Study of arrayed side branch silencer for ventilation door
(Theoretical analysis and measurement of transmission loss)

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Abstract
This study focuses on acoustic silencers on indoor-use doors positioned in an array. In this paper, we discuss our studies of side branch silencers which are built in the ventilation door. By designing and fabricating a special attachment, we were able to attach silencers to the measurement tube that had larger cross sections than the impedance measurement tube. Using this attachment, we measured acoustic transmission losses for each of six different prototype silencers. By adding orifice silencer effects, we obtained transmission losses across a wide frequency range. However, attenuation decreased in frequency ranges below the attenuation peak of the side branch tubes. A wedge-shaped longitudinal cross section for the side branch tubes can double the length of the silencer and develop lower-frequency attenuation effects, while maintaining the same volume. This wedge-shaped side branch tube is suitable for a long silencer placed side by side in an array formation. We performed theoretical analyses of acoustic transmission losses of silencers using the transfer matrix method based on a one-dimensional wave equation. We performed element decomposition on the transfer matrix for silencers with side branch tubes with a wedge-shaped longitudinal cross section. We obtained calculated results that were sufficiently valid compared to our experimental measurements.

Key words: Noise control, Sound transmission loss, Side branch silencer, Ventilation door, Silencer designs

1. Introduction

For a sustainable society, natural ventilation offers two important advantages: it does not consume energy, and does not generate noise. In Japan, houses are becoming increasingly air-tight and are often fitted with thermal installations. However, housing with high air-tightness may not meet ventilation standards established in the Building Standard Law, creating problems of physiological sustainability and health. Thus, the demand for so-called “ventilation doors” is expected to continue to rise. However, ventilation doors with large aperture ratios can prevent acoustic transmission loss from being achieved.

This study focuses on acoustic silencers on indoor-use doors positioned in an array. To enable natural ventilation that allows people to feel refreshed, indoor-use ventilation doors require an aperture ratio of approximately 1/3 (Yamaguchi, et al., 2005). Thus, we investigated a silencer with an aperture ratio of 1/3, for more than 500 Hz which is the range that contains many first formants and all second formants in human voices (Peterson and Harold, 1952). One important aim of this study is to investigate an effective configuration for silencers within a limited space.

The study of the performance of the ventilation door is conducted (Yamada, et al., 2014), and the commercialization of the ventilation door is also performed. However, sound insulation performance of the ventilation door is not studied.
There have been studies on silencers that apply large aperture ratios, such as louvers with silencing functions (Sakamoto, et al., 2014a), (Yamaguchi, et al., 2010), (Matsumoto, et al., 2011) and silencers for dog cages (Sakamoto, et al., 2014b).

An acoustic tube that is closed at one end that placed in the space acts as a side branch silencer. For example, using an array silencer formed of thin plate-like lined narrow tubes as louver slats, we can obtain significant attenuation effects while maintaining a high aperture ratio (Sakamoto, et al., 2013b).

In this paper, we discuss our studies of side branch silencers which are built in the ventilation door. To evaluate the silencer, we determined acoustic transmission losses by theoretical analysis and experimentation.

In the theoretical analyses, we calculated transmission losses by the transfer matrix method with accounting for sound attenuation in the branch tube. We analyzed a side branch tube in which the cross-sectional form changes continuously through a component decomposition of the transfer matrix. This allowed us to conduct a simulation to find the optimal shape of the silencer. Based on this theoretical analysis, we created prototype silencers and conducted measurements of the transmission loss using a special made sample holder of extra size for a four-microphone impedance measurement tube.

2. Test samples and measurement apparatus
2.1 Apparatus for transmission loss measurement

A schematic of the measuring apparatus is shown in Fig. 1. Measurements of transmission loss were performed by placing a prototyped silencer within a Brüel & Kjær type 4206T four-microphone impedance measurement tube. Two microphones were placed on the wall of the tube in front of the test sample and two were placed behind the test sample. Reference signals between 50 Hz and 1600 Hz were used to generate sound waves. The microphones measured the sound pressure before and after waves passed through the test sample; subsequently, these signals were sent to an FFT analyzer. We calculated the normal incident transmission loss according to ASTM E2611-09 (Ohi, et al., 2003).

Figure 2 shows a schematic of the test sample positioned between the impedance measurement tubes. As mentioned in the following section, the silencer was positioned between two base plates with apertures. The test sample was made of an aluminum alloy; by combining block materials, silencers having a variety of dimensions and shapes could be formed. To ensure that no sound absorption or leakage occurred from gaps in the blocks that made up the silencer or the connections between the silencer and the impedance measurement tube, we sealed all connections with petroleum jelly.

Fig. 1 Four microphone impedance tube for transmission loss measurement

Fig. 2 Sectional view of test sample holder of extra size between upstream side and downstream side of impedance tube
2.2 Available volume of silencers

Figure 3 shows the area of the base plate aperture. The circular area of the impedance measurement tube has an internal diameter of 100 mm, which is 12 times the area of a square having sides of 25.58 mm. So, if four square apertures, each with sides of 25.58 mm, are placed within a 100-mm diameter circle, the aperture ratio is 1/3. In this apparatus, for ease in fabricating the apertures, we used squares with sides of 25.7 mm. The total area of the four apertures was \( S_1 = 2642 \text{ mm}^2 \), and the total area of the remaining closed surface was \( 2S_1 = S_2 = 5284 \text{ mm}^2 \).

Figures 4 and 5 show the top and cross-sectional views of the Type 2 silencer. In Figure 4, the total area of the aperture is \( S_1 \), and the total area of the four side branch tubes in the top view is \( S_2 \). In this case, ignoring the thickness of the material (the dark shaded portion), the aperture ratio is 1/3. To eliminate sound transmitted through the materials in the test samples used in the experiments, we used a 12-mm-thick aluminum alloy. In actual applications, the device could be constructed using plywood or medium-density fiberboard with a thickness of only a few mm, approaching the aperture ratio of 1/3.

Figure 5 shows the silencer inserted and attached to the impedance measurement tube. There is a 25.7-mm space in the thickness direction of the silencer. Let us consider the space between the surface materials of both sides of the door as 25.7-mm-thick shown in Fig. 5. This case is the same as for the area discussed above for Fig. 4, but extended to the volume. In other words, we can use eight cubes with 25.7-mm sides as the volume of the silencer. In this paper, eight times the volume of a cube with 25.7-mm sides is used as the side branch silencer volume for the silencers tested (Types 2–6).

Figure 6 shows an example of the silencers placed side by side. In the case of the wedged-shaped silencers discussed below in Types 5 and 6, the effective length of the side branch tube can be maintained with half the volume. As shown in Fig. 6, the devices can be placed side by side.

\[
S_1: \text{Total apertures area} \\
S_2: \text{Closed area (used for silencers)} \\
\text{Inner diameter of impedance tube: 100 mm} \\
\text{Inner diameter of impedance tube: 100 mm} \\
\text{Impedance tube} \\
\text{Base plate with apertures} \\
\text{Side branch silencers} \\
\text{Base plate with apertures} \\
\text{Impedance tube}
\]
2.3 Shapes and dimensions of test samples

In this section, we describe the six types of test samples used in the experiments. Table 1 summarizes the specifications of the silencers.

Figure 7 shows a sectional view, perspective view and photo of the Type 1 silencer. It has four apertures, each a square with a side of 25.7 mm. This test sample was created to confirm the attenuation characteristics of only the aperture. In other words, it acts as an orifice silencer with the aperture ratio of 1/3. The length of the aperture holes are twice the base plate thickness (12 mm) plus the 25.7-mm gap between the base plates, or 49.7 mm.

Table 1  Typical specifications of silencers

|                         | Type 1 | Type 2 | Type 3 | Type 4 | Type 5 | Type 6 |
|-------------------------|--------|--------|--------|--------|--------|--------|
| Number of side branch silencers | ---    | 4      | 2      | 4      | ←      | 2      |
| Length of side branch silencer [mm] | ---    | 51.4   | 102.8  | ←      | ←      | 205.6  |
| Width of side branch silencer [mm] | ---    | 25.7   | ←      | ←      | ←      | ←      |
| Thickness of side branch silencer [mm] | ---    | 25.7   | 25.7   | 12.85  | 25.7 → 0 | 25.7 → 0 |
| Aperture area of branch tube [mm²] | ---    | 25.7 x 25.7 | ← | 25.7 x 12.85 | 25.7 x 25.7 | ← |
| Total volume of side branch silencers [mm³] | ---    | 135800 | ← | ← | ← | ← |
| Aperture ratio                | 0.333  | ←      | ←      | ←      | ←      | ←      |
Figure 8 shows a sectional view, perspective view and photo of the Type 2 silencer. Type 2 is the basic silencer. As explained above, the space occupied by the silencer between the two base plates is eight cubes with sides of 25.7 mm. In Type 2, two cubes with sides of 25.7 mm were placed on each of the four apertures. In other words, it is a silencer with four side branch tubes having lengths of 51.4 mm and square cross sections. In the top-view drawing for Type 2, ignoring the thickness of the material, the width ratio of the aperture to silencer is 1:2. Therefore, in this silencer array, we can maintain the 1/3 aperture ratio while silencers placed side by side vertically and horizontally.

![Figure 8](image1)

(a) Sectional view with dimensions  
(b) Perspective view without top base  
(c) Photograph without top base plate

Fig. 8  Sectional view, perspective view and photograph of Type 2

Figure 9 shows a sectional view, perspective view and photo of the Type 3 silencer. In Type 3, four cubes with sides of 25.7 mm are placed on each of two apertures. In other words, it is a silencer with two side branch tubes having lengths of 102.8-mm and square cross sections. The final two apertures are simple orifice silencers. As with Type 2, Type 3 can be placed side by side.

![Figure 9](image2)

(a) Sectional view with dimensions  
(b) Perspective view without top base  
(c) Photograph without top base plate

Fig. 9  Sectional view, perspective view and photograph of Type 3
Figure 10 shows a sectional view, perspective view and photo of Type 4. By filling the volume of eight cubes with sides of 25.7 mm in half in the thickness direction, we get 16 half-cubes with dimensions of 25.7 mm × 25.7 mm × 12.85 mm. In Type 4, we placed four such cubes on each aperture. In other words, it is a silencer with four side branch tubes having 25.7 mm × 12.85 mm cross sections and lengths of 102.8 mm. As shown in Table 1, Type 4 has the same volume as Type 2 - Type 6. Type 4 is horizontally wider than Types 2 and 3. For this reason, by turning the arrays of the same silencer over (as in Fig. 6), they can be attached horizontally and placed side by side.

Figure 11 shows a sectional view, perspective view and photo of the Type 5 silencer. Type 5 is wedge-shaped in the longitudinal cross section of the branch tube. The silencer has tubes of 102.8-mm length on each aperture shown in Fig. 11. The total volume of these four side branch tubes is equal to the volume of eight cubes with sides of 25.7 mm. As with Type 4, Type 5 can be placed side by side.
Figure 12 shows a sectional view, perspective view and photo of the Type 6 silencer. Type 6 is wedge-shaped in the longitudinal cross section of the branch tube. The silencer has tubes of 205.6-mm length on two apertures. The remaining two apertures are simple orifice silencers. The total volume of these two side branch tubes is equal to the volume of eight cubes with sides of 25.7 mm. As with Types 4 and 5, Type 6 can be placed side by side.

(a) Sectional view with dimensions
(b) Perspective view without top base
(c) Photograph without top base plate
Fig. 12 Sectional view, perspective view and photograph of Type 6

3. Theoretical analysis
3.1 Four-terminal constants and transfer matrix of acoustic tube elements

We analyze silencers Types 1–6 using transfer matrices related to sound pressure and volume velocity based on a one-dimensional wave equation. For each acoustic tube element, using the sound tube cross-sectional area $S$, length $l$, characteristic acoustic impedance of the medium $Z_c$, and propagation constant $\gamma$, the transfer matrix $T_{loss}$ and the four-terminal constants of the sound tube elements $A_{loss}$–$D_{loss}$ are expressed by

$$T_{loss} = \begin{bmatrix} A_{loss} & B_{loss} \\ C_{loss} & D_{loss} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & \frac{Z_c}{S} \sinh(\gamma l) \\ \frac{S}{Z_c} \sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix}$$ (1)

We consider sound wave attenuation within the branch tube to be related to the characteristic acoustic impedance $Z_c$ and propagation constant $\gamma$.

Suyama and Hirata experimentally found the attenuation constant for electric-resistance-welded steel pipe with an internal diameter of above 20 mm (Suyama, et al., 1979). In theoretical analyses, that accounts for boundary layer viscosity, propagation constants having been derived for cylindrical tubes (Tijdeman, et al., 1975) and clearances between parallel plates (Beltman, et al., 1998) (Stinson, et al., 1992) (Allard, et al., 2009). In a previous report (Sakamoto, et al., 2014c), we converted the analytic method in cylindrical coordinate systems (Tijdeman, et al., 1975) to a Cartesian coordinate system; subsequently, we determined the characteristic acoustic impedance and propagation constant for a clearance between two parallel plates.

We assumed that sound wave attenuation was significant in the small clearance at the tip of the wedges in Types 5 and 6. In other words, we used the previously reported method (Sakamoto, et al., 2014c) in the derivation of the characteristic acoustic impedance $Z_c$ and propagation constant $\gamma$ while taking into account sound wave attenuation within the branch tube. We use the transfer matrix of aperture ignoring sound wave attenuation. At this case, the characteristic acoustic impedance $Z_c$ is the product of the speed of sound in air $c_0$ and the density of air $\rho_0$, $j$ represents the imaginary units, while the propagation constant $\gamma$ is the wave number $k$. 

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3.2 Equivalent circuit and transfer matrix of the silencer

Figure 13 shows an equivalent circuit corresponding to the acoustic system of a silencer that has four apertures. Each four-terminal circuit corresponds to the transfer matrix of the acoustic tube. Here, T₁ shown at the top and bottom of Fig. 13 correspond to impedance tube. The four four-terminal circuits $T_{pn}$ ($n$=1, 2, 3, 4) correspond to the four apertures. The four circuits $T_{p1}$-$T_{p4}$ are connected in parallel and are connected to the upper and lower $T_r$.

Figure 14 shows an equivalent circuit corresponding to each aperture and branch tube. The four-terminal circuit $T_2$ shown at the top and bottom of Fig. 14 corresponds to half of the aperture (cross-section: 25.7-mm square, length: 49.7 mm) lengthwise. Between the two $T_2$, the branch-tube impedance $Z_b$ is connected in parallel. The impedance $Z_b$ is not necessary for apertures that do not have side branch tubes, such as in Types 1, 3, and 6.

Consider the parallel connection between $T_{p1}$-$T_{p4}$ shown in Fig. 13. The transfer matrices for the two apertures $T_{p1}$ and $T_{p2}$ are given by

$$T_{p1} = \begin{bmatrix} A_{p1} & B_{p1} \\ C_{p1} & D_{p1} \end{bmatrix}$$

$$T_{p2} = \begin{bmatrix} A_{p2} & B_{p2} \\ C_{p2} & D_{p2} \end{bmatrix}$$

The transfer matrix $T_{para2}$ that connects these in parallel is given by

$$T_{para2} = \begin{bmatrix} A_{para2} & B_{para2} \\ C_{para2} & D_{para2} \end{bmatrix} = \begin{bmatrix} \frac{A_{p1}B_{p2} + A_{p2}B_{p1}}{C_{p1} + C_{p2}} & \frac{B_{p1}B_{p2}}{B_{p1} + B_{p2}} \\ \frac{B_{p1} + B_{p2}}{C_{p1} + C_{p2}} & \frac{B_{p1}B_{p2}}{B_{p1} + B_{p2}} \end{bmatrix}$$

By repeating this process, the transfer matrices $T_{p1}$-$T_{p4}$ are linked in parallel. The transfer matrix of $T_{p1}$-$T_{p4}$ linked in parallel is given as $T_{para}$.

The branch tube impedance $Z_b$ in Fig. 14 can be represented as a transfer matrix that expresses impedances connected in parallel,

$$T_b = \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/Z_b & 1 \end{bmatrix}$$

we explain the calculation of $Z_b$ in Section 3.3.

To integrate the equivalent circuits, we link their transfer matrices in cascade. Using equation (4), the equivalent circuit in Fig. 14 can be expressed in terms of the three transfer matrices on the right side of Eq. (5). The left side is expressed as $T_{para}$.

$$T_{pn} = \begin{bmatrix} A_{pn} & B_{pn} \\ C_{pn} & D_{pn} \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}$$

Using $T_{para}$ in Eq. (3), the equivalent circuit in Fig. 13 can be expressed in terms of the three transfer matrices on the right side of Eq. (6). The left side is expressed as $T_{all}$.

$$T_{all} = \begin{bmatrix} A_{all} & B_{all} \\ C_{all} & D_{all} \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_{para} & B_{para} \\ C_{para} & D_{para} \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}$$

Using the four-terminal constants in Eq. (6), the overall silencer transmission loss $TL$ can be expressed as
where $S_{tube}$ is the cross-sectional area of the impedance measurement tube.

### 3.3 Branch-tube acoustic impedance $Z_b$

We express a branch tube using a transfer matrix related to sound pressure and volume velocity based on a one-dimensional ($x$-direction) wave equation. When a branch tube with $z$-direction thickness $H$ and $y$-direction depth $l$ is expressed in Cartesian coordinates with sound waves inserted in the positive $x$-direction, we get the situation shown in Fig. 15 (Sakamoto, et al., 2014c). In Figure 15, when the thickness $H$ of the clearance between the two planes is sufficiently small compared to the length in the $y$-direction, sound wave propagation is determined by the $x$- and $z$-components of the clearance, while the $y$-direction propagation is uniform. Thus, the cross-sectional area $S$ on the $yz$-plane can be written as the product of the thickness $H$ and the unit length in the $y$-direction, $l$.

Thus, the transfer matrix $T_b$ and the four-terminal constants $A_b–D_b$ of the unit acoustic elements can be expressed as

$$
\begin{bmatrix}
\frac{p_1}{Hu_1} \\
\frac{p_2}{Hu_z}
\end{bmatrix}
= \begin{bmatrix}
A_b & B_b \\
C_b & D_b
\end{bmatrix}
\begin{bmatrix}
\frac{p_1}{Hu_1} \\
\frac{p_2}{Hu_z}
\end{bmatrix}
= \begin{bmatrix}
\cosh(H) & \frac{Z_c}{H} \sinh(\gamma l) \\
\frac{H}{Z_c} \sinh(\gamma l) & \cosh(\gamma l)
\end{bmatrix}
\begin{bmatrix}
\frac{p_1}{Hu_1} \\
\frac{p_2}{Hu_z}
\end{bmatrix}
$$

(8)
Here, $p_1$, $u_1$, $p_2$, and $u_2$ are the respective sound pressures and particle velocities at the entrance and terminal of the branch tube. Because the terminal of the branch tube is a rigid wall, the particle velocity $u_2 = 0$, and the specific acoustic impedance $Z_b$ can be written as

$$Z_b = \frac{p_1}{u_1} = \frac{A_b}{C_b} H$$  \hfil (9)

### 3.4 Wedge-shaped side branch tubes

Figure 16 shows the wedge-shaped cross section of a branch tube such as those used in Types 5 and 6. To calculate the specific acoustic impedance as seen from the entrance to the branch tube, we approach the wedge-shape of the $xz$-plane as shown in Fig. 17. In other words, we analyze the clearance between two parallel planes so that the thickness $H$ changes in the $x$-direction over $i$ steps (Sakamoto, et al., 2014c). If we rewrite the branch tube portion in Fig. 14 as transfer matrices divided into $i$ steps, as shown in Fig. 17, we obtain Fig. 18. The equivalent circuit of the branch-tube portion shown in Fig. 18 can be written in terms of a transfer matrix as

$$T_b = \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} = \begin{bmatrix} A_{c1} & B_{c1} \\ C_{c1} & D_{c1} \end{bmatrix} \begin{bmatrix} A_{c2} & B_{c2} \\ C_{c2} & D_{c2} \end{bmatrix} \cdots \begin{bmatrix} A_{ci} & B_{ci} \\ C_{ci} & D_{ci} \end{bmatrix}$$  \hfil (10)

Here, the four-terminal constants $A_{ci}$–$D_{ci}$ of $T_{ci}$ are given by Eq. (8). The length of the divided branch tube in the $x$-direction can be written as $l/i$, dividing the tube length $l$ by the number of divisions $i$. Note that $H$ becomes smaller in steps corresponding to the position of the division in the $x$-direction.
4. Results from calculations and measurements

4.1 Comparisons of experimental and calculated results for each silencer type

In general, an open end correction must be applied to the length of the tube used in the calculations, and there are many studies related to the open end correction (Bolt, et al., 1949) (Ingård, et al., 1953) (Benade, et al., 1967).

In these silencers, the aperture tube length is short, like an orifice within the impedance measurement tube. For this reason, we used 0.4, which is the open end correction related to orifices (Bolt, et al., 1949). Thus, the open end correction is 0.4 times the equivalent radius of the aperture (25.7 mm x 25.7 mm), and by adding this value to the internal and external sides of the aperture, we found that computational results were in good agreement with experimental values (Sakamoto, et al., 2013a). The same value was used for the open end of the side branch tubes.

We used Type 1 to check the attenuation effects of just the aperture. Because the aperture ratio for Type 1 is 1/3, it acts as an orifice silencer. The frequency characteristics for attenuation of an orifice silencer are determined by the length of the aperture and the aperture ratio. In the theoretical analysis, we took into account the area and length of the aperture in $T_{\text{eq}} - T_{\text{eq}}$ for the equivalent circuit in Fig. 13.

Figure 19 compares the experimental and calculated values for Type 1. Both match closely. The transmission loss across a wide frequency range in Fig. 19 is characteristic of Type 1. In particular, we obtained an approximately 5-dB attenuation effect in the frequency range above 1200 Hz. This feature of Type 1 also occurs in the frequency range above the attenuation peaks in Types 3–6, as described below.

Figure 20 shows experimental and calculated values for transmission loss in Type 2. At a frequency of approximately 1500 Hz, the length of the branch tube, with open end correction applied, matches the quarter wavelength of the sound wave. For this reason, the first attenuation peak appears near the upper frequency bound of the measured range.

Figure 20 does not show the orifice silencer effects that occurred in Type 1. This is thought to be due to the peak attenuation frequency of the side branch silencer, so a drop in transmission loss occurs at low frequencies.

Figure 21 compares experimental and calculated values for transmission loss in Type 3. Because the length of the side branch silencer in Type 3 is twice that of Type 2, the first attenuation peak appears near 750 Hz. An orifice silencer feature appears in the frequency range above the peak frequency, and we obtain an attenuation of approximately 5 dB. However, attenuation below 650 Hz is only about 1 dB, resulting in nearly no attenuation effects.

Figure 22 shows experimental and calculated values for transmission loss in Type 4. Comparing Type 4 (Fig. 22) with Type 3 (Fig. 21), we see that both the experiment and calculated values show the same frequency characteristics. This can be explained as follows: The number of side branch tubes in Type 4 differs from that in Type 3. However, the lengths of the side branch tubes are the same, and the total cross-sectional areas of the side branch tubes of both are twice that of a 25.7-mm square. These similarities are reflected in both the measured and experimental results, giving nearly identical results.
Figure 23 compares experimental and calculated values for transmission loss in Type 5. In the theoretical analysis of Type 5, we performed element decomposition. To converge the calculate value the number of divided elements was set to 100. The calculated and measured values for Type 5 were similar regardless of changes to the cross-sectional area of the side branch tubes in the lengthwise direction. This suggests that the analytic method using element decomposition in Section 3.3 is valid.

Now let us compare the performance of Type 5 with that of Type 4, which has four silencers of the same length. The attenuation peak frequency of Type 5 occurs in a higher frequency range than in Type 4. This is thought to be because the wedge shaped terminal of the side branch tube shortens the effective tube length.

Figure 24 shows experimental and calculated values for transmission loss in Type 6. The number of divided elements was also set to 100 for Type 6. Since the length of the side branch tube in Type 6 was 205.6 mm, twice of that in Type 5, we obtained an attenuation peak at approximately 600 Hz, which is half of that for Type 5. Type 6 maintains an approximately 4-dB attenuation effect until approximately 1200 Hz. Using Type 5 as an example, we discuss the differences in the peaks of the experimental and calculated values in Section 4.3.
4.2 Comparing different types of silencers

Figures 25 and 26 compare experimental results for different types of silencers. Figure 25 compares Types 2 and 5, while Fig. 26 compares Types 3 and 6. Types 5 and 6 have the same volume per side branch tube as Types 2 and 3, respectively, but the cross sections of the tubes in Types 5 and 6 are wedge-shaped and the tube length is twice that of Types 2 and 3. In both figures, because the side branch tubes of Types 5 and 6 are longer, the peak attenuation frequency is lower. This demonstrates the validity of using wedge shapes. Figure 26 shows that the transmission loss in the flat region above the peak frequency is lower in Type 6 than in Type 3. This is because transmission loss for an orifice silencer, as shown in Fig. 19, is lower at lower frequency ranges.

![Figure 25](image1.png)  
**Fig. 25** Comparison between experimental value of Type 2 and Type 5

![Figure 26](image2.png)  
**Fig. 26** Comparison between experimental value of Type 3 and Type 6

![Figure 27](image3.png)  
**Fig. 27** Comparison between with and without sound wave attenuation (Sakamoto, et al., 2014c) of Type 5
4.3 Comparing between with and without including sound wave attenuation

In this section, we use theoretical values for transmission loss to study the effects of sound wave attenuation (Sakamoto, et al., 2014c). Similar to the case of porous sound absorption materials that have continuous pores, sound wave attenuation mainly occurred because of friction caused by viscosity in the boundary layer (Wesley, 1958) on the wall within the tube. Figure 27 compares theoretical values obtained when sound wave attenuation was included and neglected in the side branch tubes for Type 5. For reference, we also show the experimental value. (Note the difference in the size of the vertical axes in Figs 23 and 27.) In Figure 27, the two theoretical values differ at the peak of transmission loss near 1300 Hz. The theoretical curve with sound wave attenuation has less sharpness in the peak of transmission loss and is closer to the experimental curve. Based on these results, we included sound wave attenuation within the side branch tubes when calculating the theoretical values reported in this paper. Differences between our theoretical and measured values are attributed to the one-dimensional approximation and the insufficient estimation of sound wave attenuation within the silencer.

5. Conclusions

We performed theoretical analyses of acoustic transmission losses of silencers using the transfer matrix method with accounting for sound attenuation in the branch tube. We performed element decomposition on the transfer matrix for silencers with side branch tubes with a wedge-shaped longitudinal cross section. We obtained calculated results that were sufficiently valid compared to our experimental measurements.

By designing and fabricating a special attachment, we were able to attach silencers to the measurement tube that had larger cross sections than the impedance measurement tube. Using this attachment, we measured acoustic transmission losses for each of six different prototype silencers. By adding orifice silencer effects, we obtained transmission losses across a wide frequency range. However, attenuation decreased in frequency ranges below the attenuation peak of the side branch tubes.

A wedge-shaped longitudinal cross section for the side branch tubes can double the length of the silencer and develop lower-frequency attenuation effects, while maintaining the same volume. This wedge-shaped side branch tube is suitable for a long silencer placed side by side in an array formation.

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