A Study on the Correlation Between Fluctuating Velocity in a Muffler and Air Flow Noise*

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This paper describes an experimental study on the relationship between fluctuating velocity in mufflers and flow induced noise for the expansion cavity type muffler and the perforated straight-through pipe type muffler. The visualization of internal flow and the measurement of fluctuating velocity in a muffler were performed using the smoke-wire method and a hot-wire velocimeter. From these experiments, the flow pattern and the distribution of the fluctuating velocity were able to be clearly shown for each type of muffler. The correlation between the fluctuating velocity at each point in the muffler and the flow induced noise which radiated from the open end was also studied by calculating the coherence function between them. It was seen that the flow induced noise was closely correlated with the fluctuating velocity of the internal flow, especially in the ranges of tail pipe and/or cavity resonance frequencies.

Key Words: Sound, Air Flow Noise, Muffler, Fluctuating Velocity, Coherence Function

1. Introduction

In order to reduce exhaust noise or duct noise, mufflers have been commonly used in engines, boilers, air supply systems etc. The attenuation effect of a muffler without air flow can be predicted generally by applying acoustic theory.

The derivation of and ways to reduce air flow noise generated from expansion cavity type mufflers with steady flow and their head losses were discussed in previous papers⁽¹⁾⁽²⁾. It was clarified that muffler structures which are able to prevent the collision of the jet stream from their leading pipes with the tail pipe inlet end reduce air flow noise generation. When high speed air flow exists, however, a large air flow noise sometimes radiates from the open end of the mufflers, exceeding the overall acoustic reduction effect.

Ramakrishnan et al.⁽³⁾ discussed the mechanisms of sound generation by flow-acoustic coupling in

expansion chamber resonators. Obata et al.⁽⁴⁾⁽⁵⁾ and Kurasawa et al.⁽⁶⁾ reported on the acoustic oscillation phenomenon caused by an air jet impinging on a straight pipe closely set on the jet nozzle. However, the cause and mechanism of the air flow noise generation in mufflers are not sufficiently clear; therefore, it is necessary to investigate the relationship between the internal flow and the air flow noise of the muffler.

As an attempt to clarify the generation mechanism of the air flow noise, in this paper, the internal flow was visualized by the smoke-wire method for the two typical structures of expansion cavity type mufflers, i.e., the simple cavity structure and the perforated straight-through pipe structure. The fluctuating velocity at each point in the muffler was also measured using the hot-wire velocimeter. Then, the point having the strongest relation between the fluctuating velocity and the air flow noise was determined by calculating the coherence function between them.

2. Experimental Apparatus and Procedures

The flow supply system to the test muffler was the same as that used in the previous report⁽²⁾. The air

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flow noise generated by the blower was silenced through the sound absorbing material inside the walls of the pre-muffler set. The steady stream obtained by this system was supplied to the test muffler set in an anechoic room. The visualization of the internal flow was performed through the smoke-wire method. A nichrome wire with a diameter of 0.1 mm was stretched across the acrylic muffler, and liquified paraffin on the wire was misted by feeding a DC current to it. Traces of the paraffin mist were photographed by flashing a light after a time T_d from the current feed. During the internal flow visualization, the flow velocity in the leading pipe was kept constant at 10 m/s.

Figure 1 shows a block diagram of the measuring and analyzing facilities of the fluctuating velocity and air flow noise. An I-type hot-wire velocimeter probe was set facing the axial and radial directions of the muffler, to detect the velocity component in the vertical cross section. The fluctuating velocity measurements were carried out at 192 points distributed in the upper half of the cross section. The sound pressure level of air flow noise L_p was measured at a point 300 mm away from the tail pipe, making an angle of 45 degrees with the muffler axis. Prior to the fluctuating velocity measurements, it was confirmed by a speaker noise source experiment that the influence of resonance sound on velocimeter responses was sufficiently

Table 1 Main specifications of test mufflers

Type	D mm	L mm	d mm	l mm
A2	$\phi 100$	200	$\phi 20$	100
A3	$\phi 100$	300	$\phi 20$	100
A4	$\phi 100$	400	$\phi 20$	100
A5	$\phi 150$	430	$\phi 30$	150
B3	$\phi 100$	300	$\phi 20$	100
	$\phi 8$	3.0	0.14	54

Fig. 1 Block diagram of measurements and analyses of air flow noise and internal flow in mufflers

small in both the cavity and tail pipe of the muffler. These signals were analyzed with the aid of an FFT analyzer and 1/3 octave band filters, and were processed by an A/D converter and computers.

The calculation of the coherence function between the fluctuating velocity and air flow noise was performed on the obtained data of 0.5-1.0 second and the results were processed by a Hanning Window. The main specifications of the test mufflers are shown in Table 1, where d_h is the diameter of the perforated hole, ϵ , is the ratio of the open area to the total area of the perforated straight-through pipe, and n is the number of holes.

3. Flow Pattern in Muffler and Generated Air Flow Noise

3.1 Simple cavity type mufflers

As already reported⁽²⁾, one of the most effective ways to reduce air flow noise generation is to introduce a muffler structure which is able to prevent the collision of the jet stream from the leading pipe with the tail pipe entrance. The sound pressure level of the air flow noise was thus investigated, changing the cavity length L of the simple cavity type muffler while the area ratio of the cavity to tail pipe section m was kept constant at 25, and the flow rate w at 50 m/s.

Figure 2 shows the results of this experiment. The air flow noise radiated from the open end of the simple cavity type muffler peaks at a tail pipe resonance frequency of 1.7 kHz and at its harmonic frequencies. These peaks contribute greatly to the overall value of the sound pressure level. When the cavity length L becomes smaller than 300 mm, the air flow noise increases, especially in the low and middle frequency range. The cause of this tendency seems to be that the flow pattern in the muffler changes with cavity length.

The flow, visualized by the smoke-wire method,

Fig. 2 Effects of cavity length on air flow noise

Type A2

Fig. 3 Result of visualization of air flow in a simple cavity type muffler

Fig. 4 Comparison of air flow noise with and without bell-mouth adapters in simple cavity type mufflers ($w = 50$ m/s)

is shown in Fig.3. The jetting stream from the leading pipe reaches the entrance of the tail pipe without wide dispersion or much velocity loss. Considering this flow pattern and the results shown in Fig. 2, it seems that the air flow noise is largely increased in the low and middle frequency range by the jet striking against the pipe entrance, causing the tail pipe to resonate. We refer to this noise, hereafter, as the air flow noise generated by jet flow collision.

The use of a bell-mouth structure for the cavity inlet and outlet is a practical way to prevent or to mitigate noise generation. Figure 4 shows the effects of the bell-mouth adapter on air flow noise generation. With a cavity length of $L=300$ mm, the air flow noise decreases when bell-mouth adapters are attached, while no reduction effect is observed with a cavity length of $L=400$ mm. The internal flow is visualized, as shown in Fig. 5, to clarify these tendencies of noise generation.

In Fig. 5(a), the jet flow reaches the tail pipe entrance without much loss of flow velocity when $L=$

Fig. 5 Comparison of velocity distribution of internal flow with and without bell-mouth adapters ($w=10$ m/s)

300 mm without bell-mouth adapters. When the adapters are attached, the dispersion of the jet flow becomes strong; consequently, the flow velocity around the muffler axis rapidly decreases along the stream. Therefore, air flow noise may be greatly decreased through attaching bell-mouth adapters when $L=300$ mm.

In the case of $L=400$ mm, shown in Fig. 5(b), the air flow reattaches to the side wall of the cavity around 300 mm from the cavity inlet, and the flow velocity around the muffler axis is relatively small. Consequently, the reduction effect through bell mouth adapters becomes quite small because of the low generation level of the air flow noise itself.

3.2 Perforated straight-through pipe type mufflers

A muffler structure with a perforated straight-through pipe is one of the most effective and practical means to prevent air flow noise generated by jet flow collision and to mitigate head loss, mainly because of the abrupt change of the cross section area.

Figure 6 shows the air flow noise radiated from the outlet of a perforated straight-through pipe type muffler in comparison with a simple cavity type muffler. A straight pipe 5 mm thick with 54 holes 8 mm in diameter drilled evenly over its 300 mm length ($\epsilon=0.14$) was used for the perforated straight-through pipe. It is seen that with the attachment of the perforated pipe, the air flow noise caused by the collision of the jet flow is decreased in the low and middle frequency ranges, just as in Fig. 2, while it is increased in the frequency range above 1.25 kHz.

As the results of a frequency analysis of the air flow noise performed with the aid of a narrow band analyzer show, the high frequency components of the air flow noise generated by this type of muffler have peaks at frequencies corresponding to the resonance frequencies of the cavity and tail pipe. It is also

Fig. 6 Air flow noise radiated from a perforated straight-through pipe type muffler ($w=50$ m/s)

Fig. 7 Result of internal flow visualization of a perforated straight-through pipe type muffler ($w=10$ m/s)

clarified that the sound pressure levels of these peaks depend on the flow velocity, the diameter of small holes, the ratio of the open area ϵ and the thickness of the straight-through pipe. This noise seems to be generated by the air flow passing through the perforated holes, which we refer to hereafter, as whistling noise.

For the observation of the flow pattern around these holes, the hot-wire visualization method was performed with a Type B3 muffler, and the result is shown in Fig. 7. As is evident from this figure, the air flows into the straight-through pipe through the last row of holes, and flows out to the cavity through other holes. It was also clarified that the direction of the streams passing through the holes are perpendicular to the pipe when the diameters of the holes are small and the pipe is thick, while they lean toward the downstream direction, to some extent, when otherwise. However, it is necessary to measure the fluctuating velocity around the perforated holes for a better understanding of whistling noise generation.

4. Distribution of Fluctuating Velocity in Mufflers

4.1 Simple cavity type muffler

The distribution of the fluctuating velocity was investigated by measuring the velocity component of the turbulent flow in the vertical cross section of the cavity and tail pipe of a muffler through a hot-wire velocimeter. The muffler employed here had a cavity length of $L=430$ mm and a tail pipe length of $l=150$ mm.

Figure 8 shows the power spectra of the fluctuating velocity at each point on the muffler axis. As seen in this figure, the frequency components of the fluctuating velocity at the cavity entrance are kept

Fig. 8 Frequency characteristics of fluctuating velocity along the center axis of a muffler ($w=50$ m/s)

low over a wide range, owing to the leading pipe. The fluctuation level rapidly increases for every frequency at the cavity entrance, then slowly decreases in the high frequency range as it flows down, which in turn, rapidly decreases in the low frequency range at the cavity exit and slowly recovers in the middle and high frequency ranges as the air flows through the tail pipe. When we compare the frequency characteristics of the fluctuating velocities at the cavity entrance with those at the tail pipe of the muffler, the latter is 5-8 dB higher than the former, especially in the low and middle frequency ranges, as is observed with air flow noise generation.

Figure 9 shows the mean spectra of the fluctuating velocity across each section of the tail pipe. The mean spectrum is displayed in terms of the power spectrum of the fluctuating velocity passing through the unit area. The tail pipe length of the tested muffler is $l=150$ mm; therefore, the resonance frequency of the fundamental mode becomes 1.2 kHz. As is evident from this figure, the fluctuating velocities show peaks in the frequencies corresponding to the harmonics of tail pipe resonance at the tail pipe entrance where the turbulence is increased. It seems, therefore, that the resonance of the tail pipe and the intensity of the fluctuating velocity at the tail pipe entrance are correlated.

4.2 Perforated straight-through pipe type muffler

A whistling noise may be caused by the air flow passing through holes in this type of muffler. Figure 10 shows the distribution of the air velocity around the perforated holes in the first and third rows from the tail pipe side. The air flows out of the pipe to the

Fig. 9 Power spectra of fluctuating velocity at each cross section of a tail pipe ($w=50$ m/s)

cavity from a hole in the third row, as shown in Fig. 10(a), while it flows in at a hole in the first row, as shown in Fig. 10(b). The position where the mean velocity reaches its maximum Value at each hole shifts to the downstream side.

Figure 11 shows the frequency characteristics of fluctuating velocity around the perforated holes. At the third row holes, shown in Fig. 11(a), there is no peak in the power spectrum of the fluctuating velocity in the downstream side of the hole; in the upper-stream side of the hole, the highest peak of the power spectrum is observed in the frequency range of 1.6 k-1.8 kHz, corresponding to the resonance frequencies of both the cavity and tail pipe.

At the first row holes, where the air flows into the tail pipe, shown in Fig. 11(b), the predominant peak is observed in the 1.7 k-1.8 kHz range over the entire hole. The frequencies of both the first resonance of the tail pipe and the third resonance of the cavity of the test muffler are very close to each other; therefore, it is difficult to distinguish them in this figure. Therefore, the fluctuating velocity at the center of the first row holes and the air flow noise radiated from the open end of the muffler were examined with the aid of an FFT analyzer, by changing the tail pipe length.

In Fig. 12(a), the frequency component of 1.75 kHz shows a sharp peak, even in the case without a tail pipe, so it seems that this velocity component is closely correlated with cavity resonance. The fluctuating velocity shows a peak at the resonance frequency in the 1.5 k-2.0 kHz range when the tail pipe length changes in the range of 115-85 mm. From these facts, it was clarified that the fluctuating velocity around perforated holes is influenced by the tail pipe resonance. These phenomena were also observed with the air flow noise, as shown in Fig. 12(b).

(a) Third row hole from tail pipe entrance

(b) Last row hole

Fig. 10 Velocity distributions around perforated holes

(a) Third row hole from tail pipe entrance

(b) Last row hole

Fig. 11 Power spectra of fluctuating velocity around perforated holes ($w=50$ m/s)

(a) Fluctuating velocity

(b) Air flow noise

Fig. 12 Effects of tail pipe length on fluctuating velocity and air flow noise ($w=50$ m/s)

5. Correlation between Fluctuating Velocity and Air Flow Noise

The relationship between fluctuating velocity inside the muffler and air flow noise radiated from the open end was investigated, calculating the coherence between them.

Fig. 13 Correlation between fluctuating velocity and air flow noise of a simple cavity type muffler

Fig. 14 Contour maps of correlations between fluctuating velocity and air flow noise around cavity exit (maximum value from 100-500 Hz)

Fig. 15 Correlation distributions between fluctuating velocity and air flow noise around perforated holes ($w=50$ m/s)

5.1 Coherence distribution in a simple cavity type muffler

Figure 13 shows the distribution of coherence between the fluctuating velocity and air flow noise calculated for each point in the cross sections of $x = -15$ mm and $x = -5$ mm apart from the cavity exit of the simple cavity type muffler, where r is the distance from the center axis of the muffler. Strong correlations are seen around the muffler axis in the low and middle frequency range in which the air flow noise is generated by the jetting air flow collision noise.

The correlation contour maps in the vicinity of the cavity exit are shown in Fig. 14, for investigating the maximum value of coherence in the frequency range of 100–500 Hz. The region which has the largest coherence was observed just in front of the tail pipe inlet. When the length of the cavity is shortened from 300 mm to 200 mm, this region seems to shift slightly to the upstream side, a distance of nearly 10 mm.

5.2 Coherence distribution in the perforated straight-through pipe type muffler

Figure 15 shows the coherence of the frequency characteristics calculated around the third row holes and the first row holes from the cavity exit. In the case of the third row holes, the strongest correlation is seen in the upstream side area where the power spectrum of fluctuating velocity peaks in the 1.6 k–1.8 kHz range, as shown in Fig. 11(a). In the case of the first row holes, an extremely strong correlation is observed at the tail pipe resonance frequency of 1.6 kHz–1.7 kHz, the cavity's third resonance frequency of 1.8 kHz, and their two-fold frequencies.

From these findings, it becomes clear that the whistling noise generated by the perforated straight-through pipe type muffler is caused by the turbulent flow passing through the perforated holes, and is strongly correlated with the resonance of the tail pipe and/or the cavity.

6. Conclusions

The air flow noise generated by the steady flow was investigated for the simple cavity type mufflers and the perforated straight-through pipe type mufflers which are commonly used in practical silencers. The results obtained in this research are summarized as follows.

(1) In a simple cavity type muffler with a small cavity length, the low and middle frequency components of air flow noise are increased, and the tail pipe resonance is caused by the collision of jetting flow from the leading pipe to the tail pipe entrance.

(2) The visualization of the internal flow shows that the attachment of bell-mouth adapters expands the flow, and therefore mitigates the collision of the flow to the tail pipe entrance.

(3) In a perforated straight-through pipe type muffler, the air strongly flows into the pipe through perforated holes in the last row, while it flows out through other holes. The fluctuating velocity shows peaks at frequencies corresponding to those in which the air flow noise peaks appear over the holes.

(4) The coherences calculated between the fluctuating velocity and air flow noise show large values in front of the tail pipe entrance in a simple

cavity type muffler, but around the last row holes in a perforated straight-through pipe type muffler.

(5) We are thus able to conclude that the air flow noise radiated from the open end closely correlates with the fluctuating velocity at the resonance frequencies of the cavity and/or the tail pipe of a muffler.

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