

Accurate Measurement of Small Absorption Coefficients

J. Han, D. W. Herrin, and A. F. Seybert

Department of Mechanical Engineering, University of Kentucky

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ABSTRACT

In this paper procedures for estimating the sound absorption coefficient when the specimen has inherently low absorption are discussed. Examples of this include the measurement of the absorption coefficient of pavements, closed cell foams and other barrier materials whose absorption coefficient is nevertheless required, and the measurement of sound absorption of muffler components such as perforates. The focus of the paper is on (1) obtaining an accurate phase correction and (2) proper correction for tube attenuation when using impedance tube methods. For the latter it is shown that the equations for tube attenuation correction in the standards underestimate the actual tube attenuation, leading to an overestimate of the measured absorption coefficient. This error could be critical, for example, when one is attempting to qualify a facility for the measurement of pass-by noise. In this paper we propose a remedy – to measure the actual tube attenuation and to use this value, as opposed to the value recommended by the standards, to correct the measured sound absorption. We also recommend an alternative way to determine the microphone phase error.

INTRODUCTION

The sound absorption coefficient is commonly used to characterize and rank sound absorbing materials used to reduce noise. Normally, the sound absorption coefficient is reasonably high (e.g., between 0.5 and unity), and small errors in its measurement are not very important. For example, an uncertainty of 10 percent in the measurement of the sound absorption coefficient translates into an uncertainty of approximately 0.5 dB in the sound power absorbed, an acceptable error.

There are a number of situations where the accurate measurement of low values of absorption coefficient is important. Pavements used in pass-by facilities for the measurement of automobile, truck, or tire noise must have a sound absorption coefficient less than 0.1 at

certain band center frequencies.[1] This is often a difficult criterion to meet, and precise measurement of the pavement absorption coefficient is necessary to avoid potentially costly rework of the pavement. Another example is barriers used for noise reduction which also double as absorbers even though their absorption coefficient may be quite low. A third example where low absorption coefficients are important are mufflers where even a low absorption coefficient is important to reduce the effects of resonances.

Unfortunately, the primary standards[2,3] that guide absorption measurements do not specifically address the problem of accurate measurement of low absorption coefficients. These problems fall into three areas: (1) tube construction, (2) microphone phase error correction, and (3) correction for latent tube attenuation. With respect to tube construction, the standards give broad latitude to the materials used, suggesting only that the tube should be “massive”[2] and “heavy”[3] to avoid vibration resonances in the working frequency range of the tube. Only if the tube is made of metal is a tube thickness of 5 percent of the diameter recommended[3] by one standard; no explanation or source is given for this value. Our preference is to use brass pipe having a wall thickness of approximately 10 percent of the diameter. Brass is also superior to aluminum which has a low elastic modulus and damping compared to brass.

The standards recognize the importance of making accurate phase measurements and provide methods for measuring and correcting phase error, due mainly to the microphones. Even so-called “phase matched” microphones can produce appreciable error when measuring low sound absorption coefficients if the phase error is not corrected. The standards recommend a microphone switching method to determine the microphone phase error. In the switching method (discussed below), a specimen of absorbing material is placed in the tube. The type of the specimen is not specified by the standards, except that it should be “absorptive”[3] or “highly absorptive.”[2] Below we show this recommendation is too vague when one is

measuring small sound absorption coefficients; we recommend placing the microphones in a rigid plate located at the end of the tube to determine the phase error.

Tube attenuation results from viscous and thermal losses at the walls of the tube. The standards recommend not ignoring tube attenuation, but only when the distance from the specimen to the nearest microphone exceeds three tube diameters, regardless of the absorption of the specimen. Both standards recommend correcting for tube attenuation by replacing the wave number with a complex wave number where the imaginary part, the *attenuation constant*, is a function of frequency and the diameter of the tube. In this paper we show that the attenuation constant recommended by the standards underestimates the value found in practice, thereby overestimating the measured absorption coefficient, even when the microphones are close to the specimen.

THE TWO-MICROPHONE METHOD

The two-microphone method[4] shown schematically in Figure 1 is based on plane wave theory. A specimen of the material to be tested is placed in a specimen holder and mounted at the non-source end of a straight tube.[2,3] The transfer function H_{12} is measured between the two microphones located near the specimen. In this measurement, the microphone closer to the source is the reference channel. From the transfer function H_{12} , the sound pressure reflection coefficient R of the material is determined from

$$R = \frac{e^{-jkx_2} - H_{12}e^{-jkx_1}}{H_{12}e^{jkx_1} - e^{jkx_2}} \quad (1)$$

where x_1 is the distance from the specimen face to Microphone 1, x_2 is the distance from the specimen face to Microphone 2, $k = 2\pi f / c$, f is the frequency, and c is the speed of sound. The specific surface acoustic impedance z and sound absorption coefficient α can be determined from

$$z / \rho_0 c = r' + jx' = (1 + R) / (1 - R) \quad (2)$$

and

$$\alpha(\phi) = 4r' \cos \phi / [(1 + r' \cos \phi)^2 + (x' \cos \phi)^2] \quad (3)$$

where ρ_0 is density and ϕ is the angle of incidence of the sound wave.[5]

CORRECTION FOR MICROPHONE PHASE ERROR

When employing the two-microphone technique, the phase error between the microphones is unavoidable and must be corrected. The transfer function H_{12} used in Eq. (1) is found from

$$H_{12} = \frac{\hat{H}_{12}}{H_c} \quad (4)$$

where \hat{H}_{12} is the uncorrected (measured) transfer function between the two microphones and H_c is the *calibration factor*.

$$H_c = \left(\frac{H_{12}^I}{H_{12}^{II}} \right)^{1/2} \quad (5)$$

where H_{12}^I and H_{12}^{II} are the transfer functions obtained using an “absorptive” specimen, as discussed previously, when the microphones are in the switched (H_{12}^I) and un-switched (H_{12}^{II}) configurations.

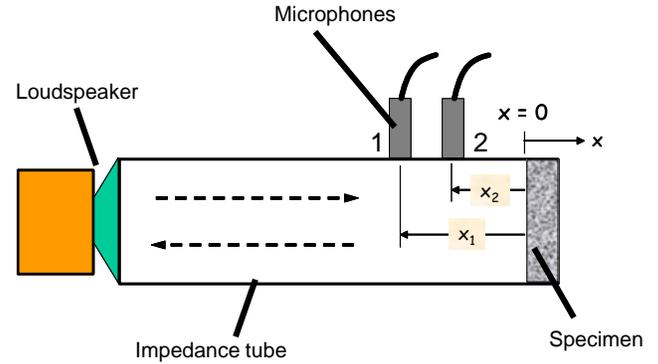


Figure 1 Experimental setup for the two-microphone method.

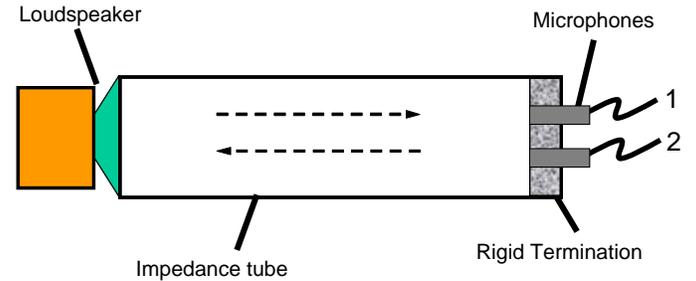


Figure 2 Measurement of phase error using a rigid termination.

Alternatively, one also can determine H_c using a rigid termination method, as shown in Figures 2 and 3. In this method, preferred by us, the microphones are placed in a rigid plate located at the end of the tube. In this arrangement, the microphones are exposed to the same sound pressure and phase, so that a measurement of the transfer function determines the microphone phase and amplitude error directly. When the microphones are located in a rigid termination, the sound pressure measured by each will be a maximum in the tube, and the signal coherence will be very close to unity (by contrast, the signal coherence will be less than unity at some frequencies when the switching method is used).



Figure 3 Photo of rigid plate used for phase error measurement.

Figure 4 shows the phase error obtained by the two methods. The phase error obtained by the switching method and recommended by the standards appears to be specimen dependent; these data also exhibit erratic behavior, not typical of microphone phase response. By contrast, the phase error measured using the rigid termination method is smooth, owing to the high signal coherence, and is similar to that obtained by factory calibration methods.

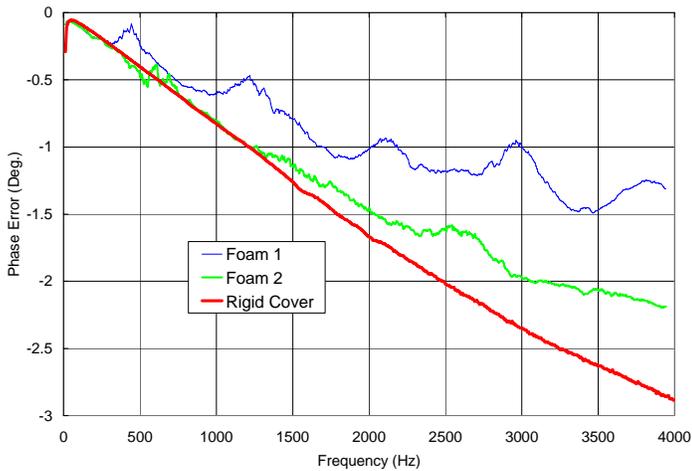


Figure 4 Measured phase error obtained by the switching method (two foam specimens) and the rigid termination method.

Are the differences observed in Figure 4 significant? It depends on the absorption coefficient of the specimen being tested. If the absorption coefficient is relatively high, the effect of differences in the measured phase error shown in Figure 4 is small, as shown in Figure 5. By contrast, when the absorption coefficient is quite small, the effect of not fully correcting microphone phase errors is significant, as shown in Figure 6.

CORRECTION FOR TUBE ATTENUATION

WHAT THE STANDARDS RECOMMEND

The incident and reflected sound waves that propagate within the tube are subject to attenuation due to viscous and thermal losses.[2] To correct for tube attenuation, the standards recommend replacing the real wave number k by a complex wave number:

$$k' = k - jk'' \quad (6)$$

where $k = 2\pi f / c$ and k'' is attenuation constant. An empirical relationship for the attenuation constant provided in the standards is

$$k'' = A\sqrt{f} / cd \quad (7)$$

where d is the diameter of the tube and A is a constant; $A = 0.02203$ [2] and $A = 0.0194$ [3]. The attenuation constant in Eq. (7) is plotted in Figure 7 for several tube

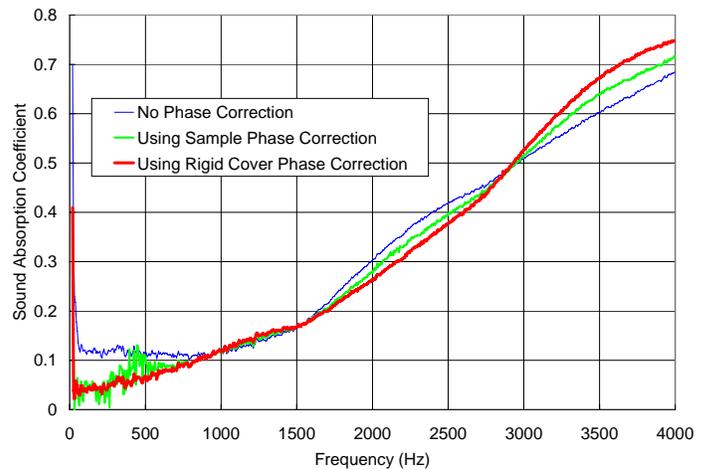


Figure 5 Normal incidence sound absorption coefficient for a specimen having relatively high absorption.

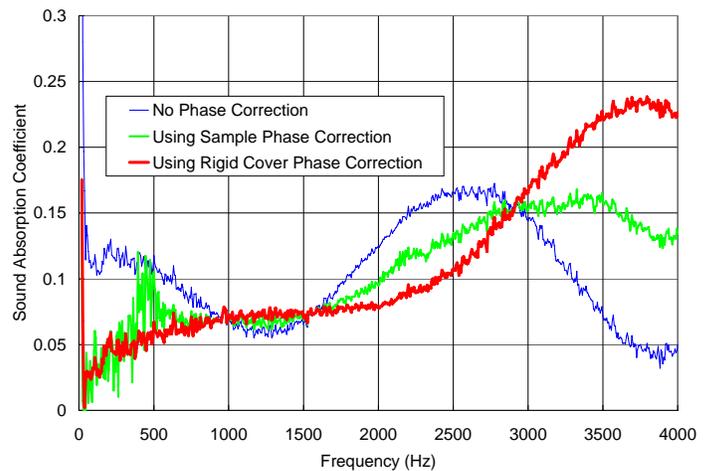


Figure 6 Normal incidence sound absorption coefficient for a specimen having low sound absorption.

diameters using an average value of $A = 0.021$. (The attenuation constant is not plotted for frequencies above the plane wave region of the tube.) As seen in Figure 7, correction for tube attenuation becomes increasingly important for smaller tube diameters used for high frequency measurements of sound absorption coefficient.

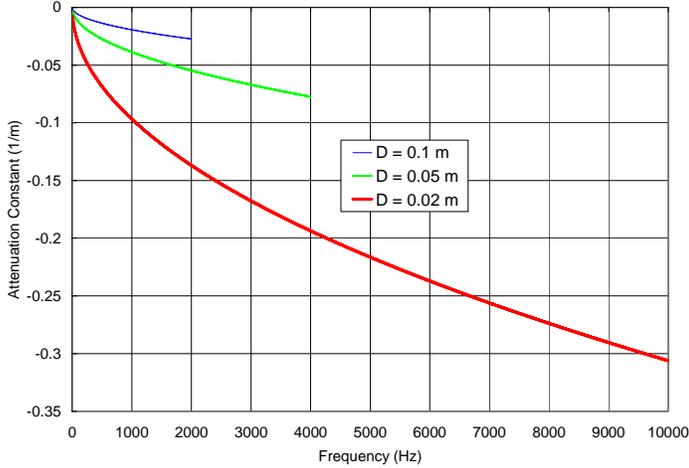


Figure 7 Attenuation constant from Equation (7) with $A = 0.021$.

MEASUREMENT OF ATTENUATION CONSTANT k''

An alternative to Eq. (7) is to measure directly the attenuation constant. This may be done by closing the tube with a rigid termination and measuring the transfer function H_{12} (corrected for phase error). Substituting Eq. (6) into Eq. (1), solving for H_{12} and assuming $R = 1$ (for the rigid termination), one obtains:

$$H_{12} = \frac{e^{-jk'x_2} + e^{jk'x_2}}{e^{-jk'x_1} + e^{jk'x_1}} = \frac{\cos(k'x_2)}{\cos(k'x_1)} = \frac{\cos[(k - jk'')x_2]}{\cos[(k - jk'')x_1]} \quad (8)$$

Using the measured H_{12} , Eq. (8) may be solved numerically for k'' by means of a Newton-Raphson iteration scheme.[7]

EXPERIMENTAL RESULTS

The procedure in the previous section was used to measure the attenuation constant of a 34.9 mm diameter impedance tube. Figure 8 shows the measured attenuation constant compared to the value obtained using Eq. (7) with $A = 0.021$. It may be observed that the measured attenuation constant exceeds the value obtained from Eq. (7) by a factor of five at high frequency. As confirmation, the measured normal incidence absorption coefficient for the tube with the rigid termination is shown in Figure 9. The two results in which tube attenuation were accounted for were obtained using Eq. (1) with k replaced by k' ; in one case the attenuation constant from Eq. (7) was used, and in the other the measured attenuation constant (Figure 8) was used. The desired result of zero is nearly achieved using the measured attenuation constant.

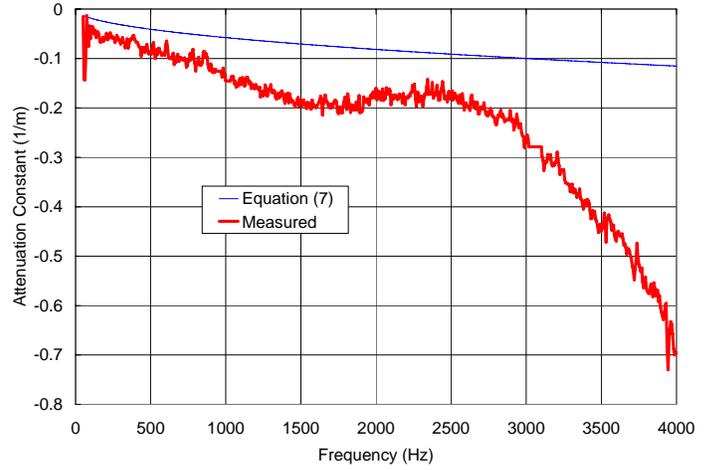


Figure 8 Attenuation constant for 34.9 mm diameter tube.

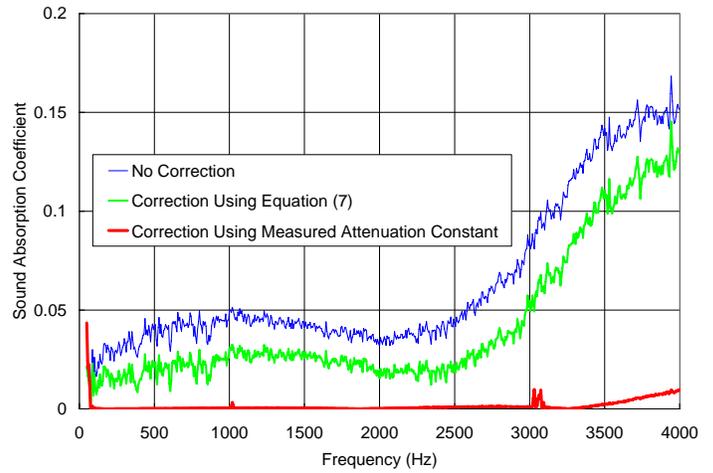


Figure 9 Normal incidence sound absorption coefficient of tube with rigid termination.

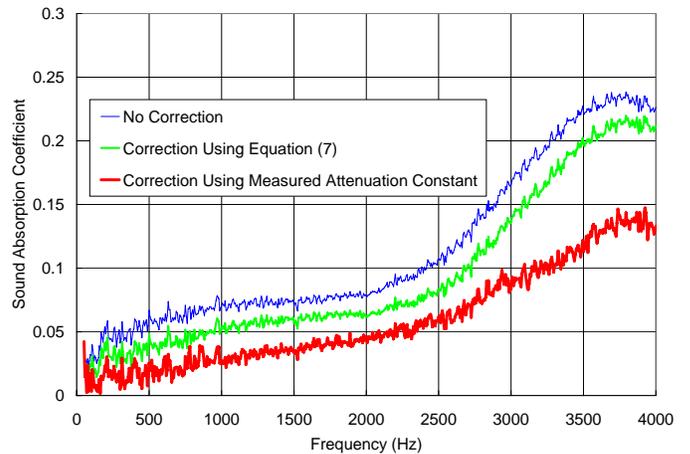


Figure 10 Normal incidence sound absorption coefficient of a low-absorption specimen.

Figure 10 shows the effect of correcting for tube attenuation in the measurement of the normal incidence sound absorption coefficient of a specimen having low sound absorption characteristics. The effect of using no correction is to overestimate the sound absorption by a factor of two; using the correction procedure recommended by the standards is better, but still not correct. Using the measured attenuation constant from Figure 8 achieves the minimum sound absorption coefficient, as seen in Figure 10.

SUMMARY AND DISCUSSION OF RESULTS

When the impedance tube method is used to measure small sound absorption coefficients, care must be exercised to account for sources of error from microphone phase errors and tube attenuation. It has been shown that the procedures recommended by the standards,[2,3] though adequate when the specimen has high absorption, are insufficient when measuring small sound absorption coefficients. The selection of an absorptive specimen for the measurement of phase error is problematic; it has been shown that different specimens can yield different results for the phase error. An alternative method in which the microphones are placed in a rigid plate at the end of the tube has been shown to be more accurate.

It was also demonstrated that the procedures recommended in the standards for correcting for tube attenuation underestimate the actual tube attenuation, resulting in an overestimate of the measured absorption coefficient. A procedure for measuring the actual tube attenuation constant was demonstrated. This method yields results superior to those recommended by the standards. The reason no doubt is that the proposed method is non-phenomenological – it is not based on a knowledge of the types and nature of tube attenuation – in contrast to the method in the standards. Thus, the proposed method will include any and all sources of tube attenuation such as damping and leaks, as well as thermal and viscous losses at the tube walls.

ACKNOWLEDGMENTS

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CONTACT

For additional information concerning this article, please contact A. F. Seybert at (859) 257-6336 Ext. 80645 or via email at seybert@engr.uky.edu.