Theoretical Analysis and Measurement of Sound Transmission Loss in Louver Elements with a Sound Attenuating Function Using a Narrow Tube Array *

Shuichi SAKAMOTO**, Hokuto SATO***, Minoru YAMAZAKI ***, Ryohei SUGAHARA*** and Hiromichi KAWASE****
**Department of Mechanical and Production Engineering, Niigata University, 2-8050 Ikarashi, Nishi-ku, Niigata, Japan
E-mail: sakamoto@eng.niigata-u.ac.jp
*** Graduate School of Science and Technology, Niigata University
**** Dainichi Co., Ltd., 780-6 Kita-Tanaka, Minami-ku, Niigata, Japan

Abstract
Sound transmission loss is relatively small in thin louver boards with a high aperture ratio. This study investigated louver elements with a sound attenuating function. Using narrow tubes, an array silencer was built into composite louver boards and a high aperture ratio was maintained. Several constructions for such louvers were prototyped, measured, and analyzed theoretically. Sound transmission loss was measured using four-microphone impedance tube. Then, sound transmission loss was calculated by a transfer matrix based on one-dimensional axial coordinate system analysis. The attenuation of sound in tubes should be calculated because a thin louver board must comprise narrow tubes. Therefore, an accurate propagation constant and a characteristic impedance based on two-dimensional analysis were introduced to enable theoretical analysis. The calculation results, including attenuation, and the experimental results had good coincidence. Moreover, the theoretical analysis confirmed that the silencer worked effectively and could be applied to silencer designs.

Key words: Sound and Acoustics, Noise Control, Sound Transmission Loss, Array Silencer, Side Branch Silencer, Silencer Designs

1. Introduction
Louvers are used for many purposes. When installed at openings for ventilation, the angle of the louver elements can control the direction of airflow, light, and visibility from outside, in addition to keeping rain out. Sound transmission loss in louvers made from thin boards having a high aperture ratio is generally low, but there exist studies on various soundproof louvers[1][2]. Attempts have also been made to achieve active noise control[3] by adding a sound source to louvers.

This study investigates a louver that has a silencing structure. We use thin boards made of narrow tube elements aligned side by side as the louver elements, enabling installation of an arrayed silencer while maintaining a high aperture ratio. We made several such louvers and analyzed them experimentally and theoretically. First, we measured sound transmission loss using a four-microphone impedance tube. Next, we calculated the theoretical values of sound transmission loss using the transfer-matrix method. For narrow tube elements in thin-board louvers, attenuation in the tubes must be accounted for. Such sound attenuation occurs because of friction due to viscosity at the boundary layer of the tube’s inner wall,
which is the case in a porous sound-absorbing material having continuous pores. To account for the sound attenuation caused by the viscosity of air in the narrow tubes, we calculated the propagation constant and the characteristic impedance using Navier–Stokes equations. We examined sound absorbing characteristics by comparing the experimental and theoretical values of the obtained sound transmission loss. We report our results here.

2. Samples and Measuring Device

2.1 Samples

Fig. 1 shows the dimensions of the louver sample Type 01, which is the basis of each of the other four types. Five louver elements are attached to the inside of a cylinder whose external diameter and thickness are 100 and 0.5 mm, respectively. For Type 01, the frequency to be attenuated is unambiguously determined by the depth $l_{ap}$ of the louver elements. However, because $l_{ap}$ of the louver elements can be restricted by design, we examined the various forms shown below to ensure that it is possible to choose the attenuation frequency and transmission loss under a given restriction. Figs. 2–7 show the photographs and details of the louver elements of Types 01–05, respectively. Figs. 8 and 9 are the photographs of Type 01 samples with different narrow tube diameters.

Table 1 shows the positional relationship of the open ends of the narrow tubes and the sound source.

Table 2 shows the specifications of the tubes and samples, such as aperture ratio. Aperture ratio is defined as the ratio of the geometrically visible section when looking from one end to the other to the cross-sectional area of the 100-mm diameter sample. The aperture ratio is approximately 80% for Type 01, 73% for Types 02 and 05, and 55%–57% for Types 03 and 04. The cross-sectional shape of the narrow tubes of the louver elements is circular; thus, they suit the theoretical analyses described in Chapter 4. The tubes are made from polypropylene, and the average external and internal diameters of those used in the samples are 4.9 and 4.57 mm, respectively.

For Types 01–04, we supported the louver elements in the impedance tube by using a cylinder of external diameter and thickness approximately 100 and 0.5 mm, respectively. The cylinder was built with PET resin as the frame, and the louver elements were attached to its inside.

For Type 01 (Fig. 2), the depth of the louver elements $l_{ap}$ is 60 mm, and the axial direction of the narrow tubes coincides with the depth direction of the louver elements.

Type 02 louver (Fig. 3) also has an $l_{ap}$ of 60 mm, but because the narrow tube elements are inclined by approximately 30° from the propagation direction of the sound waves, the sound attenuating curve shift to the low-frequency side without increasing the depth of the louver elements. The lengths of the narrow tubes on the corner of the louver elements range from 10 to 70 mm.

Type 03 louver (Fig. 4) uses two of the 60-mm wide Type 01 louver elements stacked together.

Type 04 louver (Fig. 5) uses 120-mm long narrow tubes that are slit and folded such that $l_{ap}$ of the louver elements is 60 mm, doubling its thickness, and making the aperture ratio approximately the same as that of Type 03.

Type 05 louver (Figs. 6 and 7) has an $l_{ap}$ of 30 mm; the narrow tube elements are inclined by 60° from the propagation direction of the sound waves, and the lengths of all the
narrow tubes become 60 mm. Because the ends of the louver elements in Type 05 protrude radially from the impedance tube, we machined an aluminum alloy frame, which also serves as an extension of the impedance tube. How the sample is attached to the impedance tube is described in the next section. When the narrow tubes are inclined from the louver elements, if the louver elements are sufficiently long laterally, the effect of the ends (as seen in Type 02) would be relatively small, leading to results similar to those obtained with Type 05.

![Fig. 1 Typical dimension of test sample (Type 01)](image)

**Table 1** End condition of tube element

<table>
<thead>
<tr>
<th>Upstream side</th>
<th>Sound source side</th>
</tr>
</thead>
<tbody>
<tr>
<td>open</td>
<td>open</td>
</tr>
</tbody>
</table>

**Table 2** Typical specifications of test samples

<table>
<thead>
<tr>
<th></th>
<th>Type 01</th>
<th>Type 02</th>
<th>Type 03</th>
<th>Type 04</th>
<th>Type 05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter [mm]</td>
<td>2.5</td>
<td>3.5</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Outer diameter (average) [mm]</td>
<td>2.46</td>
<td>3.5</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Inner diameter (average) [mm]</td>
<td>2.32</td>
<td>3.26</td>
<td>4.57</td>
<td>4.57</td>
<td>4.57</td>
</tr>
<tr>
<td>Number of tubes</td>
<td>332</td>
<td>166</td>
<td>83</td>
<td>35+</td>
<td>156</td>
</tr>
<tr>
<td>Blocked area by louver elements [mm²]</td>
<td>1578</td>
<td>1597</td>
<td>1565</td>
<td>2092</td>
<td>3318</td>
</tr>
<tr>
<td>Aperture area of whole louver [mm²]</td>
<td>6120</td>
<td>6101</td>
<td>6133</td>
<td>5606</td>
<td>4380</td>
</tr>
<tr>
<td>Aperture ratio of whole louver</td>
<td>0.795</td>
<td>0.793</td>
<td>0.797</td>
<td>0.728</td>
<td>0.569</td>
</tr>
</tbody>
</table>
Fig. 2  Outlook of test sample and dimension of louver element (Type 01, diameter of tube: 4.9 mm)

Fig. 3  Outlook of test sample and dimension of louver element (Type 02)

Fig. 4  Outlook of test sample and dimension of louver element (Type 03)

Fig. 5  Outlook of test sample and dimension of louver element (Type 04)
This silencing structure, where arrayed side branch tubes are placed in the main tube, can be considered a variation of a side branch silencer. For a reactive silencer, the sharpness of the transmission loss peak is likely to change when internal attenuation increases; to determine if this is valid, we made samples with tubes of cross-sectional areas approximately 1/2 and 1/4 of that of Type 01, as shown in Figs. 8 and 9. To maintain approximately the same aperture ratios for the samples with tubes of nominal external diameters 4.9, 3.5, and 2.5 mm, we customized tubes of external diameters and thicknesses 3.5 and 2.5 mm, respectively.

Because a narrow gap with a long perimeter possess a significant sound-absorbing effect(4), gaps between the narrow tubes (external diameter 2.5 mm) of Type 01, Type 03 and Type 04 were filled with modeling clay to eliminate effects other than those due to the narrow tubes.

![Fig. 6 Outlook of test sample and dimension of louver element (Type 05)](image1)

![Fig. 7 CAD drawing of test sample (Type 05)](image2)

![Fig. 8 Outlook of test sample (Type 01, diameter of tube: 3.5 mm)](image3)

![Fig. 9 Outlook of test sample (Type 01, diameter of tube: 2.5 mm)](image4)
2.2 Measuring Transmission Loss

Fig. 10 shows the configuration of the measuring device. Samples were inserted in a Brüel & Kjær 4206T four-microphone impedance tube, and two microphones were attached to walls in front of and behind the samples. A sound wave was generated by a reference signal. After measuring the sound pressure before and after the sound wave passed through the samples using microphones, an AD converter, and the measurement software, we calculated the normal incidence transmission loss\(^5\). The sound pressure level measured by the microphone was approximately 102 dB. We confirmed in the preliminary experiment that there were no non-linear behaviors when the sound pressure level in the tube varied by about 30 dB.

Types 01–04 were inserted into the impedance tube along with their frames. To prevent sound absorption due to the gaps between the tube’s inner surface and the frames, the gaps were sealed with modeling clay.

Because Type 05 partly protrudes radially, the frame also serves as part of the impedance tube, as shown in Figs. 6 and 7. Fig. 11 shows the configuration when the sample is attached to the middle of the impedance tube.

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**Fig. 10** Four microphone impedance tube for transmission loss measurement

**Fig. 11** CAD drawing of extra size test sample type 05 between upstream side and downstream side impedance tube
3. Theoretical Analysis

3.1 Four-Terminal Constants of the Acoustic Tube Elements

We analyzed louvers made of narrow tubes using the transfer-matrix method (6)(7) with sound pressure and volume velocity based on the one-dimensional wave equation. Using the cross-sectional area \( S \) and length \( l \) of the narrow tubes, the characteristic impedance \( Z_c \) of the medium, propagation constant \( \gamma \), transfer matrix \( T_{\text{loss}} \) and four-terminal constants \( A_{\text{loss}} \)–\( D_{\text{loss}} \) of the acoustic tube elements are as described in Equation (1).

\[
T_{\text{loss}} = \begin{bmatrix} A_{\text{loss}} & B_{\text{loss}} \\ C_{\text{loss}} & D_{\text{loss}} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & \frac{Z_c}{S} \sinh(\gamma l) \\ \frac{S}{Z_c} \sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix}
\]  

(1)

\( T_{\text{loss}} \) denotes the transfer matrix when ignoring attenuation in the tube, which is used for the parts of the main tube other than the louver elements. In Equation (1), \( Z_c \) is the product of the speed of sound \( c_0 \) (343.7 m/s) in air and air density \( \rho_0 \) (1.2046 kg/m\(^3\)), \( j \) is the imaginary unit, and \( \gamma \) is the propagation constant. When ignoring attenuation in equation (1), \( \gamma \) becomes the wave number \( k \). The four-terminal constants \( A_{\text{loss}} \)–\( D_{\text{loss}} \) when ignoring attenuation are as described in Equation (2).

\[
T_{\text{loss}} = \begin{bmatrix} A_{\text{loss}} & B_{\text{loss}} \\ C_{\text{loss}} & D_{\text{loss}} \end{bmatrix} = \begin{bmatrix} \cos kl & \frac{j \rho_0 c_0}{S} \sin kl \\ \frac{j S}{\rho_0 c_0} \sin kl & \cos kl \end{bmatrix}
\]  

(2)

3.2 Acoustic Impedance of a Narrow Tube

Let \( p_1 \) and \( p_2 \) be the sound pressures and \( \dot{u}_1 \) and \( \dot{u}_2 \) be the particle velocities at the open and closed ends of a narrow tube, respectively. The transfer matrix is described as follows. For the transfer matrix, Equation (1) is used when attenuation in the narrow tube is accounted for, and Equation (2) is used when it is not accounted for. End correction for the narrow tube element was set to 0.6 times the inner radius of the tube because the tube had no baffles (8).

\[
\begin{bmatrix} p_1 \\ S\ddot{u}_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} p_2 \\ S\ddot{u}_2 \end{bmatrix}
\]  

(3)

Because the closed end of the narrow tube is a rigid wall with particle velocity \( \dot{u}_2 = 0 \), we get the following Equation.

\[
\begin{bmatrix} p_1 \\ S\ddot{u}_1 \end{bmatrix} = \begin{bmatrix} Ap_2 \\ Cp_2 \end{bmatrix}
\]  

(4)

From Equation (4), acoustic impedance \( Z_1 \) at the open end of the narrow tube can be described by the following equation.

\[
Z_1 = \frac{p_1}{S\ddot{u}_1} = \frac{A}{C}
\]  

(5)
Fig. 12 shows the equivalent circuit for the louver part and the impedance tube in front and behind the louver.

In the equivalent circuit, because the narrow tubes act as side branch tubes installed inside the main tube, the acoustic impedance of the narrow tubes are connected to the main tube in parallel. In the tube where plane waves are established, the position at which the impedance of each narrow tube is connected to the main tube is determined solely by its axial position. In this case, since the open ends of all the narrow tubes are located at the same axial position, the impedance is connected to the entrance of the louver element.

In Fig. 12, in case of the open ends of the tubes are facing the sound source, sound source is located on left side of Fig. 12. In other hand, in case of the closed ends are facing the sound source, sound source is located on right side of Fig. 12. Since it can be mathematically proven using Equation (10) that transmission loss is the same for these two cases, the calculated results are also the same. The experimental results (Chapter 4) also had almost the same values for the two cases.

First, we combine the impedance $Z_1$ of $N$ narrow tubes into a collective impedance $Z_A$, as follows.

$$Z_A = \frac{Z_1}{N} \quad (6)$$

Because Type 02 has narrow tube elements of different lengths, the reciprocal of the sum of the reciprocals of the impedances was used instead of Equation (6).

For the impedance $Z_A$ of the narrow tubes as side branch tubes, the transfer matrix of the parallel impedance can be described as follows.

$$\begin{bmatrix}
1 & 0 \\
\frac{1}{Z_A} & 1
\end{bmatrix} \quad (7)$$

Fig. 12 Equivalent circuit for narrow tubes and opening area between louver elements
($Z_1$: Impedance of each tube, $T_1$: Transfer matrix of opening area between louver elements, $T_0$: Transfer matrix of impedance tube)
Subtracting the cross-sectional area of the louver elements from that of the impedance tube gives the cross-sectional area $S_{ap}$ of the louver aperture.

The louver aperture can be treated as an acoustic tube of cross-sectional area $S_{ap}$ and length $l_{ap}$, and using Equation (2), it can be described as follows.

\[
\begin{bmatrix}
A_{ap} & B_{ap} \\
C_{ap} & D_{ap}
\end{bmatrix} =
\begin{bmatrix}
\cos kl_{ap} & j \frac{\rho_{0}c_{0}}{S_{ap}} \sin kl_{ap} \\
\frac{S_{ap}}{\rho_{0}c_{0}} \sin kl_{ap} & \cos kl_{ap}
\end{bmatrix}
\]  

(8)

Therefore, the transfer matrix of the entire louver can be described as follows.

\[
\begin{bmatrix}
A_{all} & B_{all} \\
C_{all} & D_{all}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
\frac{1}{Z_{\lambda}} & 1
\end{bmatrix}
\begin{bmatrix}
\cos kl_{ap} & j \frac{\rho_{0}c_{0}}{S_{ap}} \sin kl_{ap} \\
\frac{S_{ap}}{\rho_{0}c_{0}} \sin kl_{ap} & \cos kl_{ap}
\end{bmatrix}
\]  

(9)

Using the four-terminal constants on the left-hand side of Equation (9), the transmission loss $TL$ of the entire louver is described by Equation (10)\(^7\). The cross-sectional area of the impedance tube $S_{tube}$ at the front and back of the samples is reflected in the calculation results using Equation (10).

\[
TL = 10\log_{10} \left( \frac{A_{all} + \frac{S_{tube}}{\rho_{0}c_{0}} B_{all} + \frac{\rho_{0}c_{0}}{S_{tube}} C_{all} + D_{all}}{4} \right)^{1/2}
\]  

(10)

### 3.3 Propagation Constant and Characteristic Impedance with Sound Attenuation in Narrow Tube

For sound attenuation in the tube, Suyama and Hirata\(^9\) experimentally obtained the attenuation constant for an electric resistance welded steel tube of inner diameter >20 mm. For the propagation constant and characteristic impedance due to the viscosity of air in the tube, Tijdeman\(^10\) studied circular tubes and Stinson\(^11\) studied triangular and other forms of tubes.

In this study, to account for sound attenuation in the narrow tube, we used the Tijdeman method\(^10\). We derived the propagation constant $\gamma$ and characteristic impedance $Z_{\lambda}$ in the narrow tube by solving the Navier–Stokes equations, the continuity equation, gas state equation, and energy equation with respect to tube length direction and radial direction in a cylindrical coordinate system, using an approximation. Here we assumed that air is a compressible fluid and that the viscosity of air is constant. For boundary conditions, we assumed the axial and radial particle velocities at the tube wall to be 0, and the tube wall to be isothermal.

When attenuation is accounted for, $\gamma$ in the circular tube can be described as follows\(^10\). Here, $\kappa$ is the specific heat ratio of air (1.403), $\sigma$ is the square root of the Prandtl number (0.8677), $J_{0}$ and $J_{2}$ are Bessel functions of the first kind, $\mu$ is the viscosity of air (1.869 × 10\(^{-5}\) Pa·s), $R_{r}$ is the inner radius of the tube, and $\omega$ is the angular frequency.
Next, we show the characteristic impedance $Z_c$ in the narrow tube when attenuation is accounted for.

Using the particle velocity $u^+$ and sound pressure $p^+$ of the traveling wave, $Z_c$ is described by the following equation.

\[
Z_c = \frac{p^+}{u^+} \tag{12}
\]

$u^+$ and $p^+$ in a circular tube with attenuation are described by Equations (13) and (14), where $\beta$ is an arbitrary constant, $P_s$ is the atmospheric pressure ($1.013 \times 10^5$ Pa), $x$ is the position in the axial direction of a cylindrical coordinate system, $\eta$ is the position $r$ in the radial direction of the cylindrical coordinate system normalized by the inner radius $R_r$ of the tube, and $t$ is time.

\[
\tilde{u}^+ = c_0 \frac{j \gamma}{\kappa k} \left[ 1 - \frac{J_0\left(j^{3/2} \eta s\right)}{J_0\left(j^{3/2} s\right)} \right] (-\beta e^{-jx}) e^{j\omega t} \tag{13}
\]

\[
p^+ = P_s \beta e^{-jx} e^{j\omega t} \tag{14}
\]

The obtained $Z_c$ is a function of the radial position $r$. To apply $Z_c$ to Equation (1), it must be a function of frequency alone. Therefore, we averaged $Z_c$ across the cross-sectional area by integrating it with respect to $r$, and obtained $Z_c$ as a function of frequency, as described by Equation (15).

\[
Z_c = \frac{1}{\pi R_r^2} \int_0^{R_r} Z_c 2\pi r dr \tag{15}
\]

We obtained $\gamma$ and $Z_c$ in the narrow tube from Equations (11) and (15), respectively. By substituting these equations into $\gamma$ and $Z_c$ in Equation (1), we were able to account for sound attenuation in the narrow tube.

Fig. 13 shows the propagation constant $\gamma$ obtained from Equation (11). Fig. 14 shows the characteristic impedance $Z_c$ obtained from Equation (15), normalized by the specific impedance of air $\rho c_0$. Fig. 15 shows the sound attenuation per distance, converted from attenuation constant indicated by solid lines in Fig. 13. Fig. 16 shows the phase velocity, converted from phase constant indicated by dotted lines in Fig. 13.
In Fig. 14, as frequency increases, the solid and dotted portions of the characteristic impedance approach 1 and 0, respectively. This behavior is the same as that in a porous material, where solid-borne sound can be ignored \(^{(12)}\). Moreover, the value of the characteristic impedance \(Z_c\) deviates from the specific impedance of air as the inner diameter of the tube decreases, which also occurs when decreasing the size of the pores in a porous material.

Attenuation increases as frequency increases, as shown in Fig. 15, and speed of sound decreases as frequency decreases, as shown in Fig. 16; these behaviors are also the same as those in a porous material, where solid-borne sound can be ignored \(^{(12)}\). As expected, as the inner diameter of the tube decreases, attenuation increases (Fig. 15) and speed of sound decreases (Fig. 16).
4. Comparison between Calculation and Measurement Results

4.1 Calculation and Experimental Values for Types 01–05

Figs. 17–21 show the calculated and experimental values for Types 01–05, respectively. Calculated values with and without accounting for attenuation in the narrow tube element are also shown. Although the experimental values are expected to be the same regardless of whether the open or closed ends face the sound source, as stated in Section 3.3, values for both the cases are shown for verifying the experimental results. The two experimental results were almost the same.

First, we discuss the experimental values. For Types 01–05, shown in Figs. 17–21, peaks of transmission loss are observed at frequencies at which the effective length of the narrow tube element is 1/4 of the wavelength; i.e., in the cases of Type 01 (Fig. 17), Type 03 (Fig. 19), and Type 05 (Fig. 21), the peak of transmission loss is at approximately 1400 Hz because the effective length of the narrow tube element is 60 mm. Similarly, Type 02 (Fig. 18) has a peak at approximately 1200 Hz because the effective lengths of the narrow tube elements are mainly 70 mm, and Type 04 has a peak at approximately 700 Hz because the effective length of the bent narrow tube element is slightly shorter than 120 mm.

Next, we compare the calculated and experimental values. The calculated values that do not account for attenuation have very intense peaks, which is in contrast to the experimental transmission loss values. But the calculated values that account for attenuation agree with the experimental values relatively well. Here, all the calculated values that account for attenuation have transmission loss peaks that are only slightly sharper than those of the experimental values. This may be because frequency resolution for the experimental values is 50 Hz, whereas it is just 10 Hz for the calculated values. The base of the peak curves for the calculated values that account for attenuation are slightly thinner than those of the experimental values, which suggests that attenuation estimated by approximation was slightly smaller than the actual attenuation.

Now, we discuss the characteristics of each sample.

Type 02 (Fig. 18) exhibits lower frequency curves because it mainly has 70 mm long narrow tube elements, which are longer than those in Type 01 (Fig. 17). Because of the restriction due to the necessity of fitting in the impedance tube, there are many wasted narrow tube elements, as seen at the bottom-right of Fig. 3, reducing the effective number of narrow tubes, which account for the smaller overall transmission loss of Type 02. Moreover, there are short narrow tube elements, as seen at the bottom-left side of Fig. 3, and one that is 60 mm long in particular corresponds to the peak observed 1400 Hz.

Type 03 (Fig. 19) has the same transmission loss peak frequency as Type 01 (Fig. 17). However, since Type 03 has twice the number of narrow tube elements compared with Type 01, there is greater transmission loss. Type 03 has the same aperture ratio as in Type 04 (Fig. 20), and the throttle effect due to the louver’s aperture ratio, stated in the next section, is significant. Therefore, an extra transmission loss, shown using a blue line in Fig. 22, is added to the transmission loss due to the narrow tube element.

Type 04 (Fig. 20) is discussed in the next section.

In Type 05 (Fig. 21), the narrow tube elements are inclined by 60° from the propagation direction of the sound wave, and the length of the narrow tube element is 60 mm, twice as long as the 30 mm depth of the louver element. Therefore, the peak frequency of transmission loss for Type 05 is the same as that for Type 01 (Fig. 17). However, since
the total number of narrow tube elements in Type 05 is just 57% of the number in Type 01, transmission loss is smaller than in Type 01.
4.2 Discussion on Type 04

In Type 04 (Fig. 20), the narrow tube elements are folded such that the effective length of the narrow tube is twice the depth of the louver element. As a result, the peak frequency of transmission loss is approximately half that of Type 01 (Fig. 17).

Note that there is approximately 2 dB of transmission loss at frequencies higher than the peak frequency of transmission loss for Type 04, which is due to the difference between the effective length of the narrow tube element and the depth of the louver element. To explain this effect, on the right-hand side of Equation (9), we separately calculated transmission losses obtained from the first term, which represents the narrow tube elements, and the second term, which represents the throttle effect due to the aperture ratio of the louver.

Fig. 22 shows the calculation results. According to the calculated result based only on the first term, which represents the narrow tube elements on the right-hand side of Equation (9), the peak frequency is around 700 Hz, at which the length of the narrow tube (approximately 120 mm) is 1/4 the wavelength of the sound wave. There is, therefore, almost no transmission loss at frequencies higher or lower than the transmission loss peak. On the other hand, according to the calculated result based only on the second term, which represents the throttle effect, on the right-hand side of Equation (9), the peak frequency of transmission loss is around 1400 Hz, at which the depth of the louver element (60 mm) is 1/4 the wavelength of the sound wave. These two effects are superimposed to form the experimental and calculated results of Type 04 in Fig. 20.

For Type 01 and 03, the depth of the louver elements is the same as the effective length of the narrow tube element. Therefore, the peak (and dip) frequencies of transmission loss due to the narrow tube elements and those due to the throttle coincide with each other. As a result, the throttle effect in Figs. 17 and 19 can be seen as the broadened base of the transmission loss curve.

Similar to Type 04 (Fig. 20), the depth of the louver in the axial direction and the effective length of the narrow tube elements are different for Type 02 (Fig. 18) and Type 05 (Fig. 21). However, for Types 02 and 05, since the peak of transmission loss is close to the maximum frequency measurable with the experimental equipment, the effect is not very discernible in the graphs shown in Fig. 18 and 21. Furthermore, Types 02 and 05 have large apertures (i.e., small contraction ratios), which appears to be the reason for the abovementioned effect not being as pronounced as in Type 04.

4.3 Different Narrow Tube Diameters for Type 01

Figs. 23 and 24 compare the experimental and calculated values when the external diameter of the narrow tube elements in Type 01 is 3.5 and 2.5 mm, respectively. The calculated values that account for attenuation agree with the experimental values well, with the exception of the peak values. Moreover, in this case, the peak value of transmission loss decreases with decreasing diameter, in comparison with the case shown in Fig. 17, where the external diameter of the narrow tube element of Type 01 is 4.9 mm.

Fig. 25 compares all the experimental values and Fig. 26 compares all the calculated values. For the experimental and calculated values that account for attenuation, the peak values decrease and the bases of the curves widen with decreasing diameter. Thus, the sharpness of the peak changes as the diameter changes.

In addition, for both experimental and calculated values that account for attenuation, the peak frequency slightly decreases as the diameter decreases. This may be because of (1)
the decrease in the speed of sound due to the viscosity of air, as seen in the calculated results in Fig. 16. On the other hand, (2) the effect of additional mass at the open end geometrically decreases, and the peak frequency increases with decreasing diameter. In both experimental and calculated values that account for attenuation, effects (1) and (2) appear to negate each other, leaving only a slight effect of (1): a decrease in the speed of sound.

In the calculated values that do not account for attenuation (Fig. 26), only the effect of the decreased end correction value becomes apparent with decreasing diameter. Because tube length is estimated to be shorter for smaller diameters, in contrast to the experimental results, the peak frequency increases with decreasing diameter. For tubes with diameters larger than those used in this study, the effect of attenuation would be small, and the shape of the transmission loss curve would be similar to that of the calculated values that do not account for attenuation.

5. Conclusion

We made several louvers with silencing structures, measured transmission loss, conducted theoretical analyses, and obtained the following results.

(1) Using arrayed silencers with high aperture ratios, obtained by installing narrow tubes in louver elements, resulted in significant sound-absorbing performance at attenuation frequencies that correspond to the effective lengths of the narrow tubes.

(2) By inclining the narrow tube from the depth direction of the louver, installation of narrow tubes longer than the depth of the louver element in the louver becomes
possible, thereby decreasing the attenuation frequency.

(3) Attenuation frequency can be lowered by folding the narrow tube.

(4) We examined the characteristic transmission loss curves that appear in cases where there is a difference between the attenuation frequency based on the throttle effect due to the aperture ratio and that based on the length of the narrow tube.

(5) We performed theoretical analyses using the one-dimensional transfer matrix, by treating the narrow tubes installed in the louver element as arrayed side branch tubes connected in parallel. Finally, because the transmission loss curves of the calculated values that account for attenuation agreed well with those of the experimental values, calculated values appear to be useful in designing louvers.

References


