Study for louver with sound attenuating function using rectangular flat tubes of cross-sectional area decreasing along with longitudinal direction (Estimation and experiment of transmission loss)

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Received 27 March 2015

Abstract
In this paper, we propose a louver with a simple structure and a high aperture ratio. A louver element with a sound attenuating structure composed of layered two flat rectangular tubes, each of which is wedge-shaped with thickness decreasing toward the closed end, was constructed and experimentally and theoretically analyzed. Samples having more basic structures were also constructed and compared. In the theoretical analysis, the sound attenuation characteristics of a louver element were clarified considering sound attenuation in the clearance between two planes, as is typically observed in the flat rectangular tubes furnished in the louver element. To consider the sound attenuation due to the viscosity of the air in the rectangular tube, the propagation constant and characteristic acoustic impedance were derived using the Navier-Stokes equations, etc. Further, the sound transmission loss was calculated by the transfer matrix method. The tendency of the theoretical values in consideration of the attenuation of sound wave roughly agreed with the experimental values. Note that the attenuation of sound wave is evident in a thin or wedge-shaped tube and has to be considered in the theoretical analysis. The number of flat rectangular tubes was doubled without increasing the thickness of a louver element. The structure is useful as a louver slat because sound attenuation is achieved in a wide frequency range while maintaining a high aperture ratio.

Key words: Sound and acoustics, Noise control, Sound transmission loss, Wedge-shaped side branch, Silencer designs

1. Introduction

Louvers are installed in openings for ventilation and have various functions, such as the control of airflow, light, line of sight, and rain-cover, depending on the angle of slats. However, sound transmission loss is generally small in the louvers with thin slats and high aperture ratio. Studies have been performed on the various types of acoustic absorption louvers (Suzuki, et al., 2010) (Matsumoto, et al., 2011). An active noise control system was tested using louvers with sound sources added (Yamauchi, et al., 2010). This study concerns louvers with a sound attenuating function (Sakamoto, et al., 2013a) (Sakamoto, et al., 2014). In an earlier paper (Sakamoto, et al., 2013a), the authors achieved a silencing effect, which was effective while maintaining a high aperture ratio, by furnishing a muffler made of narrow tube elements in the form of thin plate arrays arranged in the louver element. However, the structure of a louver with narrow tubes is complicated. In addition, in the louver element in which two sound attenuating structures are stacked, the aperture ratio becomes small due to the
louver elements being twice as thick even if the bandwidth of transmission loss could be widened.

In this paper, we propose a louver with a simple structure and a high aperture ratio. A louver element with a sound attenuating structure composed of layered two flat rectangular tubes, each of which is wedge-shaped with thickness decreasing toward the closed end, was constructed and experimentally and theoretically analyzed. Samples having more basic structures were also constructed and compared.

In the theoretical analysis, the sound attenuation characteristics of a louver element were clarified considering sound attenuation in the clearance between two planes, as is typically observed in the flat rectangular tubes furnished in the louver element. To consider the sound attenuation due to the viscosity of the air in the rectangular tube, the propagation constant and characteristic acoustic impedance were derived using the Navier–Stokes equations, etc. Further, the sound transmission loss was calculated by the transfer matrix method (Suyama and Hirata, 1979a).

In the experiment, the sound transmission loss was measured using a four-microphone impedance measurement tube.

The results are reported on the sound attenuation characteristics by comparing the calculated and experimental values of sound transmission loss.

2. Measurement samples and measurement system

2.1 Measurement samples

Figure 1 shows the schematic of the constructed samples. Four louver elements of width 87.62 mm, depth 100 mm, and thickness \(H_o\) were attached inside a square tube of outer width 88.62 mm and thickness 0.5 mm. A louver element with an external thickness \(H_e\) encloses a set of flat rectangular tubes having one end open and the other end closed. These flat rectangular tubes function as a side branch muffler in the space. The materials used for the construction of the samples include PET resin plates for square tube, and SUS 304 plates for louver elements.

Three types of samples—Type 01, 02, 03—were constructed with different layout methods and different cross sections of the flat rectangular tube. The appearances of the samples are shown in Figures 2–4, and the specifications of Type 01–03 are as summarized in Table 1. Note that the shapes of Types 01 and 02 are more basic than Type 03.

For all louver element types, the length of the flat rectangular tube is 100 mm, and the internal width is 20 mm.

In Type 01, the external thickness of the element is \(H_o = 6\) mm, and the internal thickness of the flat rectangular tube \(H = 4\) mm. Because there are 4 flat rectangular tubes per louver element, 16 flat rectangular tubes are used in the whole sample.

In Type 02, the thickness of the external element is \(H_o = 11\) mm and the louver element has eight flat rectangular tubes; four open ends of the flat rectangular tubes are on the sound source side and another four on the other side. The internal thickness of the flat rectangular tubes is \(H = 4\) mm. Thus, the whole sample comprises 32 flat rectangular tubes.

In Type 03, similar to Type 02, four open ends of the flat rectangular tubes are on the sound source side and another four are on the other side. In Type 01 and Type 02, the thickness of internal tubes \(H = 4\) mm is constant from the open end to the other end. Conversely, Type 03 has a wedge-shaped flat rectangular tube with the thickness \(H = 4\) mm at the open end and \(H = 0\) mm at the close end. In other words, the flat rectangular tube of Type 02 is transformed into a wedge shape to become Type 03. Therefore, the number of flat rectangular tubes is eight per louver element; the aperture ratio equal to that of Type 01 is obtained while the thickness of the outside element is \(H_o = 7\) mm.

Here, the function of the three partition plates positioned in a louver element shall be explained. These partition plates are prepared to maintain the shape of the louver element, but are not acoustically needed. Because the width of the flat rectangular tube is 20 mm in the samples used in this paper, the upper limit frequency, within which the sound attenuation function is valid for a plane wave, is approximately 8.5 kHz so that the half wavelength of the sound wave is equal to 20 mm against the flat rectangular tube width of 20 mm. In other words, the sound frequencies of odd degrees can be dealt with when the partition plates divide the width of the louver element. Without partition plates, the width of the flat rectangular tube is 83 mm, and the upper limit frequency of sound attenuation is approximately 2 kHz.
Fig. 1  Typical dimensions of louver system (Basic straight tube: Type 01)

Fig. 2  Photograph of test sample and dimensions of louver element (Type 01)

Fig. 3  Photograph of test sample and dimensions of louver element (Type 02)

Fig. 4  Photograph of test sample and dimensions of louver element (Type 03)
Table 1  Typical dimensions of test samples

<table>
<thead>
<tr>
<th></th>
<th>Type 01</th>
<th>Type 02</th>
<th>Type 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>External thickness of louver elements [mm]</td>
<td>6</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Number of tubes per each element</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Blocked area by elements [mm²]</td>
<td>2130</td>
<td>3855</td>
<td>2454</td>
</tr>
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<td>Aperture area of whole louver [mm²]</td>
<td>5574</td>
<td>3822</td>
<td>5224</td>
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<td>Aperture ratio of whole louver</td>
<td>0.726</td>
<td>0.498</td>
<td>0.680</td>
</tr>
</tbody>
</table>

2.2 Equipment for measurement of transmission loss

Figure 5 shows the set up of the measuring equipment. The sample is enclosed in a *Brüel & Kjær* 4206T type four-microphone impedance measurement tube, and microphones are attached to the wall surface, two in the front and two behind the sample. After generating the sound wave of the reference signal and measuring the sound pressure with microphones before and after the transmission of the measurement sample, and also measuring using an FFT analyzer, the normal incidence transmission loss is calculated in accordance with ASTM E2611-09 and others (Ohi, et al., 2003). The sound pressure level measured by the microphones was about 102 dB. In addition, it was confirmed in a preliminary experiment that nonlinearity was not observed when changing the sound pressure in the by tube up to approximately 30 dB.

The cross-section of the impedance tube is circular, while the sample is a square tube. A wire-EDM was used to construct a sample holder for the sample and the converter tube in which the cross-sectional shape continuously changes from circle to square (or from square to circle) for connecting the sample tube with the impedance tube. The sample was inserted into the sample holder by sliding the frame of the sample. The cross-section shape changes from the border of converter tube and sample holder. Thus, the resin square tube for sample frame stays in sample holder. The resin square tube is under loose fit condition with the sample holder. The end part of the frame and the inside surface of the sample holder were sealed using modeling clay to prevent acoustic absorption in the clearance between the inside surface of the sample holder and the frame of the sample. By a preliminary experiment, it has been confirmed that there is no influence from the vibration of resin square tube of the sample frame.

![Fig. 5 Four microphone impedance measurement tube for transmission loss measurement](image1)

![Fig. 6 Sample holder and converter tubes](image2)
Figure 6 shows the perspective view of the converter tube and the sample holder. The length of a side of the square was set to 88.62 mm to realize the same cross section as against the inside diameter 100 mm of the impedance tube. It has been confirmed that such converter tube operates almost correctly by previous report (Sakamoto, et al., 2013b). In this setup, repeatability error of the transmission loss is less than approximately 0.1 dB.

3. Theoretical analysis
3.1 Four-terminal constants of a sound tube element
In the louver element, a plane wave exists when looking into a flat rectangular tube from the end. Therefore, the flat rectangular tube can be treated as a sound tube. With respect to the flat rectangular tube in a louver element, we perform an analysis using the transfer matrix method (Suyama and Hirata, 1979a) on the sound pressure and the volume velocity based on the one-dimensional wave equation. Assuming cross section $S$, length $l$, characteristic acoustic impedance of the medium $Z_c$, and propagation constant $\gamma$, the transfer matrix $T_{\text{loss}}$, and the four-terminal constants of the sound tube element $A_{\text{loss}}$–$D_{\text{loss}}$ are given by the following:

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

(1)

In addition, the transfer matrix ignoring attenuation in the tube—for the main tube (except for the louver element) —is given by replacing the characteristic acoustic impedance $Z_c$ in Eq. (1) with the product of the atmospheric speed of sound $c_0$ (343.7 m/s) and the density of the air $\rho_0$ (1.2046 kg/m$^3$) and replacing the propagation constant $\gamma$ with the product of the imaginary unit $j$ and the wave number $k$.

3.2 Acoustic impedance of the flat rectangular tube
Assuming the sound pressures as $p_1$, $p_2$, and particle velocities as $\bar{u}_1$, $\bar{u}_2$ at the open and closed ends, respectively, the transfer matrix is expressed as follows:

$$ \begin{bmatrix} p_1 \\ S\bar{u}_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} p_2 \\ S\bar{u}_2 \end{bmatrix} $$

(2)

Since the closed end of the flat rectangular tube is rigid, the particle velocity $\bar{u}_2 = 0$ is substituted into Eq. (2). Then, the acoustic impedance $Z_i$ viewed from the inlet of the tube is expressed, using $p_1$ and $S\bar{u}_1$, as follows:

$$ Z_i = \frac{p_1}{S\bar{u}_1} = \frac{A}{C} $$

(3)

3.3 Transfer matrix of Type 01
Figure 7 shows the equivalent circuit for the louver part of Type 01 and the impedance tube before and after it. Because it is thought that the resonator consisting of flat rectangular tubes acts as a side branch tube furnished inside the main tube, the acoustic impedance of the flat rectangular tube is connected in parallel with the main tube in the equivalent circuit. Among the positions at which the acoustic impedance of the flat rectangular tube is connected in parallel with the main tube, only the positions in the axial direction matter in the tube where a plane wave exists. In the case of Type 01, because the open ends for all flat rectangular tubes are at the same position in the axial direction, they are connected to the starting point of the louver element.
Then, by converging the acoustic impedance $Z_t$ of $N$ flat rectangular tubes into a single acoustic impedance $Z_A$, the following equation holds:

$$Z_A = \frac{Z_t}{N} \quad (4)$$

The transfer matrix of the whole louver is expressed by Eq. (5).

As for the acoustic impedance $Z_A$ of the flat rectangular tubes interpreted as a side branch tube, the transfer matrix for the parallel impedance is given by the first part in the right side of Eq. (5).

In addition, covering the area from the inlet to the outlet of a louver, the open area of the louver is expressed by the second part in the right side of Eq. (5) when interpreted as an acoustic tube disregarding the attenuation of cross section $S_{ap}$ (the area of the cross section of the impedance tube minus the cross section of the louver element) and length $l_{ap}$.

$$
\begin{bmatrix}
A_{all} & B_{all} \\
C_{all} & D_{all}
\end{bmatrix} = 
\begin{bmatrix}
1 & 0 \\
1/Z_A & 1
\end{bmatrix}
\begin{bmatrix}
\cos kl_{ap} & j \frac{\rho_0 c_0}{S_{ap}} \sin kl_{ap} \\
\frac{S_{ap} \sin kl_{ap}}{\rho_0 c_0} & \cos kl_{ap}
\end{bmatrix} \quad (5)
$$

Using the four-terminal constants in the left side of Eq. (5), the transmission loss $TL$ of the whole louver is given by Eq. (6). Here, the cross section of the impedance tube $S_{tube}$ before and after the sample is reflected in the calculation through Eq. (6).

$$
TL = 10 \log_{10} \left( \frac{A_{all} + S_{tube} C_{all} + D_{all} + B_{all} + \frac{\rho_0 c_0}{S_{tube}} C_{all}}{4} \right) \quad (6)
$$
3.4 Transfer matrix of Type 02

Figure 8 shows the equivalent circuit for the louver part of Type 02 and the impedance tube before and after it. In Type 02, there are flat rectangular tubes with the open end on the sound source side and the same on the other side. Thereby, the former and the latter groups of acoustic impedance are respectively connected to the starting point and the downstream end of the louver element.

![Equivalent circuit for thin rectangular tubes and opening area between louver elements.](image)

Fig. 8  Equivalent circuit for thin rectangular tubes and opening area between louver elements.  
(Z: Impedance of each flat rectangular tube,  \( T_{ap} \): Transfer matrix of opening area between louver elements,  \( T_0 \): Transfer matrix of impedance tube)

In Type 02, the open ends of flat rectangular tubes are at both the starting point and the endpoint of the louver element. Therefore, integrating the transfer matrix for the flat rectangular tube in the first part in the right side of Eq. (5) and the transfer matrix for the open area of a louver in the second part in the right side of Eq. (5), the transfer matrix of Type 02 is expressed as follows:

\[
\begin{bmatrix}
A_{all} & B_{all} \\
C_{all} & D_{all}
\end{bmatrix}
= \begin{bmatrix}
1 & 0 \\
\frac{1}{Z_A} & 1
\end{bmatrix}
\begin{bmatrix}
\cos kl_{ap} & j \frac{\rho c_0}{S_{ap}} \sin kl_{ap} \\
j \frac{S_{ap}}{\rho c_0} \sin kl_{ap} & \cos kl_{ap}
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
\frac{1}{Z_A} & 1
\end{bmatrix}
\]

(7)
3.5 Transfer matrix of Type 03

Because the positions of the flat rectangular tubes for Type 03 are similar to those for Type 02 as discussed earlier, the equivalent circuit becomes as shown in Fig. 8.

To obtain the acoustic impedance of a flat rectangular tube in the case that the internal thickness $H$ of the side branch tube decreases from the open end to the closed end as in Type 03, the internal thickness $H$ of the wedge-shaped cross section in the $x$–$z$ plane in Fig. 9(a) is approximated, as in Fig. 9(b). That is, the analysis assumes a tube in which the internal thickness $H$ changes by $n$ steps in the $x$ direction. The number of division $n$ for Type 03 calculations was 100. This is a number where the calculated values are sufficiently converged for Type 03.

![Fig. 9](image)

Approximation of clearance shape on Type 03

Therefore, assuming the transfer matrix $T_{H_i}$ of the internal thickness $H_i$ at the $i$-th step, the transfer matrix of an approximately wedge-shaped tube is obtained by the series connection of transfer matrices for the internal thicknesses $H_1$–$H_n$, and the equivalent circuit is expressed as shown in Fig. 10.

![Fig. 10](image)

Equivalent circuit for each clearance of Type 03

The equivalent circuit shown in Fig. 10 is expressed as a multiplication of transfer matrices as given by Eq. (8). Here, the four-terminal constants $A_{H_i}$–$D_{H_i}$ for $T_{H_i}$ is given by Eq. (1). In addition, $l$ in Eq. (1) is replaced by $l/n$ using the number of divisions $n$, and $S$ is the cross section obtained as a product of internal thickness $H_i$ of the flat rectangular tube and the width (length in the $y$-axis direction).

$$T_{H_{1ton}} = \begin{bmatrix} A_{H_{1ton}} & B_{H_{1ton}} \\ C_{H_{1ton}} & D_{H_{1ton}} \end{bmatrix} = \begin{bmatrix} A_{H_1} & B_{H_1} \\ C_{H_1} & D_{H_1} \end{bmatrix} \begin{bmatrix} A_{H_2} & B_{H_2} \\ C_{H_2} & D_{H_2} \end{bmatrix} \cdots \begin{bmatrix} A_{H_i} & B_{H_i} \\ C_{H_i} & D_{H_i} \end{bmatrix} \cdots \begin{bmatrix} A_{H_n} & B_{H_n} \\ C_{H_n} & D_{H_n} \end{bmatrix}$$  (8)

When a wedge-shaped flat rectangular tube is connected as a side branch tube, the acoustic impedance $Z_{H_{1ton}}$ is given, similar to Eq. (3), by Eq. (9). The theoretical value of Type 03 is obtained by substituting Eq. (9) into $Z_i$ in Eq. (4).

$$Z_{H_{1ton}} = \frac{A_{H_{1ton}}}{C_{H_{1ton}}}$$  (9)
3.6 Propagation constant and characteristic acoustic impedance in consideration of the attenuation of sound waves in the flat rectangular tube

As for the attenuation of sound waves in the tube, Suyama and Hirata experimentally derived an attenuation constant that is the real part of the propagation constant for tubes with an inside diameter greater than 20 mm (Suyama and Hirata, 1979b). For the propagation constant and the characteristic acoustic impedance in consideration of the air viscosity in the tube, studies were performed on a circular tube (Tijdemann, 1975) (Stinson and Champou, 1992), an equilateral-triangular tube (Stinson and Champou, 1992), and the clearance between two planes (Beltman, et al., 1998).

The attenuation of sound wave in the clearance between two planes is meaningful for a flat rectangular tube furnished inside a laminated louver element (Sakamoto, et al., 2013b). The attenuation originates from the friction with the viscosity in the boundary layer (Wesley, et al., 1958) near the wall of the flat rectangular tube—a mechanism similar to the case of a porous acoustic absorption material having continuous pores.

In this paper, the Beltman’s method (Beltman, et al., 1998) was applied to consider the attenuation of sound waves in the clearance in the tube of thickness $H$. A rectangular coordinate system in Fig. 11 was used for dealing with the clearance of thickness $H$ between two planes. The propagation constant $\gamma$ and the characteristic acoustic impedance $Z_s$ were derived in the clearance between two planes by approximately solving the Navier–Stokes equations, continuity equation, gas state equation, and energy equation. Here, it was assumed that the air was a compressible fluid and the air viscosity was a constant. We assumed the particle velocity in the $x$-, $y$-, and $z$-directions, acoustic sound pressure, and the density and temperature of air. $x$ is the position in the long direction of the rectangular coordinate system. $(y, z)$ are the coordinates in the cross section of the clearance. $\omega$ is the angular frequency. $P_t$ is the atmospheric pressure ($1.013 \times 10^5 \text{ Pa}$). $T_s$ is the air temperature. $u$, $v$, and $w$ are minute amounts of dimensionless amplitude of the velocities in the $x$-, $y$-, and $z$-direction. $p$, $\rho$, and $T$ are minute amounts of the dimensionless amplitude of pressure, density, and temperature perturbations.

\[
\vec{u} = c_0 u(x,y,z)e^{j\omega t}, \quad \vec{v} = c_0 v(x,y,z)e^{j\omega t}, \quad \vec{w} = c_0 w(x,y,z)e^{j\omega t}
\]
\[
\vec{P} = P_t \left(1 + \rho'(x,y,z)e^{j\omega t}\right), \quad \vec{\rho} = \rho_0 \left(1 + \rho'(x,y,z)e^{j\omega t}\right), \quad \vec{T} = T_s \left(1 + T'(x,y,z)e^{j\omega t}\right)
\]

(10)

Then, we derived the following equations by substituting the assumed variables in the Navier–Stokes equations, a gas state equation, a continuity equation, and an energy equation. Where $a$ is the width of the plane, $\kappa$ is the specific heat ratio ($1.403$), $\sigma$ is the square root of the Prandtl number ($0.8677$), and $\mu$ is the viscosity ($1.869 \times 10^{-5} \text{ Pa} \cdot \text{s}$).

\[
ju = -\frac{1}{\kappa \omega l} \frac{\partial p}{\partial x} + \frac{1}{s^2} \frac{\partial^2 u}{\partial z^2}, \quad jv = -\frac{1}{\kappa \omega a} \frac{\partial p}{\partial y} + \frac{1}{s^2} \frac{\partial^2 v}{\partial z^2}, \quad -\frac{1}{\kappa} \frac{\partial p}{\partial z} = 0, \quad s = H \sqrt{\frac{\rho_0 \omega}{\mu}}\]

(11)

\[
\frac{H}{l} \frac{\partial u}{\partial x} + \frac{H}{a} \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = -j \frac{\omega H}{c_0} \rho
\]

(12)

\[
p = \rho + T
\]

(13)

\[
JT = \frac{1}{s^2 \sigma^2} \frac{\partial^2 T}{\partial z^2} + j \frac{\kappa - 1}{\kappa} p
\]

(14)

The assumed boundary condition was that the particle velocity was zero on the tube wall surface and the internal wall was isothermal. In the clearance between two planes, the propagation constant $\gamma$ in consideration of attenuation is given by the following Equation (Beltman, et al., 1998).
Then, in consideration of attenuation, the characteristic acoustic impedance $Z_c$ of a flat rectangular tube will be discussed below.

Assuming the particle velocity and the sound pressure of a traveling wave $\tilde{u}^+$ and $p^+$, the characteristic acoustic impedance $Z_c$ is given by

$$Z_c = \frac{p^+}{\tilde{u}^+}$$  \hspace{1cm} (16)

In the flat rectangular tube with attenuation, $\tilde{u}^+$ and $p^+$ are given by Eqs. (17) and (18), respectively (Beltman, et al., 1998). Here, $\beta$ is an arbitrary constant.

$$\tilde{u}^+ = c_0 B(s) \frac{j}{\kappa} \left( -\frac{\gamma}{k} \right) \beta e^{-\lambda s}$$  \hspace{1cm} (17)

$$p^+ = P \beta e^{-\lambda s}$$  \hspace{1cm} (18)
Using Eqs. (15) and (16), the propagation constant $\gamma$ and the characteristic acoustic impedance $Z_c$ were obtained, respectively, in the clearance in a flat rectangular tube. The attenuation of sound wave in a flat rectangular tube was considered by substituting these values into $\gamma$ and $Z_c$ in Eq. (1).

The characteristic acoustic impedance $Z_c$ obtained from Eq. (16) and the propagation constant $\gamma$ obtained from Eq. (15) were already shown in a previous paper (Sakamoto, et al., 2014). According to the results, the following three tendencies are enhanced as the clearance decreases: the characteristic acoustic impedance $Z_c$ becomes different from the characteristic impedance of the air; the real part of the propagation constant—namely, attenuation constant—increases; and the sound velocity, which is derived from the imaginary part of the propagation constant $\gamma$, decreases. These tendencies are similar to those found in porous materials (Koshiroi and Tateishi, 2012) in which solid-borne sound is ignored.

4. Comparison between calculation and measurement

4.1 Results of the respective types

Figure 12 shows the experimental and theoretical results of Type 01. In the experiment, a transmission loss peak of little less than 14 dB appears at around 850 Hz corresponding to the flat rectangular tube length of 100 mm. Also, the theory considering the attenuation of sound wave in the clearance in the flat rectangular tube indicates a peak at around 850 Hz, which is close to the peak in the experiment. However, in the theoretical results disregarding the attenuation of sound wave, the peak frequency agrees with the experimental value, but the peak value is approximately 24 dB, which differs greatly from the experimental value.

Figure 13 shows the experimental and theoretical results of Type 02. The peak frequency is close to that for Type 01. However, the peak value is approximately twice that of Type 01. The reason is that the number of the flat rectangular tubes per louver element is twice of that in Type 01. In addition, as in Type 01, the theoretical value considering the attenuation of sound wave is closer to the experimental value compared to the theoretical value disregarding the attenuation.

Figure 14 shows the experimental and theoretical results of Type 03. It is shown that the peak frequency of the transmission loss agrees between the experiment value and the theoretical value considering the attenuation of sound wave. However, the theoretical peak is approximately 20 dB whereas the experimental peak is approximately 14 dB; further, the bandwidth at the peak is wider in the experiment. This can be interpreted as follows: The sample is assembled manually by adhesion, and so the position varies near the tip having a close to zero internal thickness in the flat rectangular tube. The measured tube length is distributed between 94–99 mm. It is considered that the distributed tube length makes the bandwidth at the peak wider and the peak value smaller. Note here that the theoretical value was calculated using the average of the measured tube length.

In addition, in Fig. 14, without the attenuation of sound wave, not only is the theoretical peak sharper but also the peak frequency is shifted towards the high frequency side, compared with the theoretical value considering the attenuation of sound wave. This result indicates that in a wedge-shaped tube containing a thin area, (Type 03) the attenuation of sound wave influences the peak frequency more strongly compared with Type 01 and 02. Thus, it is important in the theory dealing with a wedge-shaped tube to consider the attenuation of sound waves. In all three types, in the theory considering the attenuation of sound wave, the theoretical peak value is larger than the experimental value. The reason is considered as follows: In these samples, the internal wall of a flat rectangular tube includes partition plates, whereas the partition plates are not considered in the analytical model in Fig. 11. It is considered that attenuation of sound waves is considered in theory but not to the same degree in reality.
4.2 Sound attenuation bandwidth of Type 03

Figure 15 compares the experimental and theoretical results of Type 01–03. Type 03 shows different sound attenuation frequencies compared with Type 01 and 02. The horizontal axis uses a logarithmic scale for comparison. In addition, Table 2 shows the bandwidth of transmission loss exceeding 5 dB in the three Types.

In Fig. 15, the peak transmission loss is at about 850 Hz in the case of Type 01 and 02, and at about 1200 Hz in the case of Type 03. The reason is considered to be that the flat rectangular tube of Type 03 is wedge-shaped. The resonance frequency is known to shift to the high frequency side in a tapered tube (Washio, et al., 1974).

In addition, in Table 2, the comparison between Type 01 and Type 02 shows that the peak transmission loss is larger and the bandwidth is wider in Type 02 because the number of the flat rectangular tubes of Type 02 is double. So, in Type 02, the louver element is twice as large and the aperture ratio is lower compared with Type 01.

Here, the peak value and the bandwidth of Type 01 and Type 03 are compared. In Type 03, the aperture ratio is equal to that of Type 01, whereas the peak value is larger and the bandwidth is wider. It can be said that it is useful to use wedge-shaped flat rectangular tubes in a louver element as in Type 03 because sound attenuation is achieved in a wide frequency range while maintaining a high aperture ratio.
Fig. 15  Experiments and calculations (Type 01, 02, 03)

Table 2  Bandwidth of transmission loss at threshold level 5 dB

<table>
<thead>
<tr>
<th>Type</th>
<th>$f_1$ [Hz]</th>
<th>$f_2$ [Hz]</th>
<th>Bandwidth [oct.]</th>
<th>Peak value [dB]</th>
<th>Aperture ratio</th>
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<tr>
<td>Type 01</td>
<td>Experiment</td>
<td>787.5</td>
<td>875</td>
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<td></td>
<td>Calculation</td>
<td>787.5</td>
<td>862.5</td>
<td>0.131</td>
<td>15.7</td>
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<tr>
<td>Type 02</td>
<td>Experiment</td>
<td>737.5</td>
<td>925</td>
<td>0.327</td>
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<td></td>
<td>Calculation</td>
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<td>0.346</td>
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<td>Type 03</td>
<td>Experiment</td>
<td>1087.5</td>
<td>1287.5</td>
<td>0.244</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>Calculation</td>
<td>1112.5</td>
<td>1262.5</td>
<td>0.183</td>
<td>19.9</td>
</tr>
</tbody>
</table>

5. Conclusion

This study was performed on a sound attenuation structure in which flat rectangular tubes were incorporated in a louver element, and with the following results:

The flat rectangular tube was wedge-shaped with the thickness decreasing towards the closed end. By stacking two of them, the number of flat rectangular tubes was doubled without increasing the thickness of a louver element. The structure is useful as a louver slat because sound attenuation is achieved in a wide frequency range while maintaining a high aperture ratio.

The tendency of the theoretical values in consideration of the attenuation of sound wave roughly agreed with the experimental values. Note that the attenuation of sound wave is evident in a thin or wedge-shaped tube and has to be considered in the theoretical analysis.

Acknowledgment

This work was supported by Sasaki Environment Technology Foundation.
References


