Development of a Practical Two-Microphone Impedance Tube Method for Sound Transmission Loss Measurement of Sound Isolation Materials

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ABSTRACT: This study developed a practical two-microphone impedance tube method to measure the sound transmission loss of sound isolation materials without the use of an expensive reverberation room or an acoustic intensity probe. In order to evaluate the validation and applicability of the two-microphone impedance tube method, sound transmission losses for several sound isolation materials with different surface density and bending stiffness were measured, and the measured values were compared with the results from the reverberation room method and the theory. From the experimental results, it was found that the accuracy of sound transmission loss obtained by the impedance tube method depends upon the diameter size of the impedance tube (i.e., tested sample size). For sound isolation materials having relatively large bending stiffness such as acryl, wood, and aluminum plates, it was found that the impedance tube method proposed by this study was not valid to measure the sound transmission loss. On the other hand, for sound isolation materials having relatively small bending stiffness such as rubber, polyvinyl, and asphalt sheets, the comparisons of transmission loss between the results from the impedance tube method and the theory showed a good agreement within the range of the frequencies satisfying the normal incidence mass law. Therefore, the two-microphone impedance tube method proposed by this study can be an effective measurement method to evaluate the sound transmission loss for soft sound isolation sheets having relatively small bending stiffness.

Nomenclature

c : speed of sound [m/s]
E : Young's modulus [Pa]
f : frequency [Hz]
H_{12} : acoustic transfer function
I_i : acoustic intensity of incident wave [W/m^2]
I_r : acoustic intensity of reflected wave [W/m^2]
I_t : acoustic intensity of transmitted wave [W/m^2]
k : wave number ($=2\pi f/c$)
K : bending stiffness
m : surface density [kg/m^2]
R_p : power reflected coefficient
s : microphone spacing [m]
S_{AA} : sound power spectrum for the incident wave [Pa^2]
S_{BB} : sound power spectrum for the reflected wave [Pa^2]
TL : sound transmission loss [dB]

Greek symbols

θ : incidence angle [rad]

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ρ : air density [kg/m^3]
τ : sound transmission coefficient
ω : angular frequency [rad/sec]

1. Introduction

Several kinds of sound isolation materials have been developed for the passive control of interior noises of buildings such as hotels, apartment houses, and offices. Recently, thin sound isolation sheets made of polyvinyl and metal-compound powders have been widely used, since they are not only simple to install into building constructions with good in sound isolation performance, durability, and ease of manufacturing but also efficient to save the building spaces.(1)

Acoustic performance of the sound isolation materials can be expressed in terms of the sound transmission loss defined by the logarithmic intensity ratio of the transmitted sound wave to the incident sound wave. In order to measure the sound transmission loss, the conventional reverberation room method has been used. However, during the procedures of developing a new sound isolation material, it is time consuming and expensive to measure the sound transmission loss for every sound isolation material using the reverberation room method. Also, in this method, a large test sample in size following the international standards is required.(2) Therefore, a new practical and accurate measurement method is required to conveniently obtain the sound transmission loss for sound isolation materials without the use of an expensive reverberation room.

Regarding to the point of view mentioned above, the measurement methods developed by Crocker et al.(3) and Wang and Crocker(4) were very effective methods to obtain the sound transmission loss using the sound intensity measurements with two microphones. In their methods, the intensity of the transmitted sound wave after passing through a tested sample was measured by the two microphones, and the intensity of the acoustic source room was evaluated from the averaged sound pressure level of the reverberation room. Then, the sound transmission loss was calculated from the difference of the sound intensities between the transmitted sound wave and the acoustic source room. However, in order to use this measurement method, it was necessary to have at least one reverberation room in which the diffuse sound field was maintained.

More recently, Bolton et al.(5) developed a new measuring technique to evaluate the sound transmission loss and the sound absorption coefficient for automotive acoustic sealants. In their work, the two-microphone procedure was extended to allow the measurement of the normal sound transmission loss of sealant samples placed in the middle of an impedance tube. To determine either the reflection coefficient from the incident face of the sample or the transmission loss through the sample, four microphones, two upstream and two downstream of the sample, were used. Compared with the method suggested by Bolton et al., the two-microphone impedance tube method proposed by this study used different test materials and different test procedures.(6,7) The method proposed by Bolton et al. was restricted to the use of porous materials since there were large experimental errors to evaluate transmission loss for non-porous acoustic materials due to the resonance effects at the downstream of the test sample.(8,9)

Two-microphone impedance tube method proposed by this study was a fast and practical measurement method to accurately evaluate the sound transmission loss for sound isolation materials without the use of an expensive reverberation room. In order to evaluate the validation and applicability of two-microphone impedance tube method, transmission losses for several sound isolation materials with different surface density and bending stiffness were measured, and the measured values were compared with the results from the reverberation room method and the results from the theory satisfying the mass law of sound isolation material. The effect of the diameter in size of impedance tube on sound transmission loss was also discussed.

2. Theoretical background

Fig. 1 schematically shows an acoustic impedance tube having no flow of plane sound field with two microphones used to obtain acoustic characteristics at one end of the tube. Locations of the two microphones are x_1 and x_2 from the end of the tube. A loudspeaker at the other end is used to generate a random sound signal.

Using the acoustic functions such as auto-spectral density functions $S_{11}(f)$ and $S_{22}(f)$ at x_1 and x_2, cross-spectral density functions $S_{12}(f)$, and transfer function $H_{12}(f)$, the sound power spectrum $S_{AA}(f)$ and $S_{BB}(f)$ for the incident and reflected waves are as follows.[10,11]

$$S_{AA}(f)= S_{11}(f)\cdot[1+|H_{12}(f)|^2-2\mathrm{Re}[H_{12}(f)]\cos k(x_1-x_2) + 2\mathrm{Im}[H_{12}(f)]\sin k(x_1-x_2)]/4\sin^2 k(x_1-x_2) \quad (1a)$$

$$S_{BB}(f)= S_{11}(f)\cdot[1+|H_{12}(f)|^2-2\mathrm{Re}[H_{12}(f)]\cos k(x_1-x_2) - 2\mathrm{Im}[H_{12}(f)]\sin k(x_1-x_2)]/4\sin^2 k(x_1-x_2) \quad (1b)$$

In Eqs. (1), Im and Re denote the imaginary and real parts of transfer functions, f is the frequency, $k=2\pi f/c$ is the wave number, and c is the speed of sound, respectively. Eqs. (1) can be rearranged into Eqs. (2) in terms of incident acoustic intensity, $I_i(f)$, and reflected acoustic intensity, $I_r(f)$, using the relationship of plane wave acoustic intensity which can be calculated from the time average of sound pressure and particle velocity, $I=\overline{pu}$.

$$I_i(f)= \{S_{11}(f)\cdot[1+|H_{12}(f)|^2-2\mathrm{Re}[H_{12}(f)]\cos k(x_1-x_2) + 2\mathrm{Im}[H_{12}(f)]\sin k(x_1-x_2)]\}/4\rho c\sin^2 k(x_1-x_2) \quad (2a)$$

$$I_r(f)= \{S_{11}(f)\cdot[1+|H_{12}(f)|^2-2\mathrm{Re}[H_{12}(f)]\cos k(x_1-x_2) - 2\mathrm{Im}[H_{12}(f)]\sin k(x_1-x_2)]\}/4\rho c\sin^2 k(x_1-x_2) \quad (2b)$$

where ρc is the characteristic acoustic impedance of air and $s=x_1-x_2$ is the distance between microphones. Acoustic intensity reflection coefficient at the location of x_1, $R_{p,1}(f)$, is the ratio of the reflected acoustic intensity to the incident acoustic intensity, and can be evaluated from Eqs. (2) as follows.

$$R_{p,1}(f)= \frac{1+|H_{12}(f)|^2-2\mathrm{Re}[H_{12}(f)]\cos ks-2\mathrm{Im}[H_{12}(f)]\sin ks}{1+|H_{12}(f)|^2-2\mathrm{Re}[H_{12}(f)]\cos ks+2\mathrm{Im}[H_{12}(f)]\sin ks} \quad (3)$$

Using the Chung and Blaser's[12] transfer function method, complex reflection coefficient, $R_{c,1}(f)$, also can be calculated. We can see that $R_{p,1}(f)=|R_{c,1}(f)|^2$. Thus, we can consider that Chung and Blaser's transfer function method is a special case of sound decomposition theory suggested by Seybert and Ross.[10]

If we can assume that there is no reflected wave from the sound wave passing through the sound isolation material attached at the end of the tube in Fig. 1, and we can ignore the absorption of sound isolation material, then the sound transmission loss, $TL_m(f)$, for normal incident sound wave can be evaluated as follows.

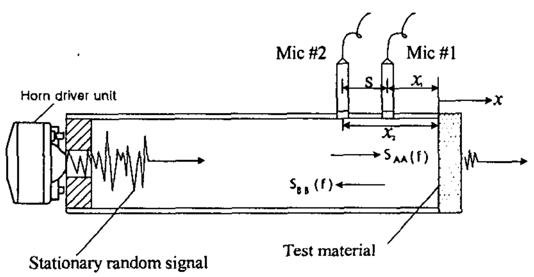


Fig. 1 Schematic of an acoustic impedance tube.

$$TL_m(f) = 10\log_{10}\left\{\frac{1+|H_{12}(f)|^2-2\mathrm{Re}[H_{12}(f)]\cos ks+2\mathrm{Im}[H_{12}(f)]\sin ks}{4\mathrm{Im}[H_{12}(f)]\sin ks}\right\} \quad (4)$$

As can be seen from Eq. (4), the sound transmission loss of sound isolation material can be easily evaluated by measuring only the transfer function $H_{12}(f)$ between the two microphones.

Sound transmission loss can be classified in two kinds, normal sound transmission loss for normal incident wave ($\theta=0$), $TL_{normal}(f)$ and random sound transmission loss for random incident wave ($\theta=0°\sim90°$), $TL_{random}(f)$. Here θ is the sound incident angle measured from the normal direction to the sound isolation material. However, for the most of sound isolation materials, sound transmission loss can be expressed as $TL_{field}(f)$ of Eq. (5), and can be usually calculated under the restriction of $\theta=0°\sim82°$ to satisfy the field-incidence mass law rather than under the restriction of $\theta=0°\sim90°$ for random incident wave.[13]

$$TL_{field}(f) \cong 20\log_{10}(mf) - 48.6 \quad (5)$$

where m is the surface density (kg/m^2). We call Eq. (5) as limp-wall mass law for soft and thin sound isolation materials. Also, Eq. (5) has the following relationship with $TL_{normal}(f)$.

$$TL_{normal}(f) \cong TL_{field}(f) + 5\,\mathrm{dB} \quad (6)$$

Meanwhile, if the incident wave transmitted into the circular impedance tube corresponds with the natural frequency of the sound isolation material to the impedance tube, then the resonance of the sound isolation material can affect the results of the sound transmission loss. Thus the resonance frequency, f_r, can be calculated as follows.[14]

$$f_r = \frac{B}{2\pi a^2}\sqrt{\frac{K}{m}} \quad (7)$$

where a is the radius(m) of the impedance tube and B is the coefficient of the resonance mode. If the resonance mode is in the first order and the fixed supporting condition, then the coefficient of the resonance mode is 10.21. Also, the bending stiffness of the sound isolation material, K(kg·m), can be evaluated from the use of Young's modulus $E(p_a)$ and Poisson's ratio ν as follows

$$K = \frac{Eh^3}{12(1-\nu^2)} \quad (8)$$

3. Experimental setup

Fig. 2 shows the experimental setup for measuring the normal-incidence sound transmission losses of sound isolation materials by the two-microphone impedance tube method.

The impedance tube was a circular acrylic pipe of 1000 mm in length and 10 mm in thickness. In order to obtain the effects of the impedance tube diameter in size on sound transmission loss, the transmission loss measurement was carried out in three kinds of impedance tubes of D=30 mm, D=50 mm, and D=78 mm in inside diameter. Two microphones of 1/4 inch pressure type were mounted flush with the inner surface of the tube. A loudspeaker was located at one end of the tube, and the test material was attached at the other end. A random sound generator provided sound signal

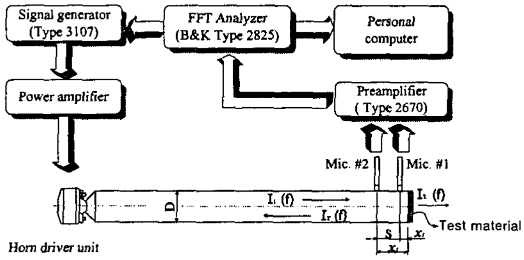


Fig. 2 Experimental setup for normal sound transmission loss measurement of sound isolation materials.

Table 1 Specifications of the test materials for sound transmission loss measurement

Sample name	Surface density m (kg/m^2)	Young's modulus E (GPa)	Bending stiffness K (kg·m)	Poisson's ratio ν
Polyvinyl sheet A	2.4	0.1	0.002	0.22
Polyvinyl sheet B	2.3	-	-	-
Rubber sheet	3.7	-	-	-
Asphalt sheet	3.4	-	-	-
Acryl plate	2.3	1.7	0.14	0.40
Aluminum plate	1.1	64.6	0.04	0.30
Wood plate	2.2	0.46	0.04	0.47

through an amplifier to the loudspeaker. The maximum frequency of the FFT analyzer was 6400 Hz with 16 Hz resolution.

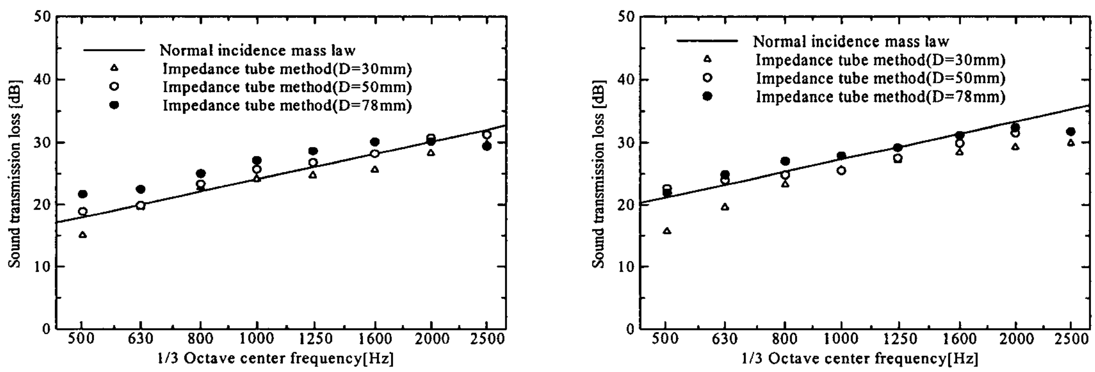
The transfer function, $H_{12}(f)$, was measured using two microphones mounted at two locations of the tube. By substituting measured $H_{12}(f)$ into Eq. (4), the normal sound transmission losses of sound isolation materials were obtained. In order to accurately measure the transfer function using two microphones, the microphone positions as well as the locations of the test material were rechecked.[7] In this study, the conditions of $x_1 = 50$ mm and $x_2 = 70$ mm were used.

The sound transmission losses for the test materials were also measured by the reverberation room method. One reverberation room was 325 m^3 in size with 100 Hz cut-off frequency, and the other room was 249 m^3 in size with 125 Hz cut-off frequency. Both rooms satisfy the ISO standards.

Table 1 shows the specifications of the tested materials for sound transmission loss measurement. The mechanical properties such as Young's modulus, bending stiffness, and Poisson's ratio were tested by UTM (Instron 4467). For all of the experiments, the sound isolation materials were accurately bonded to maintain the sealing of the tube without any leakage of sound.

4. Results and discussion

Fig. 3 show the effect of the impedance tube's diameter size on the sound transmission loss



(a) Polyvinyl sheet A (b) Rubber sheet

Fig. 3 Effects of the impedance tube's diameter size on the normal-incidence sound transmission loss.

in the frequency band satisfying the normal-incidence mass law.

The test materials used for Fig. 3 (a) and (b) were the polyvinyl sheet A and the rubber sheet, respectively. The solid lines indicate the theoretical sound transmission loss from Eq. (6) satisfying the normal-incidence mass law, and the symbols indicate the measured values from impedance tube with different diameter in size. It can be seen that sound transmission losses obtained by the impedance tube method depends upon the diameter size of the impedance tube.

Since the sound wave propagated into the impedance tube transports the energy by the

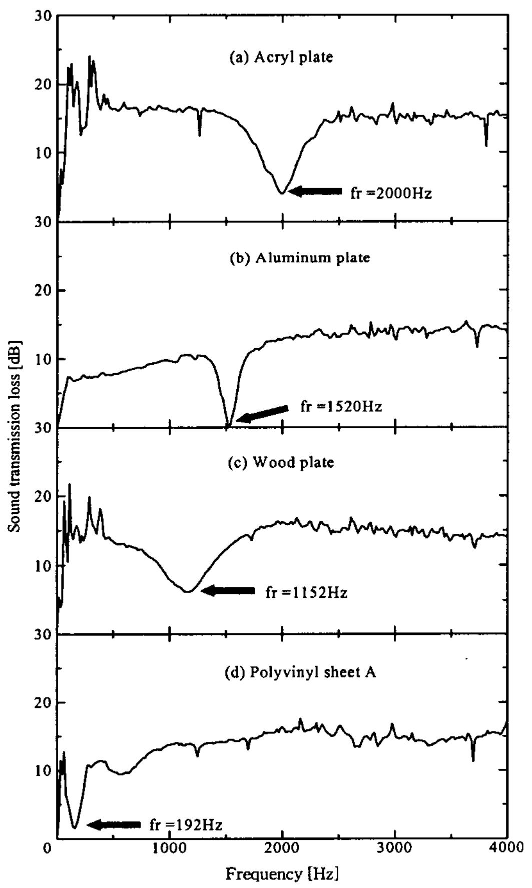


Fig. 4 Effect of the bending stiffness of sound isolation material on the normal-incidence sound transmission loss.

procedures of vibrating an air layer, the sound isolation material, and another air layer, the vibration characteristics of the sound isolation material might be affected by the diameter size of the impedance tube. However, since the measured sound transmission loss from the impedance tube of D=50 mm in diameter was agreed well with the theoretically calculated value, this study used only the impedance tube of D=50 mm in diameter.

Fig. 4 shows the results of the sound transmission loss measured by the impedance tube method for the different bending stiffness of the tested sound isolation materials. As we can see from the figures, the frequency band where the value of the sound transmission loss rapidly decreases and then increases is called stiffness-controlled region, and the frequency band higher than the stiffness-controlled region is called mass-controlled region. Resonance of the sound isolation material is occurred at the stiffness-controlled region. The values of the resonance frequency on Figs. 4 were calculated by substituting those physical properties in Table 1 into Eq. (7). The measured resonance frequencies were agreed well with the theoretically calculated values.

As we can see from the results, if the bending stiffness increases, then the stiffness-controlled region also increases. However, as the stiffness-controlled region increases, then the mass-controlled region in which we can check the performance of the sound isolation material decreases. Thus, it is difficult to measure the sound transmission loss at the desired sound frequency band for a sound isolation material. Therefore, the impedance tube method suggested by this study is limited for soft sound isolation materials.

Fig. 5 shows the comparison results between the measured and the theoretically calculated sound transmission losses for an acryl plate having relatively large bending stiffness. As we could see from Fig. 4 (a), due to the large

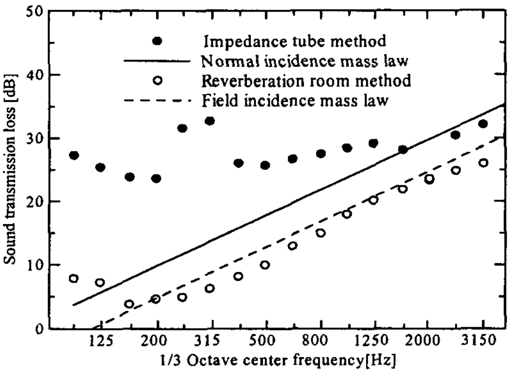
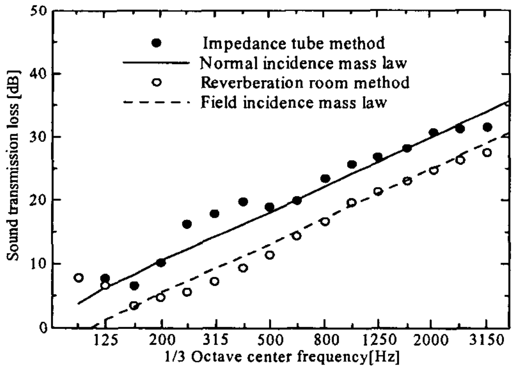


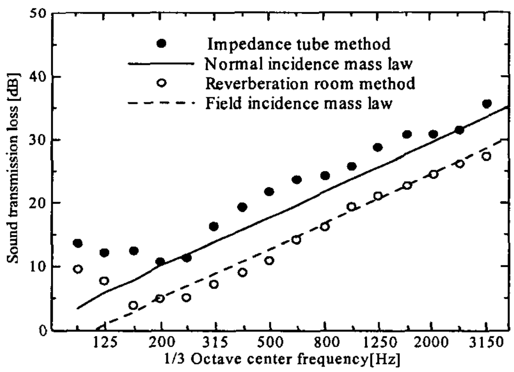
Fig. 5 Sound transmission loss for an acryl plate having relatively large bending stiffness.

bending stiffness of the acryl plate, the sound transmission loss measured by the impedance tube method is only valid beyond the frequency band of 2,000 Hz since the frequency range satisfying the mass-controlled region is decreased. Therefore, the impedance tube method suggested by this study is not applicable to the aluminum plate or wood plate having relatively large bending stiffness. Meanwhile, as we could see from Fig. 5, the sound transmission losses measured in a reverberation room and theoretically calculated from Eq. (5) agreed well each other for all of the frequency bands except for the frequency band of the stiffness-controlled region.

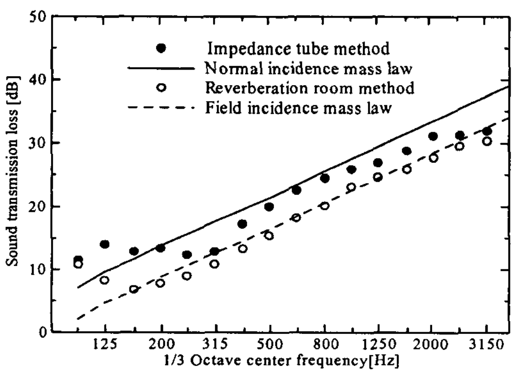
Fig. 6 shows the comparisons of the sound transmission losses between the impedance tube method and the reverberation room method for four kinds of sound isolation sheets. The dotted lines indicate the theoretical sound transmission loss from Eq. (5) satisfying the field-



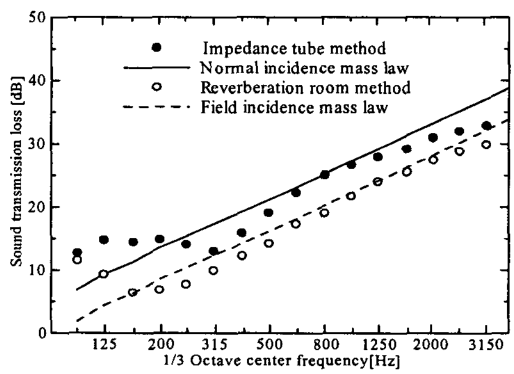
(a) Polyvinyl sheet A



(b) Polyvinyl sheet B



(c) Rubber sheet



(d) Asphalt sheet

Fig. 6 Sound transmission loss for sound isolation materials having relatively small bending stiffness.

incidence mass law, and the solid lines indicate the theoretical sound transmission loss from Eq. (6) satisfying the normal-incidence mass law. Based on the comparisons of sound transmission loss between the results from the reverberation room method and the results from Eq. (5), both of the results agreed well each other except at some low frequencies. The discrepancy at the low frequencies was due to the fact that those low frequencies were in the range of the resonance frequency. Thus, it can be found that the results from those Eqs. (5) and (6) are only good for satisfying the field-incidence or normal-incidence mass laws.

Even though the results of the sound transmission loss from the impedance tube method have some relevant errors like a resonance effect and microphone position, the differences between the results of the sound transmission losses were below about 5 dB. The difference due to the incident angle effects was in good agreement with Eq. (6). Therefore, the two-microphone impedance tube method used in this study can be an effective measurement method to evaluate the sound transmission loss for soft sound isolation sheets having relatively small bending stiffness.

5. Conclusions

This study proposed a practical two-microphone impedance tube method to measure the normal-incidence sound transmission loss of sound isolation materials without the use of an expensive reverberation room or an acoustic intensity probe. In order to evaluate the validation and applicability of two-microphone impedance tube method, sound transmission losses for several sound isolation materials with different surface density and bending stiffness were measured, and the measured values were compared with the results from the reverberation room method and the theory.

For sound isolation materials having relatively large bending stiffness such as acryl, wood, and aluminum plates, it was found that the impedance tube method proposed by this study was no longer valid to measure the transmission loss. On the other hand, for sound isolation materials having relatively small bending stiffness such as rubber, polyvinyl, and asphalt sheets, the comparisons of transmission loss between the results from the impedance tube method and the theory showed a good agreement within the range of the frequencies satisfying the normal incidence mass law. Therefore, the two-microphone impedance tube method proposed by this study is an effective measurement method to evaluate the sound transmission loss for soft sound isolation sheets having relatively small bending stiffness.

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