J.M Chen, J., Smith and J. Wolfe, "Saxophone acoustics: introducing a compendium of impedance and sound spectra" *Acoustics Australia*, **37**, 18-23 (2009)

13 Music Acoustics, "Introduction to brass acoustics", www.phys.unsw.edu.au/jw/brassacoustics.html Accessed 6/6/2010

14 A. Tarnopolsky, N. Fletcher, L. Hollenberg, B. Lange, J. Smith and J. Wolfe, "The vocal tract and the sound of a didgeridoo". *Nature*, **436**, 39 (2005)

15 A. Tarnopolsky, N. Fletcher, L. Hollenberg, B. Lange, J. Smith and J. Wolfe, "Vocal tract resonances and the sound of the Australian didjeridu (yidaki) I: Experiment", *J. Acoust. Soc. Am.*, **119**, 1194-1204 (2006)

16 J.M Chen, J., Smith and J. Wolfe, "Experienced saxophonists learn to tune their vocal tracts", *Science*, **319**, 726 (2008)

17 J.M Chen, J., Smith and J. Wolfe, "Pitch bending and *glissandi* on the clarinet: roles of the vocal tract and partial tone hole closure" *J. Acoust. Soc. Am.*, **126**, 1511-1520 (2009)