

# Mechanism of Light Weight Sound Insulation Material Using Thin-film Cells

Ikumi KURIHARA<sup>1</sup>Takashi KONDO<sup>1</sup>Takao YAMAGUCHI, Ph.D.<sup>2</sup>

## ABSTRACT

Weight reduction of the sound insulation material used to enhance cabin quietness is being advanced for the purpose of reducing vehicle weight. Sound insulation material with a structure of double walls with an intermediate layer of porous material between them is frequently used. There are reports from previous research that the use of thin-film cells instead of porous material can maintain similar sound insulation performance while enabling weight reduction. However, since the mechanism of sound insulation by thin-film cells is not clearly understood, in the present research, the question of why thin-film cells possess the same sound insulation performance as porous material was examined, with a focus on the propagation speed of sound waves transmitted through thin-film cells (apparent sound speed). The relationship between sound insulation performance and apparent sound speed was also formulated as an equation in order to obtain adequate sound insulation performance, and a method of deriving the apparent sound speed from the internal structure of the thin-film cells was devised. By means of the above examination of the mechanism, findings were obtained to enable performance design of lightweight sound insulation material using thin-film cells.

## 1. Introduction

Due to further heightening of the demand for reduction of the environmental burden from automobiles, progress is being made in reducing vehicle weight in order to enhance fuel economy performance. There is also the widespread adoption of electric vehicles, which has been accompanied by further growth of customer demand for quietness.

One of the methods used to enhance quietness is the application of acoustic insulation material. The main indicators of performance for acoustic insulation material are the vibration suppressing performance, which indicates how much the material can damp vibration; sound absorption performance, which indicates how much the material can absorb the energy of sound waves; and sound insulation performance, which indicates how much the material can block the transmission of sound waves<sup>(1)</sup>. Sound insulation structures include the single wall, the double wall with air in the intermediate layer, the double wall with porous material that has breathable porous material inserted between the two walls, and others.

Figure 1 shows an example of the sound insulation structure generally used for automobile floors. In order to enhance the sound insulation performance of steel panels in

automobiles, a double wall with porous material structure using porous material and sheets of air-impermeable material is frequently adopted. Methods for further enhancing sound insulation performance include increasing the thickness of the steel panels, increasing the thickness of the porous material, increasing the areic mass of the air-impermeable sheet, etc. In general, weight reduction and sound insulation performance are mutually contradictory.

It has been reported in previous research that the use of a double wall with thin-film-cell structure that has thin-film cells inserted as an intermediate layer provides lighter weight than the conventional double wall with porous material structure while also yielding similar sound

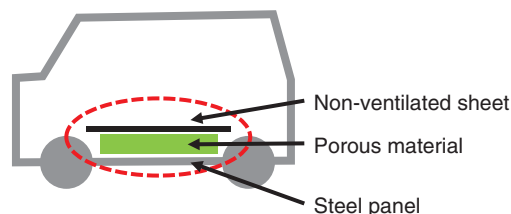


Fig. 1 Sound insulation structure of car

<sup>1</sup> Innovative Research Excellence

<sup>2</sup> Gunma University

insulation performance<sup>(2)</sup>. Figure 2 shows an example of thin-film cells, which are rows of cylindrical thin-film cells that include air.

Previous research has not clarified why the double wall with thin-film-cell structure using air-impermeable thin film that includes air can provide sound insulation performance similar to that type of structure using porous material.

The sound insulation performance of a double wall with porous material can be predicted using the Biot model<sup>(3)</sup>. The Biot model is a model of acoustic characteristics that takes into account the sound of the propagation through air of incident sound waves as they pass through the void portions of a porous material, the sound of their propagation through a solid body as they pass through framework components, and the interaction of these sounds. The parameters of the Biot model include flow resistance; viscous characteristic length, which is related to acoustic energy loss; thermal characteristic length, which is related to the amount of acoustic energy converted to heat, material damping, Young's modulus, and so on. There have been explanations of the mechanism of sound insulation performance that used these parameters. However, thin-film cells composed of thin film and air differ from porous material in that those components are heterogeneous materials so that their mechanism cannot readily be explained using the Biot model.

It is also known, however, that sound insulation performance can be enhanced by using a gas in the intermediate layer of the double wall with air for which the sound speed is slower than air<sup>(4)</sup>. It is also known that in porous material, the tortuous path length of the void portions through which sound passes is longer to enable the apparent sound speed to be lower than the sound speed in air<sup>(5)</sup>. This is said to be one of the reasons that the double wall with porous material structure has better sound insulation performance<sup>(6)</sup>. From this it can be inferred that apparent sound speed in the intermediate layer is one factor in the mechanism of sound insulation performance.

For the present research, therefore, the focus has been on the speed of sound wave propagation (apparent sound speed) as they are transmitted within thin-film cells in



Fig. 2 Thin-film cells

examining the mechanism whereby the double wall with thin-film cells provides sound insulation performance similar to the double wall with porous material. If this investigation could make it possible to predict performance by a simple and easy method, then it could serve as a guideline for examining specifications at the initial stage of performance design.

## 2. Relationship Between Sound Speed and Sound Insulation Performance

### 2.1. Comparison of Sound Insulation Materials

Figure 3 shows the single wall, double wall with air, and double wall with porous material structures. Figure 4 shows the sound insulation performance of these structures actually measured using a reverberation chamber. The sound insulation performance is shown as transmission loss, for which higher values indicate higher sound insulation performance. In the case of the double wall with air structure, sound insulation performance is enhanced relative to the single wall when the thickness of the intermediate layer is 100 mm or more, as in the double windows used in building construction. In the case of the thinner layers about 10 mm thick, as when used in automobiles, however, the figure decreases. On the other

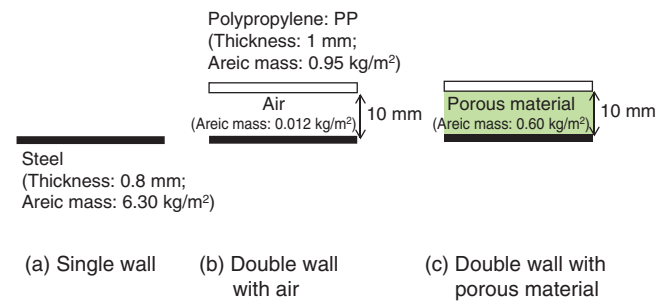


Fig. 3 Structure of sound insulation

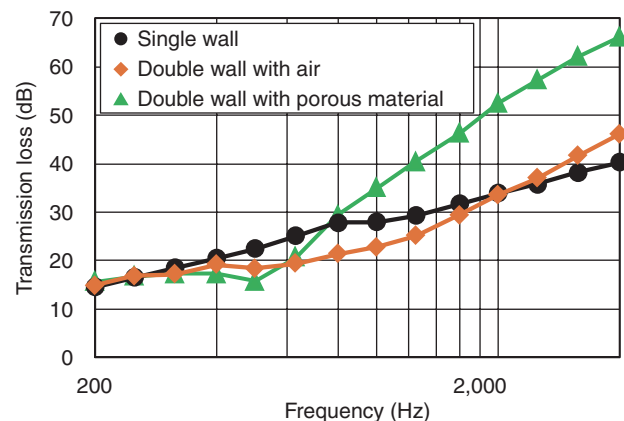


Fig. 4 Transmission loss

hand, the sound insulation performance is known to be enhanced when porous material is inserted into the thin intermediate layer. Here, the mechanism of this double-wall structure will be explained first.

## 2.2. Apparent Sound Speed and Sound Insulation Performance in the Double Wall with Air Structure

With a double wall with air, an incident plane wave with the incident angle  $\theta_i$  and sound speed  $C_i$  will have refraction angles  $\theta_n (= \theta_i)$  and sound speed  $C_n (= C_i)$  in intermediate layer  $n$ . According to Eq. (1), a larger incident angle will have a greater apparent sound speed expressed as  $C_{n-\theta n}$ . This phenomenon occurs regardless of the material in the intermediate layer.

$$C_{n-\theta n} = \frac{C_n}{\cos \theta_n} \quad (1)$$

For example, Fig. 5(a) shows an incident plane wave with an incident angle of  $0^\circ$  and sound speed  $C_i$  of 340 m/s, and Fig. 5(b) shows an incident plane wave with an incident angle of  $45^\circ$  and sound speed  $C_i$  of 340 m/s. In (a), the plane wave simultaneously arrives at the bottom surface of the intermediate layer, so that the sound speed of the intermediate layer is unchanged at 340 m/s. In (b), a portion of the oblique incident plane wave arrives at the bottom surface of the intermediate layer more quickly, so that the sound speed in the perpendicular direction  $C_{n-\theta n}$  has a greater apparent value, which according to Eq. (1) is 481 m/s.

With the double wall with air, a resonance is generated for which the areic mass of the wall is the mass and the intermediate layer acts as a spring. Its frequency  $f$  is expressed in Eq. (2).

$$f = \frac{1}{2\pi \cos \theta_n} \sqrt{\frac{(m_1 + m_2) \rho C_n^2}{m_1 m_2 l}} \quad (2)$$

$\rho$ : Density ( $\text{kg/m}^3$ ) of intermediate layer  
 $C_n$ : Sound speed (m/s) of intermediate layer  
 $m_1, m_2$ : Respective areic masses of the double walls ( $\text{kg/m}^2$ )  
 $l$ : Distance (m) between the double walls  
 $\theta_n$ : Refraction angles ( $^\circ$ ) of intermediate layer

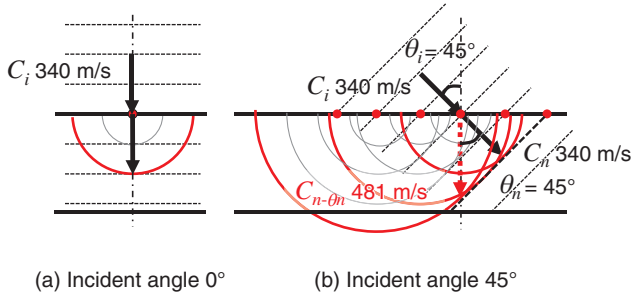


Fig. 5 Sound speeds depending on incident angles

For example, with the double wall with air shown in Fig. 3(b), the changes in sound insulation performance resulting from differing incident angles and sound insulation performance when the incident angles are random calculated from the transfer matrix method will be as shown in Fig. 6. When there is a single incident angle, the distance between the double walls is fixed so that there is one resonance frequency, and the sound insulation performance is higher at higher frequencies. As the incident angle grows larger, the apparent sound speed becomes greater according to Eq. (1) so that, in accordance with Eq. (2), the resonance frequency becomes higher and the sound insulation performance becomes lower. When sound insulation performance is measured using a reverberation chamber, the incident angles are random, resulting in the resonance frequency assuming all values from incident angles  $0^\circ$  to  $90^\circ$ , and reducing sound insulation performance as the calculated values show in Fig. 6.

## 2.3. Apparent Sound Speed and Sound Insulation Performance of Double Wall with Porous Material

Since porous material has a long and tortuous path, the plane wave takes more time to pass through the porous material and the apparent value of the sound speed will be lower<sup>(5)</sup>. This apparent sound speed due to distance is designated  $C_{di}$ .

In this case, an incident plane wave at incident angle  $\theta_i$  and sound speed  $C_i$  will become a plane wave propagated at refraction angles  $\theta_{di}$  inside the porous material according to Snell's law as shown in Eq. (3)<sup>(6), (7)</sup>.

$$\frac{\sin \theta_i}{C_i} = \frac{\sin \theta_{di}}{C_{di}} \quad (3)$$

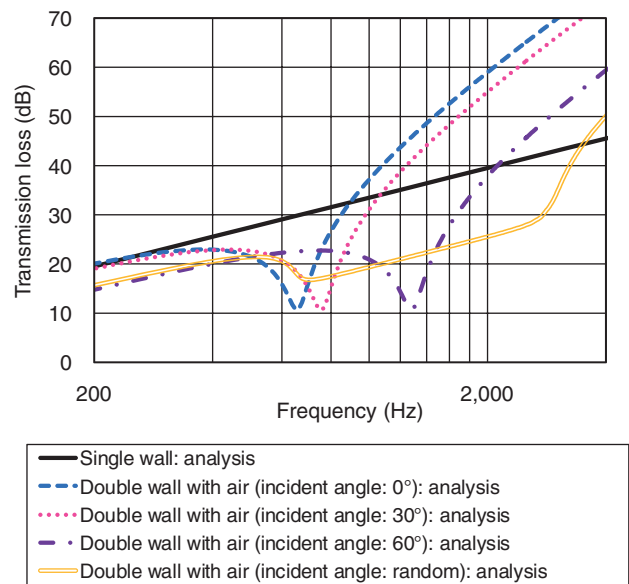


Fig. 6 Incident angles and transmission loss

Figure 7 shows an incident plane wave at incident angle  $\theta_i$  and sound speed  $C_i$  that passes through porous material with the apparent sound speed  $C_{di}$  due to the distance.

According to Eq. (1), the apparent sound speed  $C_{di-\theta di}$  resulting from the refracted plane wave becomes greater as expressed here in Eq. (4).

$$C_{di-\theta di} = \frac{C_{di}}{\cos \theta_{di}} \quad (4)$$

When the apparent sound speed of the intermediate layer is lower even in cases where incident angles are random, the refraction angles approach  $0^\circ$ , producing sound insulation performance with a higher value close to that shown in Fig. 6 for the incident angle of  $0^\circ$ .

In other words, when the apparent sound speed of the intermediate layer is lower, the sound insulation performance will be higher.

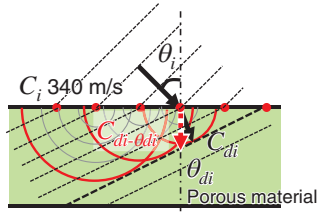


Fig. 7 Refraction angles depending on porous material

### 3. Mechanism of Apparent Sound Speed Reduction in Thin-film Cells

#### 3.1. Apparent Sound Speed of Thin-film Cells

According to previous research, the double wall with thin-film cells and double wall with porous material structures had similar sound insulation performance. It was inferred from this that thin-film cells were like porous material in having lower apparent sound speed.

The apparent sound speed of both structures was then calculated from normal incidence sound absorption coefficient measurements (ISO 10534-2) using a sound impedance tube with a diameter of 100 mm. Samples were

measured with a thickness of 100 mm and Fig. 8 shows the calculated apparent sound speed. Even though the thin-film cells are almost exclusively air, the apparent sound speed was less than the 340 m/s of air and was similar to the approximately 200 m/s of porous material.

#### 3.2. Time Delay of Sound Waves Due to Thin-film Transmission

Reasoning that the low apparent sound speed in thin-film cells was due to the time delay that occurred when the sound waves were transmitted through the thin film, the time delay of the sound waves was calculated. Figure 9 shows a conceptual drawing of the measurement method. Figure 9(a) shows the case without thin film placed between the sound source and the sound pressure measurement point, and Fig. 9(b) shows the case with thin film placed. The time until sound pressure was propagated to the measurement point was measured and the difference between times with and without thin film was calculated as the time delay of the sound waves.

Figure 10 shows the relationship between the time delay of sound waves due to the thin film and the number of thin films. It was found that increasing the number of thin films produced a greater time delay of sound waves. The time delay per single thin film was determined from the first order approximation curve in Fig. 10 to be 0.032 ms.

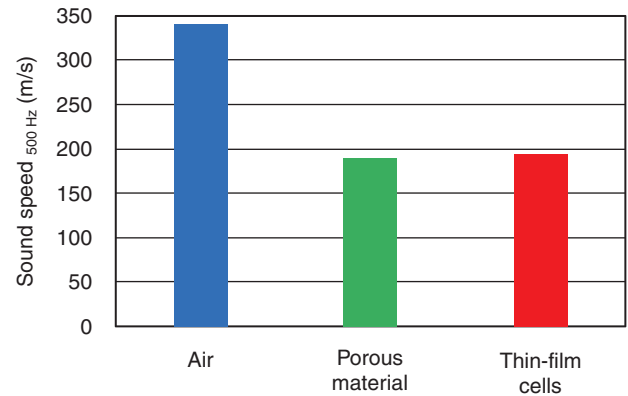


Fig. 8 Sound speed

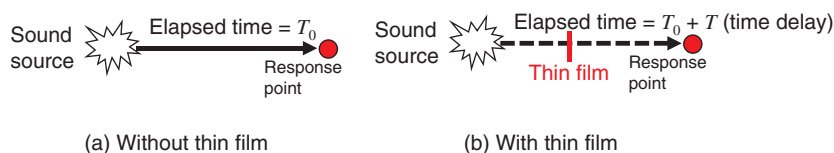


Fig. 9 Measurement of time

### 3.3. Reduction in Apparent Sound Speed Due to Thin-film Placement

From the fact that a time delay occurs in sound waves due to thin-film transmission, it can be reasoned that the apparent sound speed will decrease even more if multiple thin films are placed in the intermediate layer.

Figure 11(a) shows a plane wave that is obliquely incident to a double wall with air structure. The larger the incident angle, the higher the apparent sound speed  $C_{n-\theta_n}$ , so that the sound insulation performance decreases. On the other hand, Fig. 11(b) shows a plane wave that is obliquely incident to a double wall structure that has thin films placed in-plane. The larger the incident angle, the greater the number of thin films passed through, so that a time delay occurs in the sound waves and the apparent sound speed of the intermediate layer decreases. Taking this as the apparent value of sound speed  $C_{de}$  due to time delay, the apparent sound speed is expressed as  $C_{de-\theta_{de}}$ , which is lower than  $C_{n-\theta_n}$  in (a), so that the sound insulation performance can be considered to become higher than in (a).

Given the above examination, the mechanism by which a double wall with thin-film-cell structure possesses sound insulation performance similar to that provided by porous material was reasoned to be due to the decrease in apparent sound speed from the time delay of sound waves resulting from thin-film transmission.

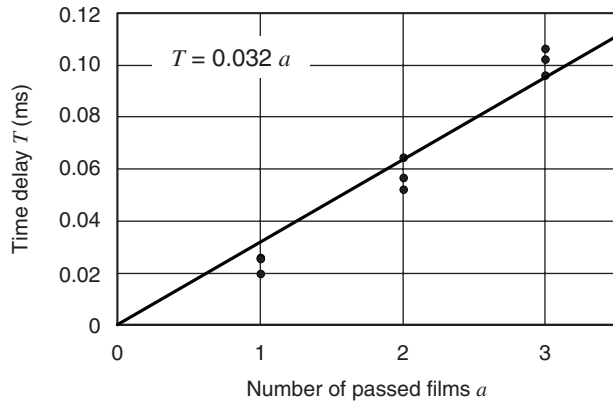


Fig. 10 Time delay of sound by number of thin films

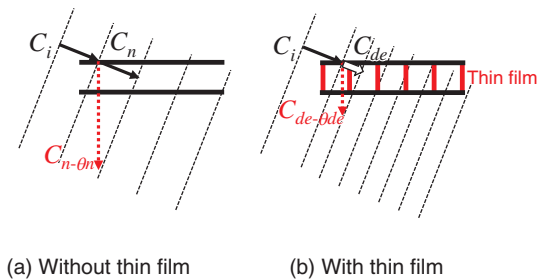


Fig. 11 Oblique incidence

## 4. Method of Verification

For direct verification of the hypothesis about this mechanism, the apparent sound speed of the intermediate layer using thin film would need to be determined. When the incident angles are random, however, since the apparent sound speed of the intermediate layer cannot readily be measured directly, the relationship between a structure using thin films and the apparent sound speed was formulated as an equation. Next, the relationship between apparent sound speed and sound insulation performance was formulated as an equation and the apparent sound speed that provides sound insulation performance similar to the double wall with porous material structure was calculated. Finally, a structure intended to realize an apparent sound speed that provides sound insulation performance similar to that of a double wall with porous material structure was created. By taking actual measurements of the sound insulation performance of the created structure, the validity of the hypothesis that sound insulation performance is enhanced by the time delay of sound waves caused by thin-film transmission was verified.

### 4.1. Formulation of an Equation for Apparent Sound Speed in Structures Using Thin Films

First, the relationship between a structure using thin films and apparent sound speed is formulated as an equation. Figure 12 shows a schematic diagram of thin-film arrangement. The thin-film structure is defined as having a height of  $l$  m, which is set as equivalent to the distance between the double walls, and the interval between thin films as  $y$  m. The number of thin films in a direction perpendicular to the wall surface is  $b$  (which is 2 in Fig. 12).

A plane wave that is incident to the thin-film structure with incident angle  $\theta_i$  and sound speed  $C_i$  will have refraction angles  $\theta_n (= \theta_i)$  within the thin-film structure. The distance  $l'$  that the wave travels through the thin-film structure is expressed by Eq. (5) and the time  $T'$  taken in traveling that distance is expressed by Eq. (6).

$$l' = \frac{l}{\cos \theta_n} \quad (5)$$

$l$ : Height (m) of thin-film structure

$\theta_i$ : Incident angle ( $^\circ$ )

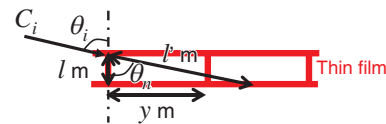


Fig. 12 Film arrangement

$$T' = \frac{l}{C_i} + at \quad (6)$$

$a$ : Number of thin films passed through

$t$ : Time delay per thin film (= 0.032 ms)

Here, the number  $a$  of thin films passed through is expressed by Eq. (7).

$$a = \frac{l \tan \theta_n}{y} + b \quad (7)$$

Therefore, the apparent sound speed  $C_{de}$  due to the time delay of sound waves passing through a thin-film structure is expressed by Eq. (8).

$$C_{de} = \frac{l}{T'} \quad (8)$$

Because a larger incident angle results in higher apparent sound speed, the apparent sound speed  $C_{de-\theta de}$  from Eq. (1) can be expressed as in Eq. (9).

$$C_{de-\theta de} = \frac{C_{de}}{\cos \theta_n} \quad (9)$$

When the incident angles are random, the average sound speed  $\overline{C_{de-\theta de}}$  is expressed by Eq. (10).

$$\overline{C_{de-\theta de}} = \frac{\int_0^{\frac{\pi}{2}} C_{de-\theta de} d\theta}{\int_0^{\frac{\pi}{2}} d\theta} \quad (10)$$

For the present research, the apparent sound speed was determined by seeking the average of incident angles from  $0^\circ$  to  $78^\circ$ <sup>(8)</sup> at  $1^\circ$  intervals using sound field incidence under conditions considered to be similar to those of an actual field.

Based on the above, the apparent sound speed can be determined by taking the thin-film structure height  $l$  and the thin-film arrangement interval  $y$  in the in-plane direction as parameters.

#### 4.2. Formulation of an Equation for the Relationship between Apparent Sound Speed and Sound Insulation Performance

In order to determine the apparent sound speed that yields the desired sound insulation performance, the relationship between apparent sound speed and sound insulation performance was formulated as an equation.

Figure 13(a) shows the model structure to be formulated in an equation. The relationships of sound speed, refraction, and sound insulation performance in a structure with a total of three layers consisting of an intermediate layer inserted into a double wall structure are to be formulated as an equation. In actual fact, while the

intermediate layer will not necessarily be uniform, here it is deemed to be so.

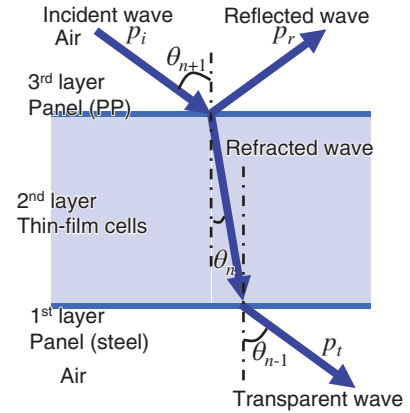
The intermediate layer was generalized as layer number  $n$  in a total of  $m$  layers through which a plane wave progresses. Figure 13(b) shows the generalized structure.

##### 4.2.1. Transfer matrix method for the intermediate layer

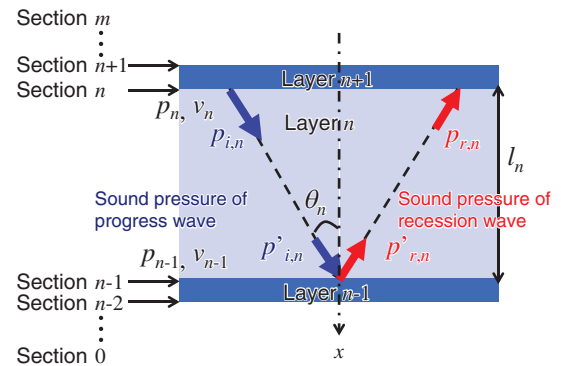
When a plane wave progresses through porous material or through a gas-like layer that is air-permeable, it becomes subject to resistance that depends on the particle velocity. In such cases, the amplitude and phase of the plane wave will change. On the hypothesis of a plane wave, the relationships of the sound pressure  $p_n$  and particle velocity  $v_n$  at cross-section  $n$  (on the incident side) of the media at layer number  $n$ , and the sound pressure  $p_{n-1}$  and particle velocity  $v_{n-1}$  at cross-section  $n-1$  are respectively expressed in Eqs. (11)-(14).

$$P_n = P_{i,n} + P_{r,n} \quad (11)$$

$$v_n = \frac{P_{i,n} - P_{r,n}}{W_{x,n}} \quad (12)$$



(a) Three-layer structure



(b) General structure

Fig. 13 Model structure

$$p_{n-1} = p'_{i,n} + p'_{r,n} \quad (13)$$

$$v_{n-1} = \frac{p'_{i,n} - p'_{r,n}}{W_{x,n}} \quad (14)$$

$p_{i,n}$ : Sound pressure (Pa) of the progressing wave at cross-section  $n$

$p_{r,n}$ : Sound pressure (Pa) of the receding wave at cross-section  $n$

$p'_{i,n}$ : Sound pressure (Pa) of the progressing wave at cross-section  $n-1$

$p'_{r,n}$ : Sound pressure (Pa) of the receding wave at cross-section  $n-1$

$W_{x,n}$ : Complex characteristic impedance when the plane wave is propagated in the  $x$  direction in layer number  $n$  of the media

$p_{i,n}$ ,  $p'_{i,n}$ ,  $p_{r,n}$ , and  $p'_{r,n}$  are determined from distance attenuation and can be expressed by Eq. (15).

$$\begin{aligned} p_{i,n} &= p'_{i,n} e^{jk_{x,n}l_n} \\ p'_{i,n} &= p_{i,n} [\cos(k_{x,n}l_n) - j\sin(k_{x,n}l_n)] \\ p_{r,n} &= p'_{r,n} e^{-jk_{x,n}l_n} \\ p'_{r,n} &= p_{r,n} [\cos(k_{x,n}l_n) + j\sin(k_{x,n}l_n)] \end{aligned} \quad (15)$$

$k_{x,n}$ : Wave number

$l_n$ : Thickness (m) at layer number  $n$

Sorting out Eqs. (11)-(15), the relationship between sound pressure and particle velocity at cross-section  $n$  and cross-section  $n-1$  can be expressed by Eq. (16). Here,  $T_{n,n-1}$  is the transfer matrix.

$$\begin{aligned} \begin{Bmatrix} p_n \\ v_n \end{Bmatrix} &= T_{n,n-1} \begin{Bmatrix} p_{n-1} \\ v_{n-1} \end{Bmatrix} \\ T_{n,n-1} &= \begin{bmatrix} \cos(k_{x,n}l_n) & jW_{x,n}\sin(k_{x,n}l_n) \\ \frac{j}{W_{x,n}}\sin(k_{x,n}l_n) & \cos(k_{x,n}l_n) \end{bmatrix} \end{aligned} \quad (16)$$

Here, when  $l_n \ll \lambda_{x,n}$ , since the equation  $k_{x,n}l_n = 2\pi \frac{l_n}{\lambda_{x,n}}$  is very small, it can be approximated as in Eq. (17).

$$\cos(k_{x,n}l_n) \cong 1, \sin(k_{x,n}l_n) \cong k_{x,n}l_n = \frac{\omega l_n}{C_{x,n}} \quad (17)$$

Therefore:

$$T_{n,n-1} \cong \begin{bmatrix} 1 & jW_{x,n}k_{x,n}l_n \\ \frac{j}{W_{x,n}}k_{x,n}l_n & 1 \end{bmatrix} \quad (18)$$

$$k_x = \frac{\omega}{C_{x,n}}, W_{x,n} = \rho_n C_{x,n}$$

$C_{x,n}$ : Sound speed (m/s) in the  $x$  direction in layer number  $n$

Therefore:

$$T_{n,n-1} = \begin{bmatrix} 1 & j\omega\rho_n l_n \\ \frac{j\omega l_n}{\rho_n C_{x,n}^2} & 1 \end{bmatrix} \quad (19)$$

Given that  $C_{x,n} = C_n \cos\theta_n$  and volume elastic modulus of  $\rho_n C_{x,n}^2 = E_n$  at layer number  $n$ ,

$$T_{n,n-1} = \begin{bmatrix} 1 & j\omega\rho_n l_n \\ \frac{j\omega l_n}{E_n \cos^2\theta_n} & 1 \end{bmatrix} \quad (20)$$

And from  $E_n = \frac{l_n}{K_n}$ :

$$T_{n,n-1} = \begin{bmatrix} 1 & j\omega\rho_n l_n \\ \frac{j\omega}{K_n \cos^2\theta_n} & 1 \end{bmatrix} \quad (21)$$

$\rho_n$ : Density (kg/m<sup>3</sup>) of layer number  $n$

$K_n$ : Spring constant (N/m) at layer number  $n$

$\theta_n$ : Angle (°) of plane wave at layer number  $n$

The spring constant  $K_n$  of layer number  $n$  is determined by FEM<sup>(2), (9)</sup>.

The angle  $\theta_n$  of the plane wave at layer number  $n$  in Eq. (21) is determined from the difference in the sound speed at the boundary surface according to Snell's law, Eq. (3)'.

$$\frac{\sin\theta_{n+1}}{C_{n+1}} = \frac{\sin\theta_n}{C_n} \quad (3)'$$

$\theta_{n+1}$ : Angle (°) of plane wave at layer number  $n+1$

$C_{n+1}$ : Sound speed (m/s) in layer number  $n+1$

$C_n$ : Sound speed (m/s) in layer number  $n$

Here, taking into account the sound speed in the intermediate layer was enabled by creating a model that incorporates Eq. (3)' in Eq. (21).

#### 4.2.2. Transfer matrix method for the wall plates

The wall plate transfer matrix  $T_{n,n-1}$  is expressed in Eq. (22)<sup>(4)</sup> by the mechanical impedance  $Z_{k,n}$  per unit area at layer number  $n$ , given the hypothesis of a plane wave.

$$T_{n,n-1} = \begin{bmatrix} 1 & Z_{k,n} \\ 0 & 1 \end{bmatrix} \quad (22)$$

Here, the mechanical impedance  $Z_{k,n}$  is expressed by Eq. (23).

$$Z_{k,n} = \gamma_{k,n} + j2\pi f \bar{m}_n \left[ 1 - \left( \frac{f}{f_{c,n}} \right)^2 \sin^2 \theta_{n+1} \right] \quad (23)$$

$$f_{c,n} = \frac{C_{n+1}^2}{2\pi} \sqrt{\frac{\bar{m}_n}{B_n (1 + j\eta_n)}}$$

$\gamma_{k,n}$ : Viscous damping coefficient per unit area of wall plate  
 $\bar{m}_n$ : Areic mass (kg/m<sup>2</sup>) of wall plate  
 $f_{c,n}$ : Coincidence limit frequency (Hz) of wall plate at layer number  $n$   
 $B_n$ : Bending rigidity (Nm<sup>2</sup>) of wall plate per unit area  
 $\eta_n$ : Loss factor of wall plate

#### 4.2.3. Transfer matrix method for laminated layers as a whole

The transfer matrix for the total number of layers  $m$  of the laminate as a whole is expressed by Eq. (24), which is the product of the individual transfer matrices.

$$T_{m,0} = T_{m,m-1} \cdot T_{m-1,m-2} \cdots T_{n+1,n} \cdot T_{n,n-1} \cdot T_{n-1,n-2} \cdots T_{1,0} \quad (24)$$

In the case of a double wall with thin-film-cell structure, there is a total of three layers (the steel-panel layer, the thin-film-cell layer, and the PP-panel layer), as in Fig. 13(a), so that it is expressed as the product of the three transfer matrices.

#### 4.2.4. Sound insulation performance of laminated layers as a whole

The relationship of the sound pressure and particle velocity at cross-sections 0 and  $m$  (on the incident side) for the total number of layers  $m$  of the laminate as a whole is expressed in Eq. (25).

$$\begin{Bmatrix} p_m \\ v_m \end{Bmatrix} = T_{m,0} \begin{Bmatrix} p_0 \\ v_0 \end{Bmatrix} \quad (25)$$

$$T_{m,0} = \begin{bmatrix} T_{m,0}^{(1,1)} & T_{m,0}^{(1,2)} \\ T_{m,0}^{(2,1)} & T_{m,0}^{(2,2)} \end{bmatrix}$$

Given the above, the transmissivity  $\tau$  can be expressed by Eq. (26).

$$\frac{p_m}{p_0} = T_{m,0}^{(1,1)} + \frac{T_{m,0}^{(1,2)}}{z_0} = \frac{1}{\tau(\theta)} \quad (26)$$

The transmission loss  $TL(\theta)$  at incident angle  $\theta_i$  can be expressed by Eq. (27).

$$TL(\theta) = 10 \log_{10} \left[ \frac{1}{\tau(\theta)} \right] \quad (27)$$

When incident angles are random, the average transmissivity  $\bar{\tau}$  at incident angles from 0 to  $\pi/2$  can be

expressed by Eq. (28) using hemispherical integration<sup>(4)</sup>. For the incidence here, as well, incident angles from 0° to 78° using sound field incidence were employed and the average transmissivity was calculated.

$$\bar{\tau} = \frac{\int_0^{\pi/2} 2\pi \tau \sin \theta \cos \theta d\theta}{\int_0^{\pi/2} 2\pi \sin \theta \cos \theta d\theta} \quad (28)$$

From the above, the transmission loss  $TL$  is expressed by Eq. (29).

$$TL = 10 \log_{10} \left( \frac{1}{\bar{\tau}} \right) \quad (29)$$

Figure 14 shows the relationship between sound insulation performance and apparent sound speed calculated using Eq. (29), where the spring constant of the intermediate layer is 9,400 N/mm, together with the actual measurement values for the sound insulation performance of a double wall with porous material. This confirmed that when the apparent sound speed is about 200 m/s, the resulting figure for sound insulation performance will be similar to that of the double wall with porous material used in the present research.

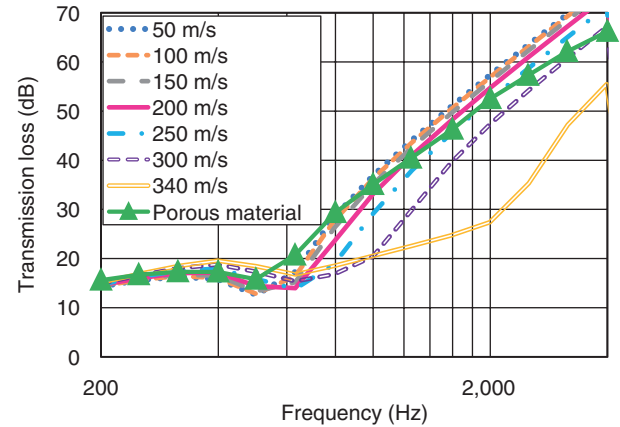


Fig. 14 Sound speed and transmission loss

## 5. Verification Results and Discussion

### 5.1. Verification by Structure Using Thin Films

Figure 15 shows the structure used for verification. Thin-film cells made primarily of polyethylene with a thickness of 0.1 mm were used and a structure was created that has cylindrical cells of 30-mm diameter and 10-mm height, containing air, at 4-mm intervals. When this structure is applied to the schematic diagram in Fig. 12,

the thin-film cells are placed at intervals of 17 mm, and the apparent sound speed of this structure is calculated using Eq. (10), the result of which is an estimated 216 m/s. In addition, the areic mass was 33% lighter in weight ( $0.5 \text{ kg/m}^2$ ) than the conventional double wall with porous material.

Figure 16 shows the actual measured sound insulation performance for the double wall with porous material and the actual measured sound insulation performance for the double wall with thin-film-cell structure estimated to have an apparent sound speed of 216 m/s, the sound insulation performance in the case of the apparent sound speed 216 m/s derived by formula.

Figure 16 indicates that generally similar results are achieved for sound insulation performance of a double wall with porous material structure, for sound insulation performance by the created double wall with thin-film-cell structure, and for sound insulation performance derived by formula.

Another structure was also created to confirm whether or not it would be possible to predict the performance of a different structure. This other structure was composed of a row of cylindrical cells of a 30-mm diameter and 5-mm height, containing air, at 4-mm intervals. Calculation of the apparent sound speed of this structure yielded an estimate

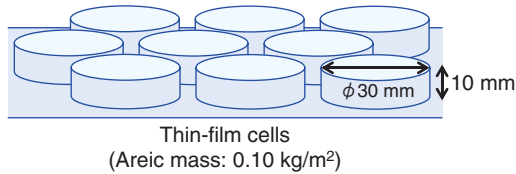


Fig. 15 Designed thin-film cells

of 153 m/s. Figure 17(a) shows actual sound insulation performance measurements for double walls with thin-film-cell structures of the heights 10 mm and 5 mm. Figure 17(b) further shows the sound insulation performance at the apparent sound speed calculated from those quantities as derived by formula. Since the structure of height 5 mm has a higher spring constant than the structure of height 10 mm, the resonance frequency is higher.

Similar trends were obtained from Figs. 17(a) and 17(b) for the actual measured sound insulation performance of the created double wall with thin-film-cell structure and the sound insulation performance determined by formula.

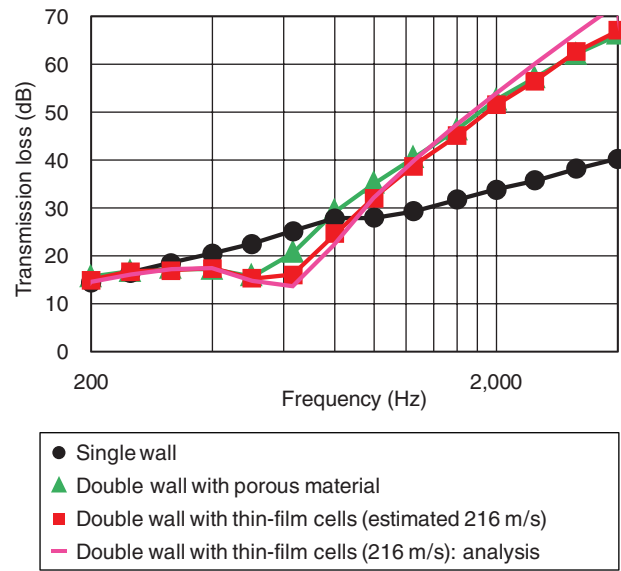
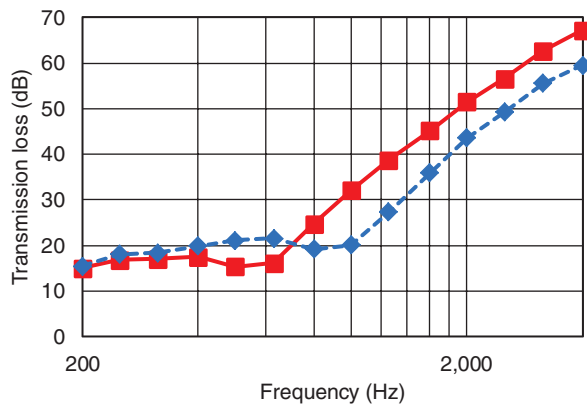
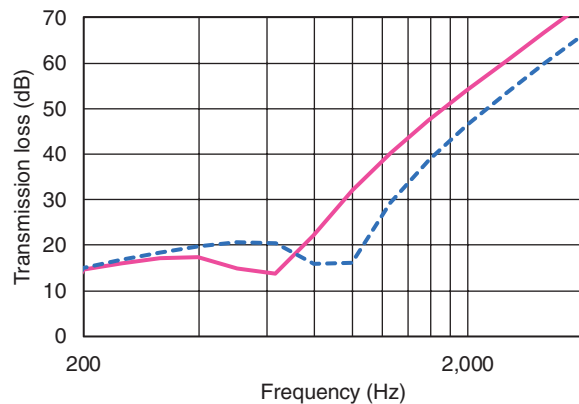


Fig. 16 Transmission loss in designed thin-film cells



| Design |                                                 |
|--------|-------------------------------------------------|
| ■      | $\phi$ : 30 mm; $l$ : 10 mm (estimated 216 m/s) |
| ◆      | $\phi$ : 30 mm; $l$ : 5 mm (estimated 153 m/s)  |

(a) Experimental



| Design                                   | Spring constant (N/mm) |
|------------------------------------------|------------------------|
| — $\phi$ : 30 mm; $l$ : 10 mm (216 m/s)  | 9,400                  |
| - - $\phi$ : 30 mm; $l$ : 5 mm (153 m/s) | 24,000                 |

(b) Analysis

Fig. 17 Transmission loss of double wall with different design of thin-film cells

## 5.2. Discussion

In the present research, the mechanism of a double wall with thin-film-cell structure was examined with a focus on the apparent sound speed in the intermediate layer. As a result, it was confirmed that the sound insulation performance calculated from the decrease in apparent sound speed caused by sound-wave time delay due to thin-film transmission realized values close to actual measurement results. The hypothesis was that thin-film cells produce sound insulation performance similar to that of porous material because the time delay of sound waves due to thin-film transmission causes the apparent sound speed to be lower, making the apparent sound speed become similar to that of porous material, and this hypothesis was judged valid.

The detailed mechanism of the double wall with thin-film cells is thought to comprise various complex phenomena, including the interaction of thin-film cells and the air inside them, reflection from the thin-film-cell walls, wave interference originating in the thin-film cells, differences in thin-film-cell materials, and so on. While a full grasp of this mechanism has not necessarily been achieved, the results of the present verification show that sound insulation performance and the apparent sound speed of the intermediate layer can be judged to be in close correlation, enabling these findings to be considered useful in the performance design of structures using thin films.

## 6. Conclusion

An examination was conducted of the mechanism of sound insulation in a double wall with thin-film-cell structure.

- (1) A method was devised for deriving the apparent sound speed in a double wall with thin-film-cell structure from the intervals between thin films and the height of the cells.
- (2) When a plane wave is more obliquely incident to a structure using thin films, the number of thin films passed through will be greater and the apparent sound speed will be lower.
- (3) The sound insulation performance calculated from a decrease in apparent sound speed that results from the time delay of sound waves caused by thin-film transmission will have a value similar to that of the actual measurement results.

Through the present research, it has become possible to conduct a quantitative evaluation of the sound insulation performance provided by a double wall with thin-film-cell structure. Detailed elucidation of the mechanism will require verification of the interaction of thin-film cells and the air inside them, the reflection from thin-film-cell walls, wave interference originating in the thin-film cells, and other such factors. However, this method will serve as relevant knowledge for the performance design of light weight sound insulation material using thin-film cells.

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## ■ Author ■



Ikumi KURIHARA



Takashi KONDO



Takao YAMAGUCHI