Development of a narrow impedance tube to measure normal absorption coefficient and transmission loss at high frequencies around 10 kHz

Hiroshi Nakagawa* and Kunikazu Hirosawa†

Nihon Onkyo Engineering Co., Ltd.,
BR Ryogoku 2nd Bldg., 1–21–10 Midori, Sumida-ku, Tokyo, 130–0021 Japan
(Received 6 February 2018, Accepted for publication 21 June 2018)

Abstract: To measure the normal incident sound absorption coefficient and transmission loss for frequencies around 10 kHz, a small impedance tube with an inner diameter of 15 mm was developed. It was found that the influences of sound attenuation, caused by the viscosity of air near the inner tube wall and the surface roughness on the wall of the tube at microphone, were non-negligible. To address these issues, we propose a correction method for the sound attenuation and an improved microphone holder to smoothen the inner wall surface. It was then possible to accurately measure the sound absorption coefficient and transmission loss with acceptable level of accuracy.

Keywords: Impedance tube, Absorption coefficient, Transmission loss, Tube attenuation


1. INTRODUCTION

The impedance tube method [1–4] is widely used to measure the normal incident sound absorption coefficient and transmission loss of a small specimen (i.e., smaller than 10 cm × 10 cm). It is often difficult to produce large specimens for reverberation chamber measurements of the sound absorption coefficient [5,6]. As the impedance tube technique is based on the one-dimensional sound field propagated by plane waves in the tube, the upper frequency is limited by the tube’s inner diameter. The ISO standard [1] governing impedance tube measurements dictates that the inner diameter must be less than 0.58 × wavelength of sound. Thus, the upper frequency of a conventional commercial impedance tube (inner diameter: 29 mm) is approximately 6.4 kHz. However, it is sometimes necessary to use sound absorbing/insulating materials to reduce any high-frequency noise that exceeds the upper frequency limit of the tube, such as the squealing noise of a vehicle brake system or the switching noise generated from the inverter of an electric vehicle or hybrid electric vehicle.

Some materials, such as loudspeaker grille and waterproof membranes for loudspeakers and microphones of smartphones, are required to be acoustically “transparent.” In these instances, it is necessary to measure the absorption coefficient or transmission loss at frequencies higher than the upper frequency limit of a conventional impedance tube.

To evaluate the sound absorption and sound insulation properties of porous materials across a high-frequency range, we developed a narrow impedance tube having an inner diameter of 15 mm. Figure 1 shows the newly developed apparatus. There are difficulties in accurately measuring the high-frequency acoustical properties of materials using a small impedance tube, although these difficulties are negligible for conventional impedance tubes. The first of these difficulties arises from the attenuation of the sound wave propagating in the impedance tube (refer to as “tube attenuation”) [1–3]; the second is caused by the surface roughness of the inside of the tube at the microphone. In this study, we address these two issues and report the absorption coefficient and transmission loss of two samples (polyethylene terephthalate (PET) felt and glass wool) to confirm the effectiveness of our system.

2. PROBLEMS WITH HIGH-FREQUENCY MEASUREMENTS USING A NARROW IMPEDANCE TUBE

2.1. Tube Attenuation

Sound waves propagating inside an impedance tube attenuate because of the influence of air viscosity and the
thermal exchange of the inner surface of the tube, which can be evaluated as the additional sound absorption. This attenuation increases as the propagating path becomes longer and as the tube diameter decreases. Here, the normal absorption coefficient of the rigid surface in our 15-mm-diameter impedance tube (without a specimen) was measured. The measurement conditions are shown in Table 1 and the layout is shown in Fig. 2. In this report, the transfer function method [2], which calculates the sound absorption coefficient from the transfer function of the sound pressure at two locations in the impedance tube, is adopted. The upper frequency limit of our tube, with an inner diameter of 15 mm, is approximately 13.3 kHz at a temperature of 20°C as a condition for propagating only plane waves in the tube, but this is altered by the relationship between the diaphragm dimensions of the 1/4-inch microphones used in our impedance tube and the wavelength of the sound [3], resulting in an effective upper frequency limit of 11.5 kHz. The distances from the rigid surface (of the impedance tube terminal) to the nearest microphone are \(x_2 = 15, 30,\) and \(45\) mm equal to one, two times the inner diameter of the impedance tube, respectively. When the distance \(x_2\) is greater than three times the inner diameter, corrections to the tube attenuation are required in accordance with the standards [1–3]. The normal absorption coefficient without any correction is shown in Fig. 3. When \(x_2 = 15\) mm (i.e., the distance from the rigid surface to the microphone is equal to the inner diameter of the tube), the maximum absorption coefficient up to 10 kHz is approximately 0.07. Moreover, as the distance increases, the absorption coefficient also increases.

Therefore, the tube attenuation must be corrected to precisely measure the absorption coefficient. We adopted the method of correction from the model of sound propagation in a cylindrical tube [7] instead of the description in the standards [1,2]. This method can evaluate correction values obtained by calculation only, on the basis of physical principles as describing below.

Consider the situation where plane waves propagate in a cylindrical tube with a circular cross section as shown in Fig. 4. The effective density \(\rho\) [kg/m³] and bulk modulus \(K\) [N/m²] of the air in the cylindrical tube with radius \(R\) [m] are expressed by the following equations [7]:

\[
\rho = \frac{\rho_0}{F(\omega)}, \tag{1}
\]

\[
K = \frac{\gamma P_0}{\gamma - (\gamma - 1)F(B^2\omega)}, \tag{2}
\]
obtained from the sound pressures $P$ function method [2]. The transfer function of the sound absorption coefficient using the transfer function method can be applied to the calculation of the sound absorption coefficient corrected for the tube attenuation is obtained. This operation will be hereafter referred to as “tube attenuation correction.”

$$\alpha = 1 - |r|^2,$$

where $r$ is the reflection coefficient and $k_0$ is the wavenumber [rad/m], where both of them do not consider the tube attenuation. By obtaining the reflection coefficient using Eq. (9), in which $k_0$ is replaced by $\xi$, the sound absorption coefficient corrected for the tube attenuation is obtained. This operation will be hereafter referred to as “tube attenuation correction.”

$$r = \frac{H - ej\omega k_0 s}{e^{j\xi} - H e^{-2j\xi}},$$

Figure 5 shows the apparent absorption coefficient caused by tube attenuation for virtual specimens with various absorption coefficients. Thin lines: absorption coefficients $\alpha = 0.0, 0.2, 0.5, 0.9$. Thick lines: apparent absorption coefficient considering tube attenuation.

Fig. 5 Apparent absorption coefficient caused by tube attenuation for virtual specimens with various absorption coefficients. Thin lines: absorption coefficients $\alpha = 0.0, 0.2, 0.5, 0.9$. Thick lines: apparent absorption coefficient considering tube attenuation.

Fig. 6 Measured absorption coefficient with tube attenuation correction. $x_2 = 15\text{ mm (thick solid line)}, x_2 = 30\text{ mm (dashed line)},$ and $x_2 = 45\text{ mm (thick solid line)}$.

Fig. 6 Measured absorption coefficient with tube attenuation correction. $x_2 = 15\text{ mm (thick solid line)}, x_2 = 30\text{ mm (dashed line)},$ and $x_2 = 45\text{ mm (thick solid line)}$.

This propagation constant can be applied to the calculation of the sound absorption coefficient using the transfer function method [2]. The transfer function $H$ can be obtained from the sound pressures $P_1$ and $P_2$ at coordinates $x_1$ and $x_2$ in the impedance tube, as shown in Fig. 2. Thus, the sound absorption coefficient $\alpha$ can be obtained as follows:

$$H = \frac{P_2}{P_1},$$

$$r = \frac{H - e^{-j\omega k_0 s} e^{2j\omega k_0 x_1}}{e^{j\omega k_0 s} - H e^{-2j\omega k_0 x_1}},$$

where $\rho_0$ is the density of air in the free space, $\gamma$ is the specific heat ratio, $B^2$ is the Prandtl number, $J_0$ and $J_1$ are the Bessel functions of the zeroth and first order, respectively, $\omega$ is the angular frequency [rad/s], and $\eta$ is the viscosity of air [Pa·s]. From the effective density $\rho$ and bulk modulus $K$ obtained by Eqs. (1) and (2), the propagation constant $\xi$ of the sound wave propagating in the cylindrical tube is given by the following equation,

$$\xi = j\omega \left( \frac{\rho}{K} \right)^{1/2}.$$

This propagation constant can be applied to the calculation of the sound absorption coefficient using the transfer function method [2]. The transfer function $H$ can be obtained from the sound pressures $P_1$ and $P_2$ at coordinates $x_1$ and $x_2$ in the impedance tube, as shown in Fig. 2. Thus, the sound absorption coefficient $\alpha$ can be obtained as follows:

$$H = \frac{P_2}{P_1},$$

$$r = \frac{H - e^{-j\omega k_0 s} e^{2j\omega k_0 x_1}}{e^{j\omega k_0 s} - H e^{-2j\omega k_0 x_1}},$$

where $r$ is the reflection coefficient and $k_0$ is the wave-number [rad/m], where both of them do not consider the tube attenuation. By obtaining the reflection coefficient using Eq. (9), in which $k_0$ is replaced by $\xi$, the sound absorption coefficient corrected for the tube attenuation is obtained. This operation will be hereafter referred to as “tube attenuation correction.”

$$r = \frac{H - e^{j\xi} - H e^{-2j\xi}}{e^{-j\xi} - H e^{-2j\xi}}.$$

Figure 5 shows the apparent absorption coefficient without tube attenuation correction for the specimens having different absorption coefficients obtained by only calculation. Virtual specimens having a constant sound absorption coefficient in the frequency characteristic and sound absorption coefficients of 0.0 (rigid), 0.2, 0.5, and 0.9 are assumed. The calculation is carried out as follows. First, the sound pressure considering the tube attenuation at $P_1$ and $P_2$ in Fig. 2 is calculated theoretically. Next, the reflection coefficient is calculated by using Eq. (7) without the tube attenuation correction instead of Eq. (9) with the correction. The calculation conditions are shown in Table I and the distance from $P_2$ to the surface of the specimen is $x_2 = 30\text{ mm}$. The influence of tube attenuation increases with decreasing sound absorption coefficient of the specimen.

Figure 6 shows the results of tube attenuation correction applied to the measured absorption coefficients of Fig. 3 using Eq. (9). The obtained sound absorption coefficients are smaller than those without the correction (as in Fig. 3). Moreover, for the corrected data, the sound absorption coefficients at the locations of the second microphone ($x_2$) are the same, irrespective of the distance from the microphone to the rigid surface. For the uncorrected measurements, the sound absorption coefficient increases with the distance from the microphone to the rigid surface. It is therefore apparent that the changes in the sound absorption coefficient with the microphone position for the uncorrected measurements are due to the influence of tube attenuation. However, for the data in Fig. 6, the sound absorption is not zero, even though the terminal condition of the tube is a rigid surface. This is because other attenuation factors affect sound absorption coefficient measurements using an impedance tube.
Tube attenuation correction is also effective for measuring TL. The TL for an impedance tube can be estimated from the transfer matrix relating the sound pressure and the particle velocity on both faces of the specimen, which is measured using the configuration shown in Fig. 7 [4,8]. The sound pressure $P_0$ and particle velocity $V_0$ on the front surface of the specimen and the sound pressure $P_d$ and particle velocity $V_d$ on the back surface of the specimen are related by the transfer matrix in Eq. (10):

$$\begin{bmatrix} P_0 \\ V_0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P_d \\ V_d \end{bmatrix},$$

where $T_{11}$, $T_{12}$, $T_{21}$, and $T_{22}$ are all the elements of the transfer matrix representing the relationship between sound pressure and particle velocity on the front and back of the specimen. $P_0$, $V_0$, $P_d$, and $V_d$ can be expressed using the sound pressures $P_1$, $P_2$, $P_3$, and $P_4$ of the four microphone positions in Fig. 7

$$P_0 = \frac{P_1 \sin k_0 x_2 - P_2 \sin k_0 x_1}{\sin k_0 s_1},$$

$$V_0 = j \frac{P_2 \cos k_0 x_1 - P_1 \cos k_0 x_2}{\rho c_0 \sin k_0 s_1},$$

$$P_d = \frac{P_3 \sin(k_0(x_4 - l)) - P_4 \sin(k_0(x_3 - l))}{\sin k_0 s_2},$$

$$V_d = j \frac{P_4 \cos k_0(x_4 - l) - P_3 \cos k_0(x_3 - l)}{\rho c_0 \sin k_0 s_2},$$

where $l$ is the thickness of the specimen [m] and $c_0$ is the velocity of sound [m/s]. The transmission coefficient $\tau$ and TL are expressed in Eqs. (15) and (16) using the elements of the transfer matrix

$$\tau = \frac{2e^{ik_0ld}}{T_{11} + (T_{12}/\rho c_0) + T_{21} \rho c_0 + T_{22}},$$

$$TL = 10 \log \left( \frac{1}{|\tau|^2} \right).$$

By applying propagation constant $\zeta$ of Eq. (5) instead of $k_0$ in Eqs. (11)–(15), it is possible to correct for tube attenuation in TL measurements using an impedance tube.

The measurement conditions are shown in Table 2, and the TL results (without a specimen) obtained by applying tube attenuation correction are shown in Fig. 8. The TL decrease as the frequency increase from 1 to 11.5 kHz when the tube attenuation correction is applied, confirming that the correction is effective. However, the TL (similarly to the absorption coefficient) is nonzero in the case of a rigid surface. This is also caused by additional attenuation factors.

### 2.2. Surface Roughness Inside the Impedance Tube at Microphone Positions

According to the standards [1–3], when side-wall-mounted microphones are used, each microphone should be mounted with its diaphragm flush with the interior surface of the impedance tube. However, a small recess on the structure is permitted [3]. Generally, to accurately mount each microphone at a predetermined position in the impedance tube, as shown in Fig. 9, a microphone holder with a flange for supporting the tip of the microphone is attached separately from the main body of the tube. In many cases, a microphone has a cover called a protection grid at the tip to protect the diaphragm, and the tip of the
protection grid protrudes approximately 1–2 mm from the diaphragm and this protection grid is flush with a flange. Therefore, the microphone diaphragm is slightly recessed from the inner surface of the tube.

Here, we experimentally investigated the extent to which the protrusion or recess of the microphone diaphragm from the inner surface of the impedance tube influences the measurements of the sound absorption coefficient. In the newly developed impedance tube having an inner diameter of 15 mm, the microphone holder was improved so that the microphone diaphragm was flush with the inner surface of the tube. We assumed that the influence of the microphone diaphragm would be non-negligible because the tube is small and the wavelength of the sound is short. The sound absorption coefficient was measured with the position of the diaphragm set to \(-2\) mm (recess) from the inner surface of the tube, 0 mm (flush with the inner surface of the tube), and +2 mm (protrusion) as shown in Fig. 10. Figure 11 shows the measurements without a specimen (rigid surface), and Fig. 12 shows the measurements with a glass wool specimen (bulk density 43 kg/m\(^3\), thickness 25 mm). Figure 13 shows the absorption coefficient differences between diaphragm positions of 0 mm and \(+2\) mm/\(-2\) mm for both the rigid surface and the glass wool specimen. There is typically a 2 mm distance from the tip of the microphone protection grid to the diaphragm, which is located in a recessed position, which corresponds to the position of the diaphragm when installed, as shown in Fig. 10. When the diaphragm of the microphone protrudes or recesses from the inner surface of the impedance tube, the measured absorption coefficients slightly change.

A number of conclusions can be drawn from Fig. 13.
A) The influence of the surface roughness should not be ignored, even if the specimen is highly sound-absorptive.

B) The influence of the surface roughness on the frequency characteristics varies between specimens with different absorption characteristics.

C) The influence of the surface roughness is also non-negligible in the low-frequency range as well as in the high-frequency range.

3. COMPARISON WITH CONVENTIONAL IMPEDANCE TUBE

Finally, we compared measurements of the absorption coefficient and TL from a conventional impedance tube having an inner diameter of 40 mm with measurements from our tube (inner diameter: 15 mm). Specimens included two types of fibrous material: PET felt (bulk density: 32 kg/m$^3$, thickness: 25 mm) and glass wool (bulk density: 43 kg/m$^3$, thickness: 25 mm). The measurement frequencies ranged from 200 to 4,800 Hz for the 40-mm-diameter impedance tube and 1,000 to 11,500 Hz for the 15-mm-diameter impedance tube. Thus, measurements from 1,000–4,800 Hz were common to both impedance tubes. Figures 14 and 15 show the sound absorption coefficient and TL of PET felt, and Figs. 16 and 17 show those of glass wool, respectively. It can be observed that the results for the 15-mm-diameter impedance tube agree well with those for the 40-mm-diameter tube. Therefore, it is possible to measure both the sound absorption coefficient and the TL across a wider frequency range by combining a conventional impedance tube and our novel 15-mm-diameter narrow tube.

4. SUMMARY

We developed a narrow impedance tube with an inner
diameter of 15 mm to measure the absorption coefficient and TL at high frequency around 10 kHz. We investigated both the influence of the tube attenuation and that of the microphone diaphragm position (recess or protrusion) relative to the inner surface of the impedance tube. We confirmed that the apparent sound absorption caused by tube attenuation was affected more as the sound absorption coefficient of the specimen became smaller and as the distance between the microphone and specimen became larger. In the case of a rigid surface (with no specimen), the apparent sound absorption was affected even when the distance between the microphone and specimen was equal to the diameter of the tube. By implementing tube attenuation correction based on the theory of the propagation of acoustic waves in cylindrical tubes, the influence of tube attenuation was reduced.

The effect of the inner tube surface roughness was also examined. It was expected that the roughness would affect measurements when the 15-mm-diameter impedance tube was used at high frequencies (i.e., short wavelengths). We measured absorption coefficients at different microphone diaphragm positions relative to the inner surface of the tube. Slight changes in the absorption coefficient were observed, which occurred even in specimens with high sound absorption.

To accurately measure the absorption coefficient and TL at high-frequencies of 10 kHz, it is necessary to minimize the inner surface roughness, especially at the microphone position, and to correctly carry out the tube attenuation. However, even under these conditions, the apparent sound absorption does not become completely zero. This indicates that tube attenuation caused by sound propagation is not the only source of attenuation. Indeed, the junctions between the tubes or the small gaps of the microphone attachment may play a role. Future research should address how to reduce these additional losses.

REFERENCES