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Impedance Tube Measurements – A Comparative Study of Current Practices*

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Several methods presently exist for obtaining acoustical measurements of materials using an impedance tube. Three methods which offer both accuracy and convenience were chosen for this study. A brief summary of the theories of these methods and a comparative experimental study of them using the same apparatus and testing materials are presented to show their relative merits.

Introduction

The tube method based on measuring the standing wave ratio (SWR) for specific acoustic impedance measurements is well known. An account of the different extrapolation procedures for the SWR method, including a new proposal, has been given by Kathuriya and Munjal.¹ Although these procedures give very accurate results, they are tedious and time-consuming. In Ref. 2, the author proposed a faster procedure that uses an iteration scheme based on the sound pressure measurements at a minimum pressure location and one other point and called it the improved standing wave ratio (ISWR) method.

Another approach to improving the SWR method, as suggested by Kathuriya and Munjal, involves measuring the sound pressure at three or more points (not necessarily the minimum or maximum pressure locations).^{3,4} However, the technique had certain inherent difficulties and weaknesses.⁵ The remedy proposed in Ref. 5 requires locating two minimum pressure points for determining the phase angle of the reflection coefficient. The magnitude is then obtained by sound pressure measurements at a few other points. This approach might not seem to be too attractive for measurements in a stationary medium, nonetheless, it remains a convenient measurement method for duct acoustics involving fluid flow.

A number of alternatives to the SWR method have been proposed and summarized by Singh.⁶ Of particular interest to

absorption and impedance measurements of acoustical materials has been the two-microphone transfer function (TF) method introduced by Seybert and Ross and further developed by Chung and Blaser.^{7,8} The TF method has now been standardized as ASTM E 1050 without consideration of the effect of tube attenuation.⁹ In Ref. 10, the author extended the TF formulation to include the tube attenuation.⁹ The TF method has also been extended to include the effect of mean flow for duct and muffler applications by Chung and Blaser and M. Åbom and H. Bodén.^{11,12} In Ref. 13, M.L. Munjal and A.G. Doige considered both effects simultaneously. The outcome illustrates that the TF method is a special case of a more general procedure, the multi-point least-square (LS) method proposed by Fujimori, Sato, and Miura.¹⁴ Both methods offer very significant savings in time if deterministic signals such as a pure tone or a broadband pseudorandom sequence are used.^{15,16} Another advantage is that conventional standing wave tubes with a single traversing probe-tube microphone can be used without modification since the sound pressures at the different locations can be measured sequentially. Phase matched microphones or elaborate calibration procedures are not required.

In Ref. 18, the author found through experiment that for precise measurements with the TF method, a pure-tone excitation should be used with properly chosen microphone loca-

tions. His recommendation is that one of the microphone positions should be close to a minimum pressure point of the standing wave pattern and that the choice of the other point is not critical as long as the separation is not close to a half wavelength. However, recent theoretical investigations of Bodén and Åbom and Banks-Lee and Peng suggest one-quarter wavelength as the optimum separation of the microphones to minimize the effect of errors in the measured input data.^{19,20} We will label this special application of the TF method the improved transfer function (ITF) method.

A brief account of the least-square method, the transfer function methods, and the improved standing wave ratio method for measurements in a stationary medium together with an experimental study of their performances will be presented in this paper. Measurement with flow is outside the scope of this paper and will not be considered here.

Theoretical Background

For the readers' convenience, a short review of the relevant formulas of the methods will be given here. Those who are interested in the details can refer to the cited references. At any driving frequency ω , the complex acoustic pressure of the one-dimensional acoustic field within an impedance tube at a location x can be expressed by:

$$P = (A e^{\gamma x} + B e^{-\gamma x}) e^{i\omega t}, \quad (1)$$

where A and B are the complex amplitudes of the incident and the reflected waves, respectively (Fig. 1). The propagation constant is γ and for small attenuation, γ is given by:

$$\gamma = i\omega/c + a \quad (2)$$

where c is the speed of sound and a is the attenuation constant. The procedure proposed by Fujimori and his colleagues is to curve fit the complex pressures at a number of locations with the standing wave pattern of Eq. (1) using the least-square (LS) method.¹⁴ The attenuation constant is assumed known and the complex reflection coefficient, R , is given by:

$$R = \frac{B}{A} = \frac{\begin{vmatrix} \sum e^{(\gamma + \gamma^*)x_n} & \sum P_n e^{\gamma^* x_n} \\ \sum e^{(\gamma - \gamma^*)x_n} & \sum P_n e^{-\gamma^* x_n} \end{vmatrix}}{\begin{vmatrix} \sum P_n e^{\gamma^* x_n} & \sum e^{-(\gamma - \gamma^*)x_n} \\ \sum P_n e^{-\gamma^* x_n} & \sum e^{-(\gamma + \gamma^*)x_n} \end{vmatrix}} \quad (3)$$

where $*$ signifies complex conjugate and the summations are performed over the index n of the measurement locations.

As pointed out by Pope, the above formulation may be reduced to that of the transfer function (TF) technique when only two locations are used.¹⁷ That is, Eq. (3) can be reduced to:

$$R = \{[H_{12} - e^{-\gamma S}] [e^{\gamma S} - H_{12}]^{-1}\} e^{2\gamma L} \quad (4)$$

where $H_{12} = P_2/P_1$ is the complex transfer function, s is the microphone separation, and L is the distance of the first microphone from the sample according to the convention of Ref. 8. Without the tube attenuation terms, the TF formulation can easily be reduced to that of the conventional standing wave ratio (SWR) method if the two points chosen coincide with the minimum and the maximum pressure points. Otherwise, the exact phase formulation has to be rederived from Eq. (1).

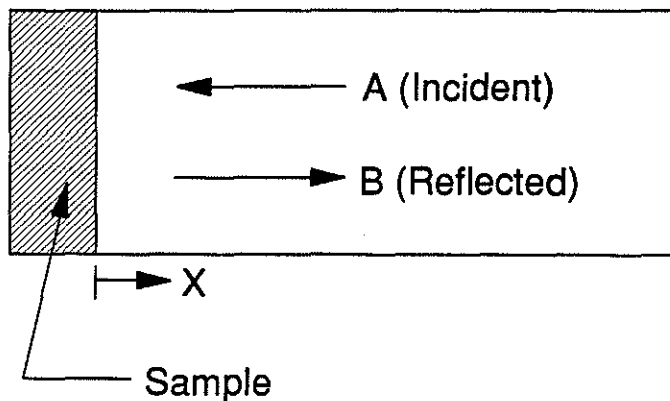


Figure 1. Sound field in the impedance tube

The improved standing wave ratio (ISWR) method proposed by the author uses an iteration scheme based on the exact plane wave analysis of the standing wave pattern in the tube.² Starting from Eq. (1), it can be shown that:

$$\varphi = -(2m+1)\pi + 2kd + \sin^{-1}[(a/2k|R|)(e^{2ad} - |R|^2 e^{-2ad})] \quad (5)$$

and

$$\frac{|P_{\min}|^2}{|P|^2} = \frac{e^{2ad} + |R|^2 e^{-2ad} + 2|R| \cos(2kd - \varphi)}{e^{2ax} + |R|^2 e^{-2ax} + 2|R| \cos(2kx - \varphi)}, \quad (6)$$

where $|R|$ and φ are the magnitude and phase of the complex reflection coefficient, R , respectively, and d is the distance from the surface of the sample to the m th pressure minimum. The wavenumber is $k = \omega/c$. Assuming that the tube attenuation is known, two sound pressure measurements (at the minimum and one other point) are all that is required for solving both $|R|$ and φ of Eqs. (5) and (6). A detailed account of the iteration procedure is given in Ref. 2 or the appendix of Ref. 18. Similar to the improved transfer function (ITF) method, the two points should not be close to a half wavelength.²⁰

Although only pure-tone excitation can be used for the ISWR and the ITF methods, both pure-tone and broad-band excitation can be used for the TF and the LS methods.

Apparatus and Test Procedures

In this study, both pure-tone and broad-band excitation were used. For the latter, a deterministic broad-band signal was used so that the same sequential sampling technique of sound pressure at different locations using a single microphone can be applied for the complete experimental investigation without the requirement of phase matched microphones or other elaborate calibration procedures.¹⁶ Although the data acquisition instrumentations were different for the two types of signals, the same impedance tube apparatus under identical conditions was used. The impedance tube is a 107-cm-long brass tube with an internal diameter, D , of 5.72 cm, giving an upper frequency limit of 2500 Hz. With a wall thickness of 0.47 cm, the tube is sufficiently massive and rigid. The tube was driven by a horn driver mounted on the side to allow a probe-tube microphone to traverse the center line. The microphone used was a 6.4 mm Brüel & Kjær condenser microphone. No unwanted vibrational problem was detected when the system was excited by a slowly sweeping sine wave from 100 to 2500 Hz. A thermistor with a digital thermometer was used to monitor the inside temperature of the tube for the calculation of the sound speed. The attenuation constant was set at $2.2032 \sqrt{f} / cD$, as suggested in Ref. 21.

Figure 2 shows the measurement system for pure-tone excitation. An HP 3325A function generator was used to provide a very stable sine wave for the experiment. The magnitude and phase of the acoustic pressure at different locations were measured sequentially with an Ithaco Dynatrac 3 lock-in amplifier using the driving signal as the reference. The lock-in amplifier has a 0.1 deg resolution for the phase measurements. The dc-outputs that correspond to the magnitude and phase information from the lock-in amplifier were sampled by a 12 bit A/D converter and the computations were performed with special Fortran programs on an IBM AT-compatible microcomputer.

Figure 3 depicts the arrangement for broad-band excitation. A periodic random sequence was used as a deterministic broad-band signal so that the complex acoustic pressures at different locations could also be measured sequentially with the traversing microphone. In this case, the magnitude and phase of the acoustic pressure as a function of frequency could be determined in one single measurement using digital signal analysis from one period of the microphone signal. Detailed discussion about this signal and the required digital processing technique can be found in Refs. 22 and 23. Although the technique is not sensitive to external electrical or acoustical background noise because of the cross-correlation procedure involving the driving and the microphone signals in the digital signal processing, ten averages have been used at each microphone location to provide additional improvement of the signal to noise ratio. Since the sequential sampling technique used in the present investigation relies on the assumption that the system remains unchanged during the experiment, it is important that the standing wave field be sampled in the shortest possible time. Thus it is not advisable to take too many unnecessary averages. For the present experiments, an IBM AT-compatible microcomputer was used together with an A/D board (Mi-

croWay A2D-160), which has a built-in sequence generator and a software package written in assembly language for computing the magnitude and phase of the complex acoustic pressures. The graphic equalizer was used to reduce the adverse effect of the tube resonances and provide a more uniform response over the frequency range.

Four specimens were used in this comparative study. The first specimen was the hard reflecting surface of a 1.27 cm thick Bakelite disk. It was chosen as a calibrating device for the experiment as the reflection coefficient is known to be real and equal to 1. The second specimen was a 4.9 cm thick open cell plastic foam. The third specimen was a dense carpet with a 5 mm thick pile. The fourth specimen was a resonant absorber consisting of a 9 mm thick perforated plate backed by a 35 mm air space. The plate has three 3.2 mm diameter holes arranged at the corners of a 33 mm side equilateral triangle. No particular attention has been paid to the details of the mounting of the specimen in this investigation since we were only interested in the relative repeatability of the results using different techniques on the same specimen. However, it is important to follow the mounting procedure recommended by the standards for accurate acoustical measurements of absorptive materials.^{9,21}

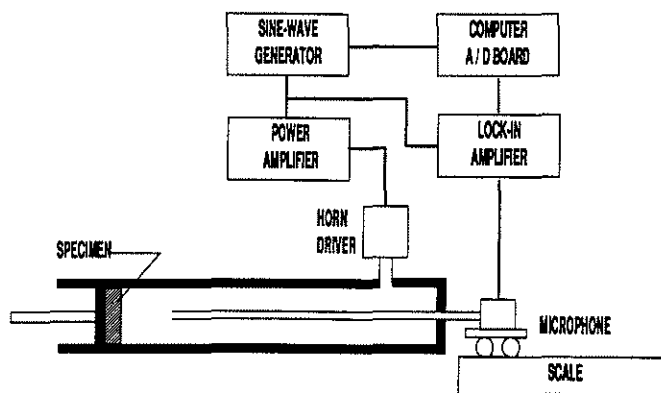


Figure 2. Apparatus for pure-tone excitation experiments

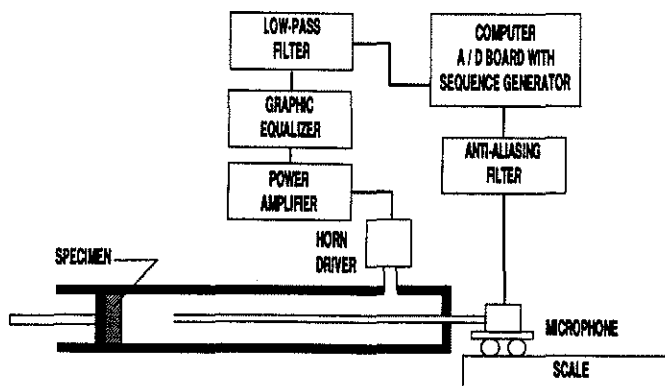


Figure 3. Apparatus for broad-band excitation experiments

Results and Discussions

Pure-Tone Excitation. Figure 4 summarizes the results of five different investigations with the hard reflecting surface using pure-tone excitation at fifteen 1/3-octave center frequencies. The five cases are:

- (1) improved standing wave ratio (ISWR) method;
- (2) improved transfer function (ITF) method with one microphone position near a minimum pressure point and the other 0.24 wavelength apart;
- (3) fixed least-square (FLS) method using three fixed positions, 6, 9, and 12.1 cm from the specimen surface;
- (4) semi-improved least-square (SILS) method using three positions, with two positions separated by a half-wavelength and one other position; and
- (5) improved least-square (ILS) method using three positions, with two positions separated by a half-wavelength and the third position at the minimum pressure point.

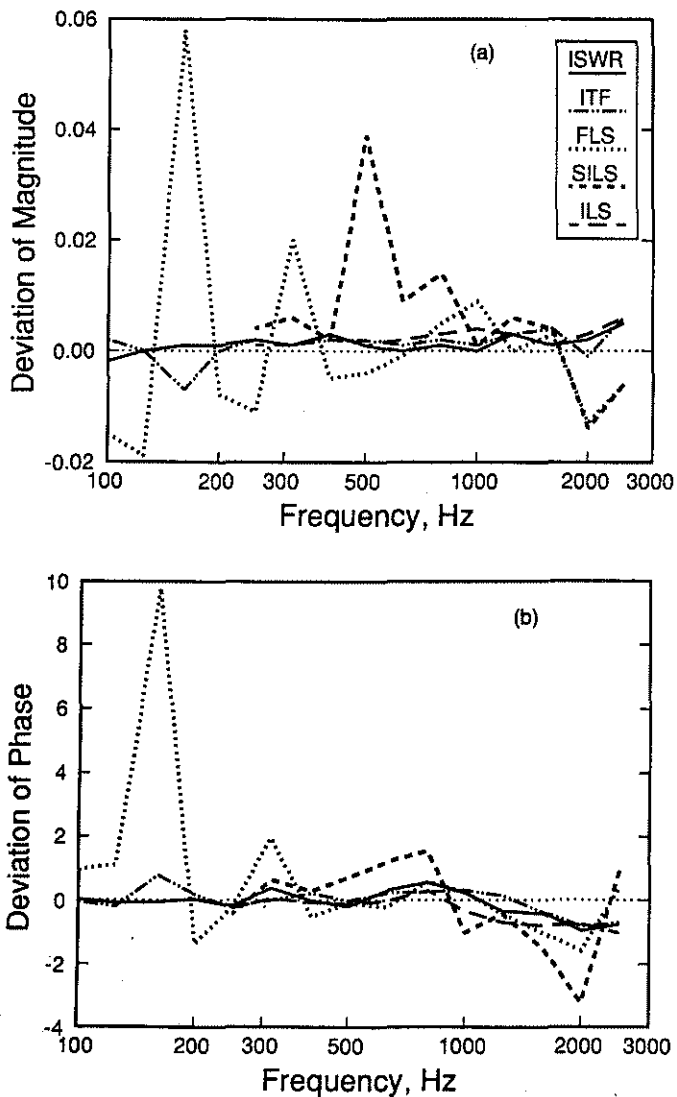


Figure 4. Deviation from theoretical values for the magnitude and phase of the complex reflection coefficient of a hard reflecting surface measured by different methods using pure-tone excitation

In Fig. 4, deviations in both magnitude and phase of the complex reflection coefficient, R , from the known values of the hard reflecting surface were plotted for the five different cases. Results indicate that both the ISWR (solid curve) and ITF (chain-dotted curve) methods give very precise results with pure-tone excitation.

The accuracy of the LS method depends upon the positions chosen, as shown by the results of the three different applications of this method. The worst case involved an arbitrary choice of the microphone positions; see the dotted curve of the FLS case. It is interesting to note that even when two of the positions are separated by a half-wavelength, the results are accurate if the third point is chosen at the pressure minimum position; see the long dashed curve of the ILS method. The length of the tube limits the low frequencies to 250 Hz for both the ILS and the SILS methods. The short dashed curve of the SILS method indicates that the results became less precise if the third point is chosen at a location other than the minimum pressure point.

Without this half-wavelength restriction, the least-square method can perform better than the transfer function method for broad-band excitation applications, as confirmed by results presented in the next section. For pure-tone excitation, it offers no advantage over the improved transfer function method.

Figure 5 shows the differences in magnitude and phase of the complex reflection coefficients, R , of the other three specimens measured by the improved standing wave ratio method and the improved transfer function method. There is very little difference in the measured magnitude and phase of R except at frequencies around the peak resonant absorption of the foam and the resonant absorber specimens; see Figs. 7 and 8 of the next section for the acoustical characteristics of these specimens. More than one degree difference in the measured phases of R was observed. However, these phase differences did not translate into significant differences in the computed normal specific acoustic impedance ratios, Z , as shown in Fig. 6 for the foam specimen. In Fig. 6, the solid circles represent results of the ISWR method and the open squares represent those of the ITF method. Also, they have no effect on the computed absorption coefficient which depends only on the magnitude of R .

With our experimental set-up, it would take more than 60 minutes to perform the standard SWR method for fifteen discrete frequencies. The time was reduced to about 20 minutes for the improved SWR method and 15 minutes for the improved transfer function method.

Broad-Band Excitation. Figure 7(a) shows the magnitude of the reflection coefficient, R , of three specimens obtained by the two point transfer function method using broad-band excitation. The solid curve depicts the average value from seven sets of measurements with different microphone positions and the shaded area shows the range of results at different frequencies from 100 to 2500 Hz with a fixed frequency resolution of 10 Hz. The choice of the microphone positions was somewhat arbitrary except that the separation of each pair was less than 6.8 cm (half-wavelength at 2500 Hz). The actual values are tabulated in Table I. Theoretical analysis of Refs. 19 and 20 and ex-

perimental results of Refs. 16 and 18 indicate that it is not possible to find a single pair of microphone positions to cover the whole frequency range with the same accuracy. This is certainly an inherent weakness of the ASTM E1050 standard.

A similar plot of results obtained by the least-square method using seven sets of seven positions each is shown in Fig. 7(b). The choice of the microphone positions was also arbitrary here. However, there is no half-wavelength restriction for this case. The actual positions used are tabulated in Table I. Comparison of these two sets of results shows that, with broad-band excitation, the LS method is better than the TF method since the LS results showed less scatter between different runs. This is supported by additional phase results of R shown in Figs. 8(a) and (b). Although not presented here, the computed standard deviations for both the magnitude and phase from the seven sets of

measurements show much lower values for the LS method, especially at low frequencies from 100 to 500 Hz. With our experimental set-up, it took less than 2 minutes to perform one set of the two-point transfer function measurement and slightly more for one set of the seven-point least-square method measurement at 241 frequencies.

In general, results obtained by the least-square method compared well with those obtained by the improved standing wave ratio or the improved transfer function methods for acoustical materials with high absorption. For comparison, the computed normal specific acoustic impedance ratios, Z , of the foam specimen from the average magnitude and phase of R has been plotted in Fig. 6; see the chain-dotted curve. The agreements with results obtained by the ISWR and ITF methods are good except at frequencies below 200 Hz where the absorption is

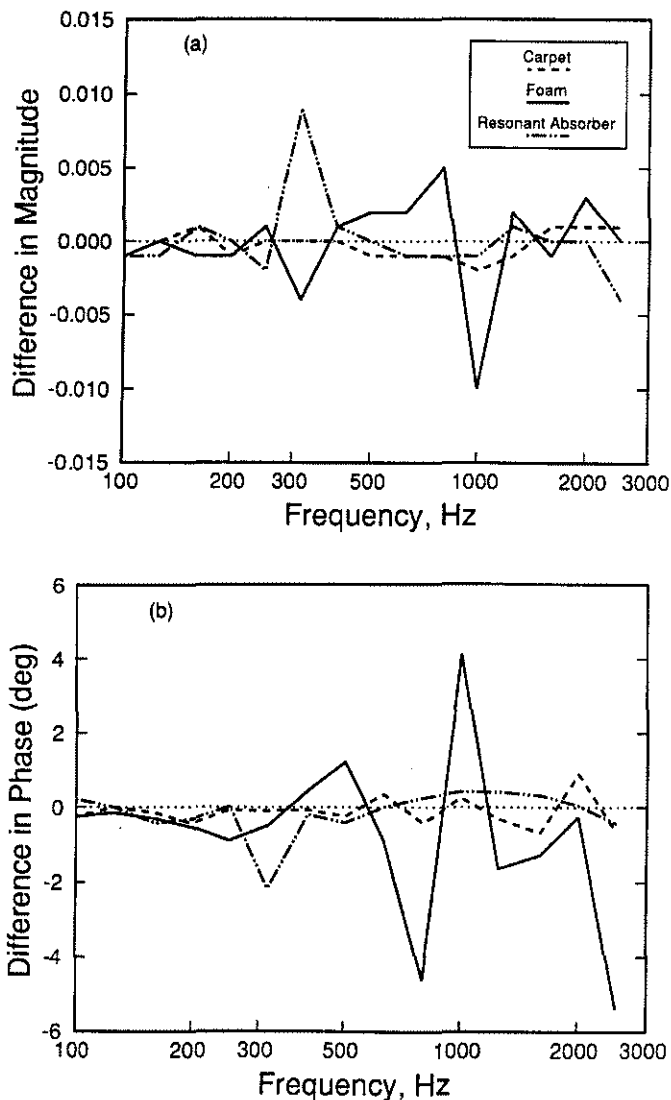


Figure 5. Differences in magnitude and phase of the complex reflection coefficient of three different specimens measured by the improved standing wave ratio method and the improved transfer function method using pure-tone excitation

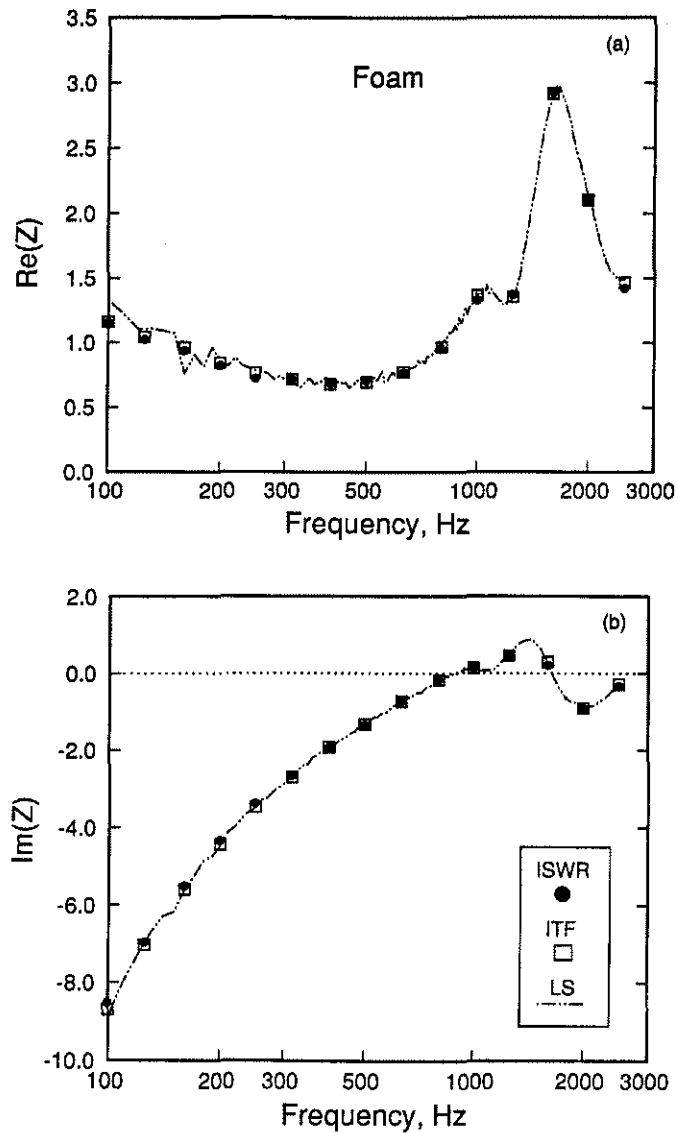


Figure 6. Comparison of normal specific acoustic impedance ratio, Z , obtained by three different methods: solid circles = improved standing wave ratio method with pure-tone excitation; open squares = improved transfer function with pure-tone excitation; chain-dotted curve = least-square method with broad-band excitation

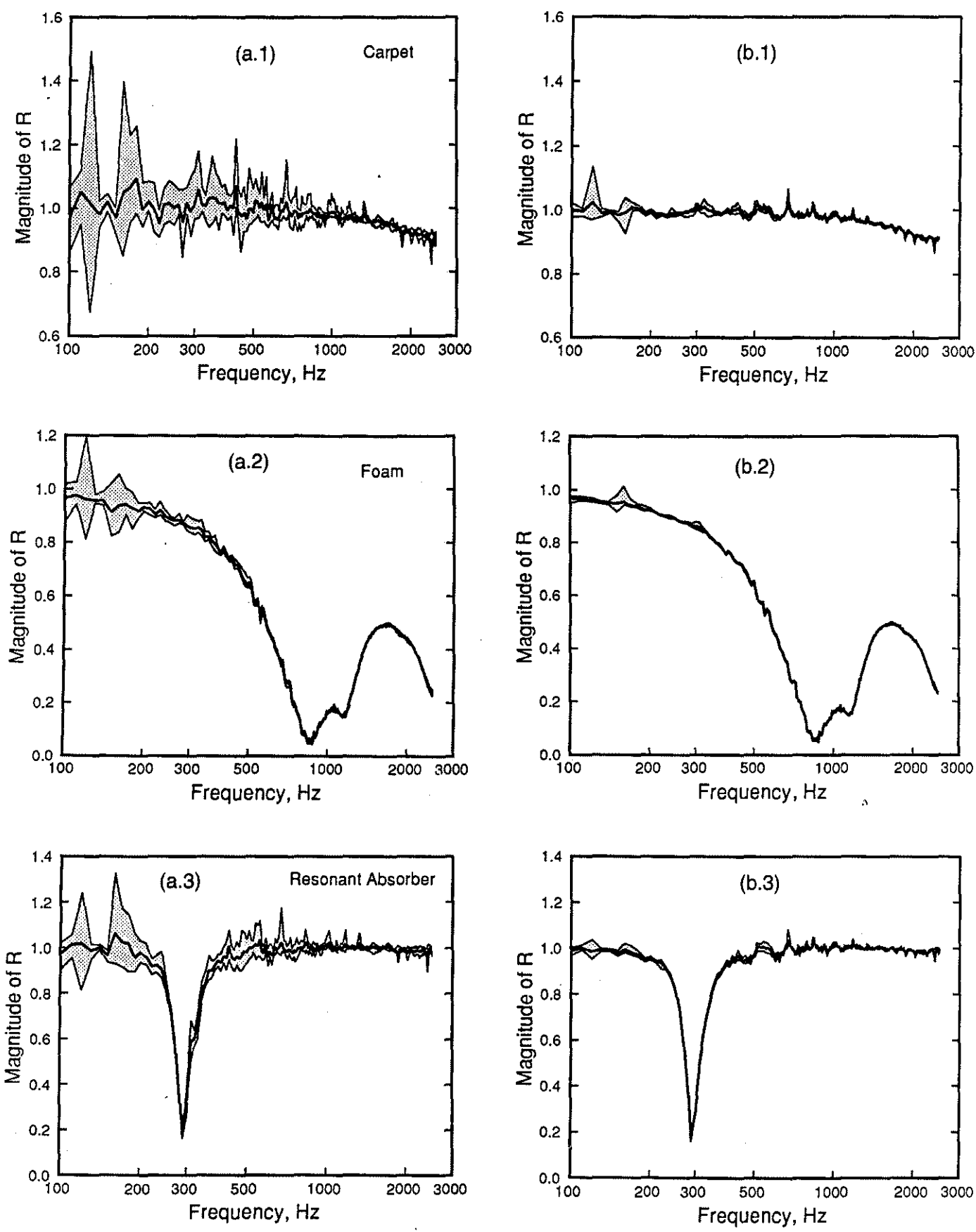


Figure 7. Comparison of the magnitude of the complex reflection coefficient of three different specimens determined by (a) the transfer function method and (b) the least-square method using broad-band excitation; solid curve = average result; shaded area = range

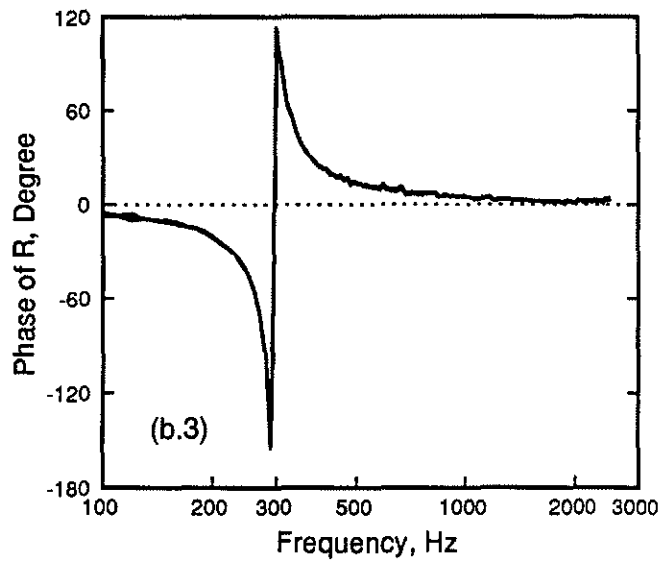
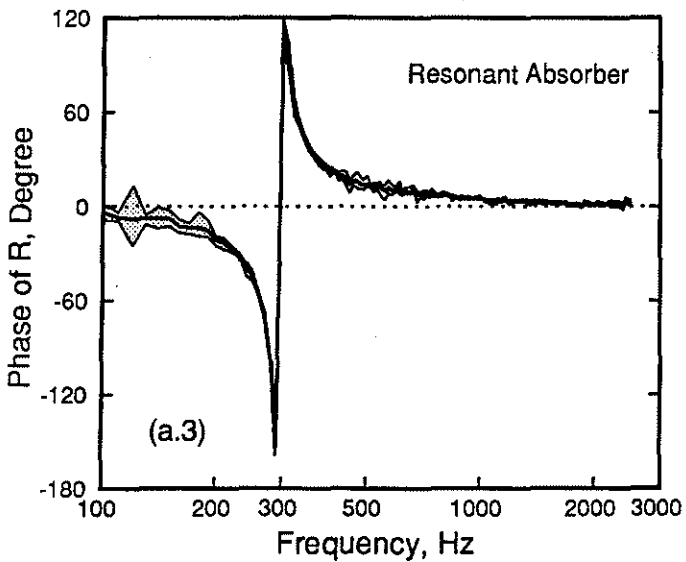
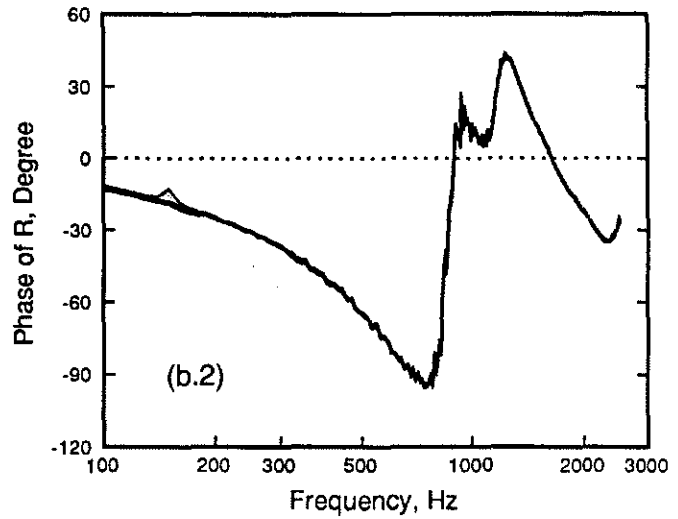
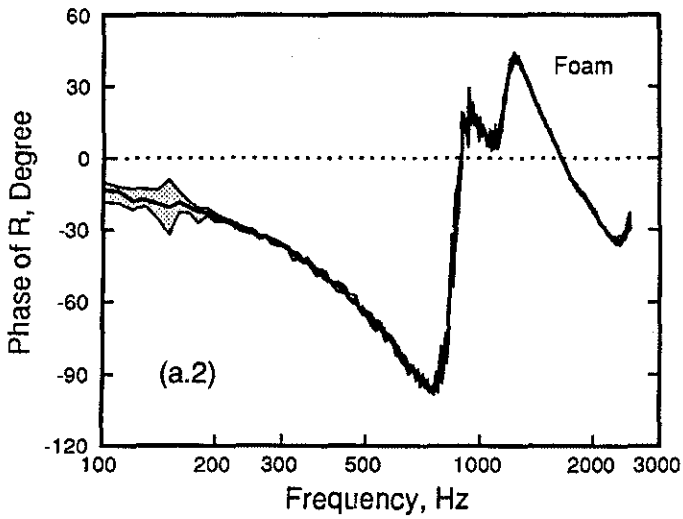
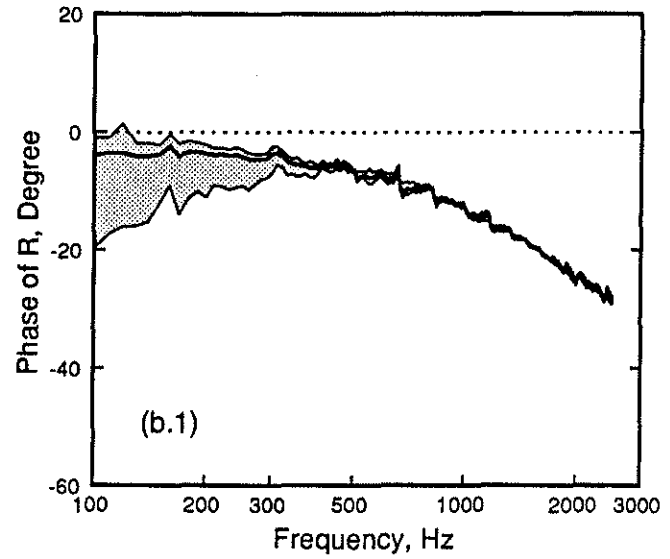
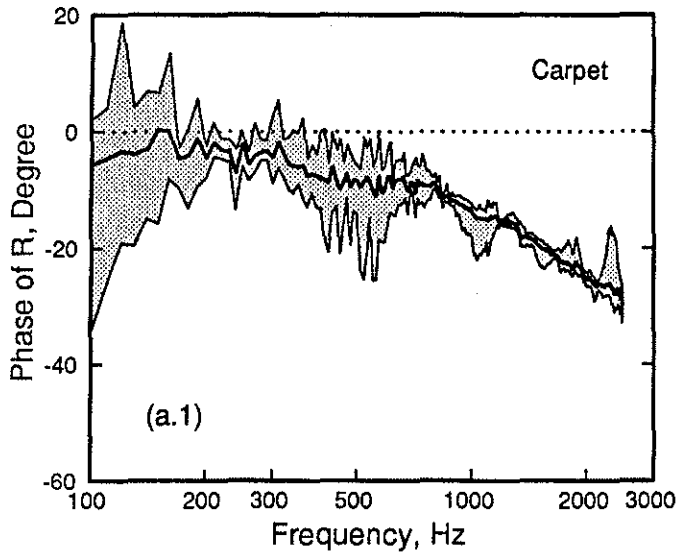


Figure 8. Comparison of the phase of the complex reflection coefficient of three different specimens determined by (a) the transfer function method and (b) the least-square method using broad-band excitation: solid curve = average result; shaded area = range

TABLE I
MICROPHONE POSITIONS USED IN THE TWO-POINT
TRANSFER FUNCTION METHOD AND THE SEVEN-POINT
LEAST-SQUARE METHOD*

Set No.	2 Point TF Method		7 Point LS Method						
1	5.9	9.7	6.0	8.0	9.5	11.0	12.7	15.0	18.5
2	6.7	10.9	6.5	9.0	13.0	16.3	27.0	41.0	55.0
3	7.2	12.4	7.0	10.5	14.5	17.8	32.0	45.0	57.0
4	20.7	26.0	20.0	22.0	24.4	27.5	29.3	32.6	35.0
5	22.5	27.2	21.0	23.0	26.3	31.5	37.5	42.7	55.0
6	30.5	36.2	30.0	33.0	37.2	40.5	44.0	47.7	51.2
7	41.5	47.0	40.0	43.5	48.0	53.0	58.2	63.5	68.0

*Distances, given in cm, were measured from the surface of the specimen.

low. Figure 7(b) shows that, for very low absorption, the measured magnitude of the reflection coefficient, R , incorrectly exceeded the value of 1 at a number of frequencies for both the carpet and the resonant absorber specimens.

Conclusion

The comparative study reported here shows that the improved transfer function method with pure-tone excitation is a simple and very precise method for impedance tube measurements provided that the microphone positions are properly chosen for each individual frequency: one close to a pressure minimum point and the other approximately a quarter-wavelength apart. It is better than the standing wave ratio method or its improved version because it does not require locating a minimum pressure point exactly.

With broad-band excitation, the least-square method using a number of positions (around seven) offers a quick but slightly less accurate way of determining the absorption properties of materials at many frequencies. Besides being more accurate, it is superior to the two microphone transfer function method because there is no half-wavelength limitation in choosing the microphone positions. Because of the quarter wavelength requirement for optimum microphone separations, the broad-band excitation methods will always be less accurate than the pure-tone excitation techniques.

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