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RÉSUMÉ

En utilisant une séquence pseudoaléatoire périodique comme source de bruit, on peut appliquer la technique de fonction de transfert à l'aide de deux microphones pour mesurer, au moyen d'un seul microphone, l'impédance et l'absorption dans un tube d'impédance, éliminant ainsi la procédure élaborée d'étalonnage et toute erreur attribuable à la non-correspondance des phases. Les résultats obtenus grâce à la technique proposée se comparent avantageusement à ceux donnés par la méthode courante du taux d'ondes stationnaires.

Transfer function technique for impedance and absorption measurements in an impedance tube using a single microphone[a)]

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Using a periodic pseudorandom sequence as the noise source, it is possible to implement the two-microphone transfer function technique for impedance and absorption measurement in an impedance tube with a single microphone, thereby eliminating the elaborate calibrating procedure and any error associated with phase-mismatching. Results obtained by the proposed procedure compared well with those obtained by the standard standing-wave-ratio method.

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INTRODUCTION

The advent of digital electronics has revolutionized many acoustic measurements. One advanced measuring technique is the two-microphone transfer function method of measuring in-duct acoustic properties using random excitation. It was introduced by Seybert and Ross[1] and further developed by Chung and Blaser.[2] Applications of this technique for measuring acoustic properties of tube or duct systems have been reported by several authors.[3–6] The new technique is claimed to be about 40 times faster than the conventional standing-wave-ratio (SWR) method.[2] It requires, however, a pair of phase-matched microphones, or elaborate calibrating procedures.

Recently, Fahy[7] demonstrated the possibility of using a single microphone for this technique. Independently, Chu[8] also came up with the same idea for more general applications, including those involving sound intensity measurements. A detailed investigation of the single-microphone transfer function technique for impedance and absorption measurements in an impedance tube is reported in this paper.

I. REVIEW OF THE TECHNIQUE

In 1977, Seybert and Ross[1] proposed a two-microphone random excitation method for determining normal acoustic properties in a tube, including the effect of a mean flow. In this method, the auto-spectral densities and the cross-spectral density of two microphone signals are used in a set of simultaneous equations to deduce the corresponding spectral functions of the incident and reflected waves. The impedance can be calculated subsequently from these spectral functions.

In 1980, Chung and Blaser[2] derived a concise and closed-form expression relating the complex reflection coefficient to the measured transfer function of the acoustic pressures at two microphone positions. Their formulation is based on the impulse–response function and on the assumption of a stationary random process. Chu[9] derived a similar result using the traditional single-frequency approach. He was able to include the tube-attenuation effect, which was ignored in the previous analyses. The complex reflection coefficient R of a specimen located at one end of an impedance tube (Fig. 1) is related to the transfer function H_{12} by the following equation[9]:

$$R(f)=\{[H_{12}(f)-e^{-s(ik+a)}]\times[e^{s(ik+a)}-H_{12}(f)]^{-1}\}e^{2L(ik+a)}, \qquad (1)$$

where H_{12} is the acoustic transfer function for the two microphone locations, f is the frequency, k is the wavenumber, a is the attenuation constant, s is the microphone separation, and L is the distance of microphone No. 1 from the surface of the specimen. For broadband excitation, H_{12} is given by the cross-spectral density between the two microphone signals, divided by the auto-spectral density of the No. 1 microphone signal.

The normal absorption coefficient α and the normal specific acoustic impedance $Z/\rho c$ of the specimen are given by the following equations:

$$\alpha=1-|R|^2 \qquad (2)$$

and

$$Z/\rho c=(1+R)/(1-R), \qquad (3)$$

where ρ is the air density and c is the speed of sound. Assuming $a=0$, Eq. (1) reduces to Chung and Blaser's result[2]

$$R(f)=\{[H_{12}(f)-e^{-iks}]/[e^{iks}-H_{12}(f)]\}e^{ik2L}. \qquad (4)$$

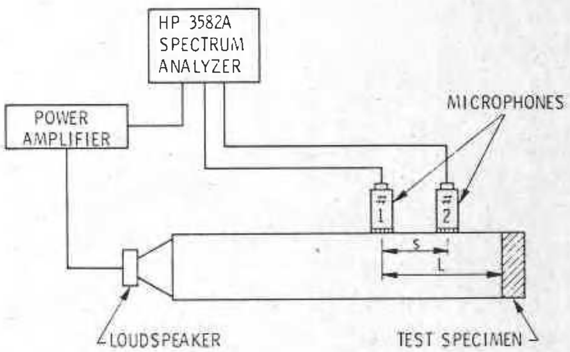

FIG. 1. Test apparatus and instrumentation for the transfer function technique of measuring impedance and absorption coefficient.

[a)] Presented in part at the 12th International Congress on Acoustics, Toronto, 24–31 July 1986.

A study by Chung and Blaser on the singular condition, $e^{iks} - H_{12} = 0$, reveals that R becomes indeterminate when

$$ks = m\pi \quad \text{for} \quad m = 1,2,3,\ldots . \tag{5}$$

Thus, to avoid these points up to a frequency f_m, the microphone spacing s must be chosen such that

$$s < c/2f_m . \tag{6}$$

Besides the limitation, the choice of s and L is also governed by accuracy considerations. Seybert and Soenarko[10] have shown analytically that random errors can be minimized by maintaining a high coherence between the two microphone signals, which implies that s should be small. However, a small microphone spacing will reduce the accuracy of the measurements at low frequencies because the magnitude of the transfer function approaches unity when the wavelength of sound is very much greater than s. Experimental evidence[10] also indicates that high coherence may not be realized when a microphone location coincides with a node point in the sound field. This suggests that different microphone positions and spacings have to be used to cover the frequency range being studied, as supported by Fahy's experiment.[7]

II. MEASUREMENT OF H_{12} USING A SINGLE MICROPHONE

By definition,

$$H_{12}(f) = P_2(f)/P_1(f) = G_{p_1p_2}(f)/G_{p_1p_1}(f), \tag{7}$$

where $P(f)$ is the Fourier transform of the pressure signal $p(t)$. The condition $G_{p_1p_2}(f)$, which is equal to $\frac{1}{2}[P_1^*(f)P_2(f)]$, is the cross-spectral density of p_1 and p_2, and $G_{p_1p_1}(f)$ denotes the auto-spectral density of p_1. Equation (7) can be written as

$$\begin{aligned} H_{12}(f) &= [P_2(f)P_1^*(f)S(f)S^*(f)]/[|P_1(f)|^2|S(f)|^2] \\ &= [G_{p_1s}(f)G_{sp_2}(f)]/[G_{p_1p_1}(f)G_{ss}(f)]. \end{aligned} \tag{8}$$

If the process is stationary, G_{p_1s} and G_{sp_2} do not have to be determined simultaneously. A single microphone can be used to measure, sequentially, the pressure at the two locations. Thus any systematic errors related to the phase mismatch and uncertainty regarding effective microphone separation will be eliminated or minimized. It is necessary, however, to use a deterministic signal to make this approach practical. One of the best signals to use is the periodic pseudorandom sequence because it is effectively a multitone signal with an almost flat-amplitude spectrum.[11]

The following experiment was performed to check the feasibility of this proposal. Two 0.64-cm ($\frac{1}{4}$-in.) Bruel & Kjaer microphones were mounted, flush with the wall, in an impedance tube (as can be seen in Fig. 1) with $L = 13$ cm and $s = 3$ cm. The tube is a 10.2-cm-diam PVC pipe, approximately 95 cm long, driven at one end by a small KEF

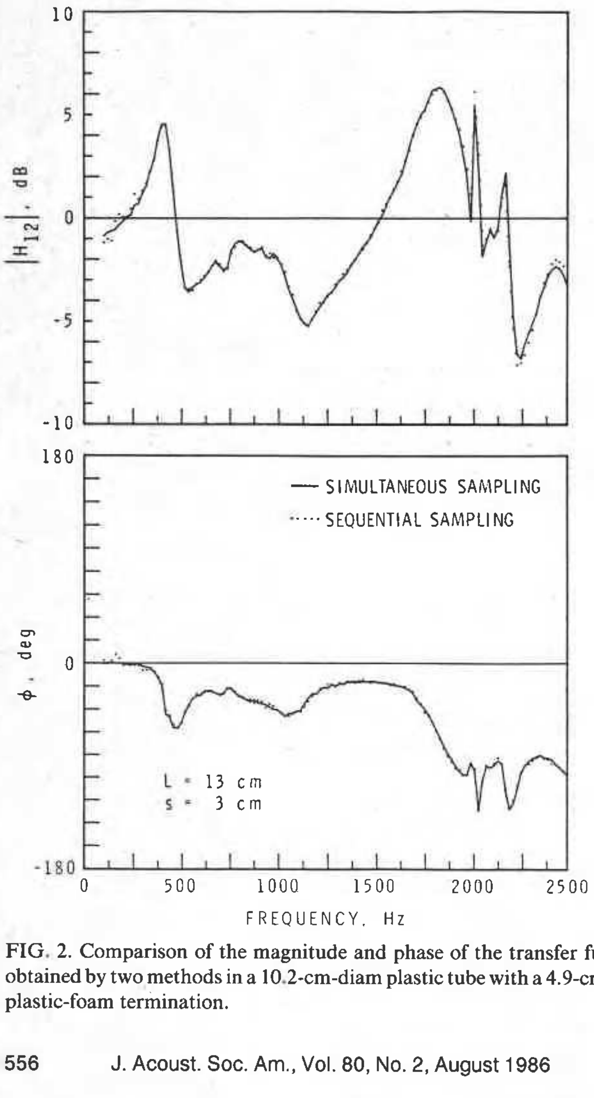

FIG. 2. Comparison of the magnitude and phase of the transfer function obtained by two methods in a 10.2-cm-diam plastic tube with a 4.9-cm-thick plastic-foam termination.

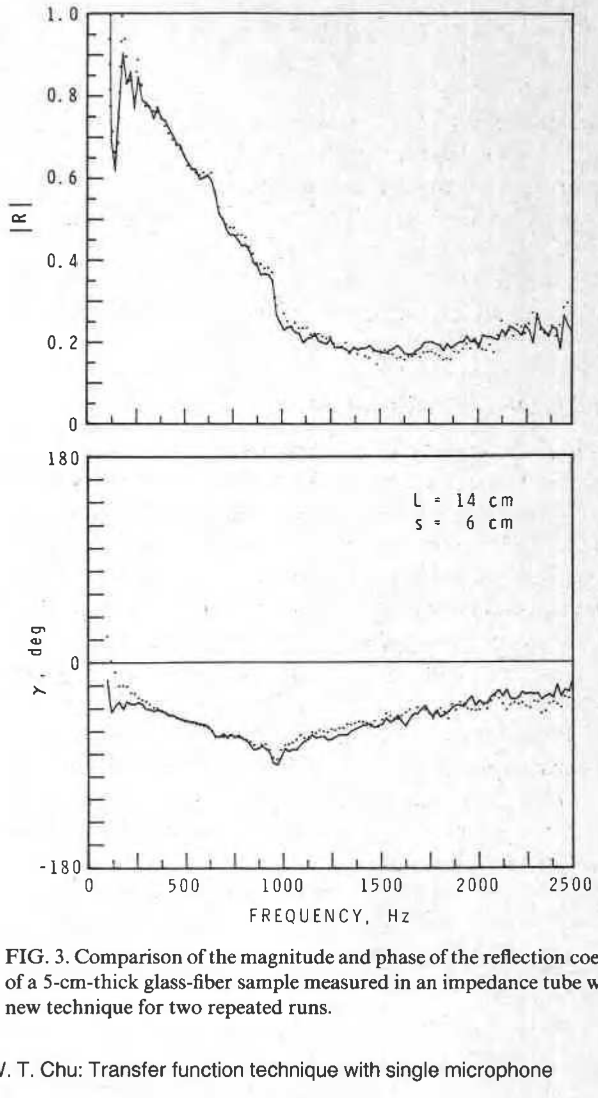

FIG. 3. Comparison of the magnitude and phase of the reflection coefficient of a 5-cm-thick glass-fiber sample measured in an impedance tube with the new technique for two repeated runs.

loudspeaker. For this tube, the upper frequency limit for plane-wave propagation is about 2 kHz. An HP 3582A dual-channel digital spectrum analyzer, used for computing the spectral functions, has a built-in periodic pseudorandom-sequence generator, and can produce 128 spectral lines for the transfer function computation. A plastic-foam sample, 4.9 cm thick, was used as the test specimen.

First, the two microphone signals were sampled simultaneously to establish the reference quantity $G_{p_1p_2}/G_{p_1p_1}$. Then the source signal and each of the microphone signals were digitized simultaneously, in pairs taken sequentially, to give $[G_{p_1s}G_{sp_2}]/[G_{p_1p_1}G_{ss}]$. Only one period of the periodic signal was used, and no averaging was performed. A comparison of the magnitude and phase of H_{12}, obtained by these two different procedures, is presented in Fig. 2. Results indicate that the proposed single-microphone technique is feasible.

A more detailed investigation was carried out, subsequently, in a smaller impedance tube equipped with a traversing probe-tube microphone, such that the acoustic properties of any specimen can be measured by the proposed single-microphone technique and the standard SWR method under the same condition for comparison. The tube has a diameter of 5.75 cm and is approximately 107 cm long. It is driven by a horn driver, mounted on the side, to allow the probe-tube microphone to traverse along the center of the tube. Experience has shown that it is necessary to use a very stable microphone for the proposed single-microphone technique. A 0.64-cm ($\frac{1}{4}$-in.) Bruel and Kjaer microphone was found to be satisfactory. Other data acquisition equipment remained the same.

Two different types of acoustical material were used in this investigation: a 5-cm-thick glass-fiber sample and a 4.9-cm-thick plastic-foam sample with a perforated vinyl backing. The microphone locations were chosen to be fairly close to the specimen, so that the tube attenuation could be neglected. Figure 3 shows a comparison of the magnitude and phase of the reflection coefficient of the 5-cm-thick glass-fiber sample, measured with the new single-microphone technique for two repeated runs, using only one period of the data. Although the result is acceptable, additional averaging could be beneficial.

III. AVERAGING PROCEDURE

With the HP 3582A spectrum analyzer, it is much faster and easier to perform the following ensemble averaging:

$$\langle H_{12}(f)\rangle = \langle G_{p_1s}(f)/G_{p_1p_1}(f)\rangle\langle G_{sp_2}(f)/G_{ss}(f)\rangle. \quad (9)$$

However, another procedure could be

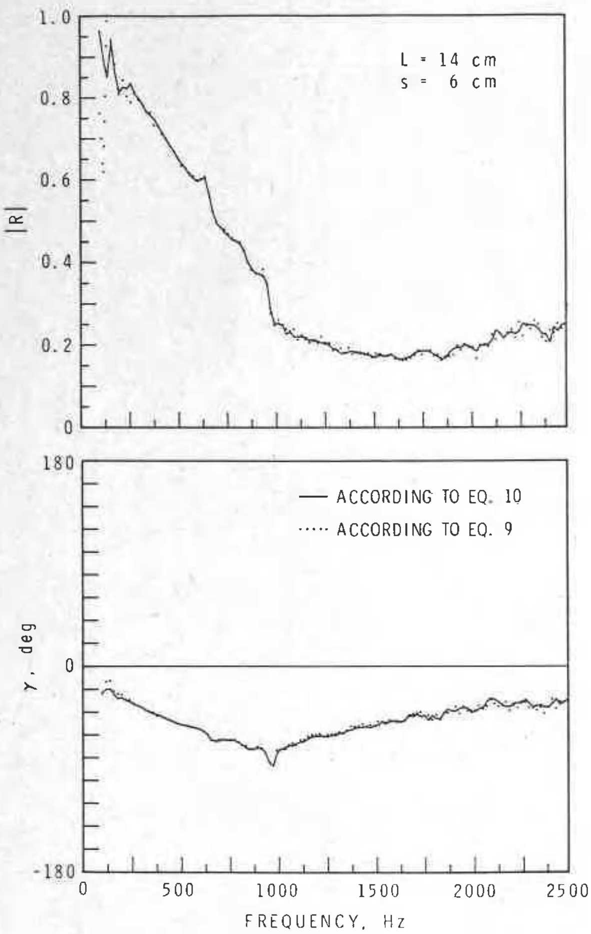

FIG. 4. Comparison of the magnitude and phase of the reflection coefficient of a 5-cm-thick glass-fiber sample measured in an impedance tube with the new technique using two different types of ensemble averaging. Eight averages were used.

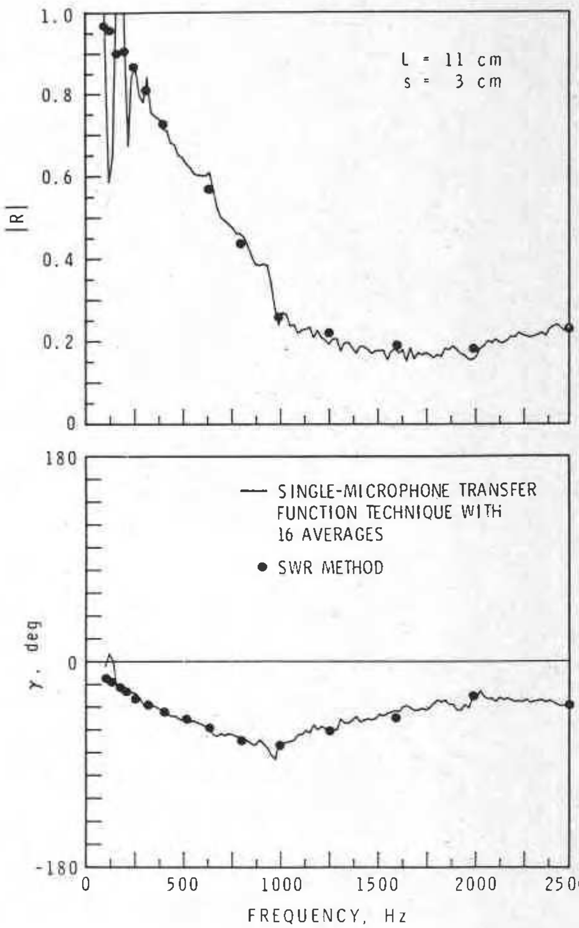

FIG. 5. Comparison of the magnitude and phase of the reflection coefficient of a 5-cm-thick glass-fiber sample measured in an impedance tube by two different methods.

$$\langle H_{12}(f)\rangle = \langle [G_{p_1s}(f)G_{sp_2}(f)]/[G_{p_1p_1}(f)G_{ss}(f)]\rangle. \quad (10)$$

Yet, as shown in Fig. 4, the measured reflection coefficients of the glass-fiber sample, using these two ways of averaging, show no significant differences except at the low frequencies. The discrepancy seemed to be caused by other effects, since it was found that repeatability was not significantly improved, even with averaging at these low frequencies, when the separation of the microphone positions was small. The effect of the microphone separation is discussed in Sec. V. For subsequent investigations, ensemble averaging, according to Eq. (10), was used.

IV. COMPARISON WITH THE SWR METHOD

The reflection coefficients of the two specimens were measured in the small impedance tube, under conditions similar to those of the glass-fiber sample, by both the proposed single-microphone technique of the transfer function method and an improved version of the standard SWR method.[12] Results are compared in Figs. 5 and 6. Except for the low frequencies, the agreement is fairly good. The proposed technique took less than 5 min to provide 128 frequency points, whereas the SWR method required at least 30 min to give 15 frequency points. Based on the repeatability check, the SWR method is more precise.

V. EFFECT OF MICROPHONE SEPARATION

Although Eq. (6) provides an approximate guideline for choosing the microphone separation s, a more precise relationship will be useful. It turned out that the bounding values between s and f_m are fairly well defined, as shown by the results depicted in Figs. 7 and 8. It is evident from these results that

$$s = 0.7(c/2f_m) \quad (11)$$

should be sufficient.

Figures 7 and 8 also show that more accurate results could be obtained at low frequencies with larger microphone separations. This is clearly illustrated by the additional results presented in Fig. 9 for the measured absorption coefficients of the 4.9-cm-thick plastic-foam sample, using different microphone spacings. Figure 9(d) indicates that locating the microphone farther away from the specimen also improved the performance at low frequencies, since H_{12} could be measured more accurately when the microphone locations were not in the broad antinode regions of the standing waves at these low frequencies. However, some deterioration in performance occurred at the intermediate frequencies because one of the microphone positions coincided with

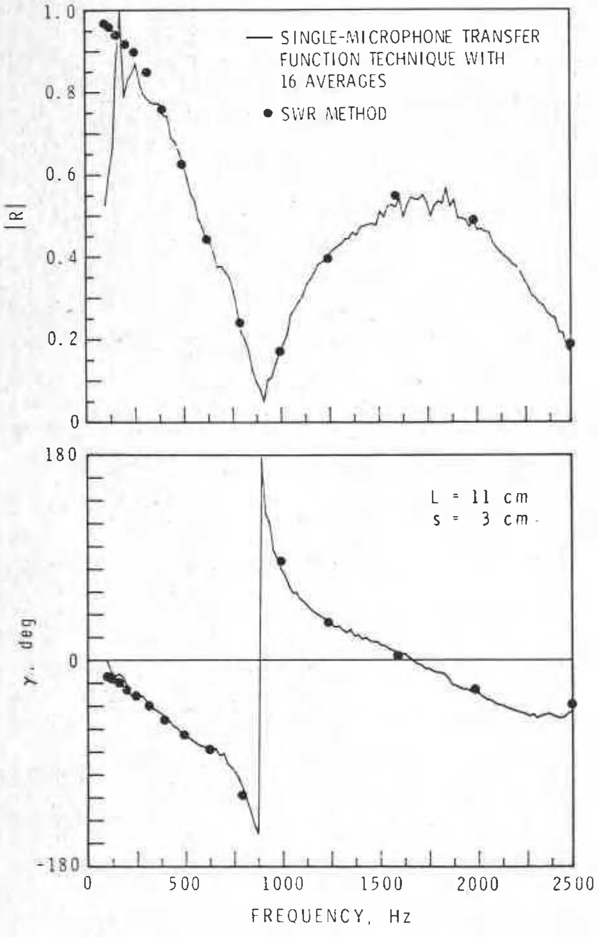

FIG. 6. Comparison of the magnitude and phase of the reflection coefficient of a 4.9-cm-thick plastic-foam sample measured in an impedance tube by two different methods.

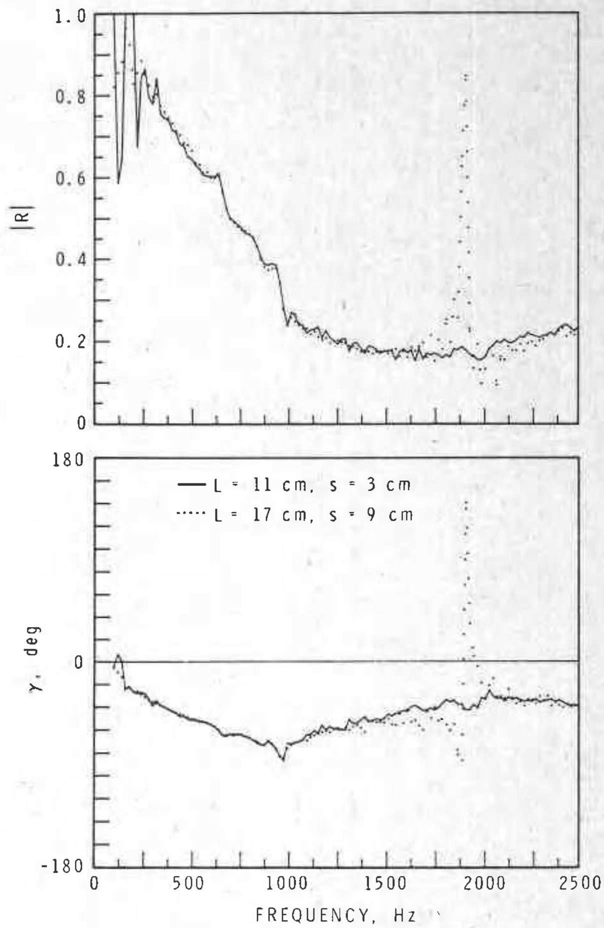

FIG. 7. Comparison of the magnitude and phase of the reflection coefficient of a 5-cm-thick glass-fiber sample measured in an impedance tube with the new technique using two different microphone separations. Sixteen averages were used.

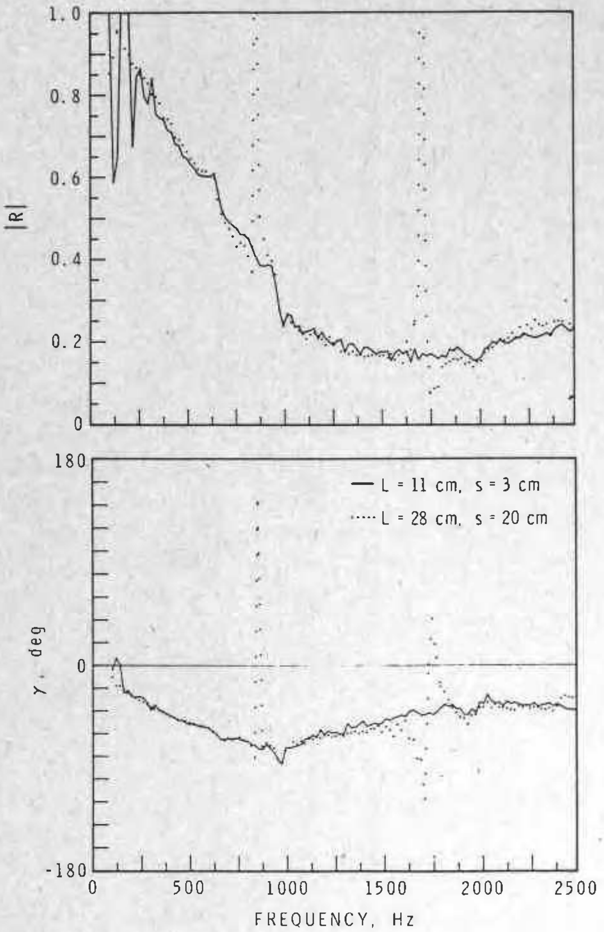

FIG. 8. Comparison of the magnitude and phase of the reflection coefficient of a 5-cm-thick glass-fiber sample measured in an impedance tube with the new technique using two different microphone separations. Sixteen averages were used.

the nodes of some of these frequencies. Thus it is necessary to try different microphone locations and separations for accurate measurements. This should pose no serious drawback since the experimental technique is very efficient.

Figure 10 shows that good results at low frequencies can

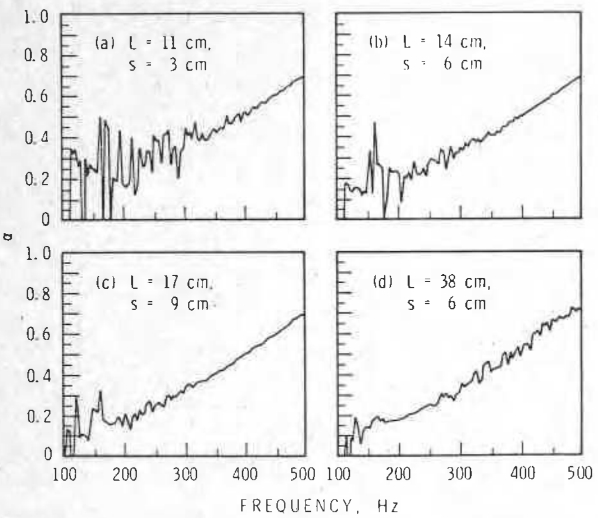

FIG. 9. The absorption coefficient of a 4.9-cm-thick plastic-foam sample measured in an impedance tube with the new technique using different microphone positions and separations. Thirty-two averages were used.

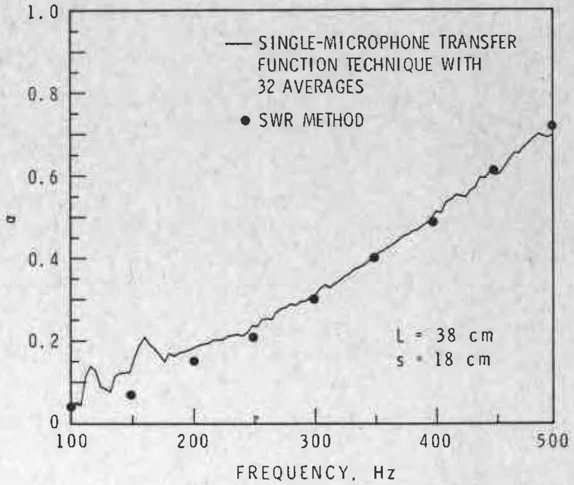

FIG. 10. Comparison of the absorption coefficient of a 4.9-cm-thick plastic-foam sample measured in an impedance tube by two different methods.

be obtained with the proper choice of microphone locations; however, a small systematic error occurs at frequencies below 250 Hz. The exact cause of the error is not clear, although the two peaks at 120 and 160 Hz are known to be caused by the 60-Hz hum and the fundamental resonance mode of the tube, respectively. Additional experiments will be conducted to resolve these difficulties.

VI. CONCLUSION

The two-microphone transfer function method for impedance and absorption measurements, in impedance tubes, has been simplified by using a periodic pseudorandom sequence as the noise source, so that a sequential sampling of the pressure signals at two locations, by a single microphone, can replace the original requirement of simultaneous sampling. Errors and difficulties associated with phase-mismatching in the two-microphone transfer function method are thereby eliminated, making the new measuring technique highly practical.

Results determined by the new technique compared well with those obtained by the SWR method. Although this new technique is not as precise as the SWR method, it is more than an order of magnitude faster and is quite adequate for routine impedance and absorption measurements. Experience has indicated that different microphone locations and separations have to be used to cover a wide frequency range, and some ensemble averaging is necessary if no frequency averaging is performed.

ACKNOWLEDGMENT

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