Studies on Reactive Mufflers
(Part 2. Mufflers with Air Flow)

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Abstract

Transmission loss characteristics of a reactive type muffler have been studied by Davis D. D. et al[1] under the assumption that the tail pipe of the muffler is a non-reflective one. On the other hand, assuming that the pipe is completely reflective, Fukuda has developed an attenuation theory in his previous paper[2].

In the case of a muffler with air flow, however, these equations are not always correct in estimating frequency characteristics of noise reduction. This is because of the change in these characteristics due to the air flow or a secondary noise inside the muffler.

The authors have studied the influence of air flow on the relationship between the figure of the reactive type muffler and the noise radiated from it. They have also investigated how to identify the sources of the air flow noise inside the cavity.

Furthermore, they have estimated air flow noise by means of calculation and experiment. As a result, many interesting conclusions have been obtained together with important data for the muffler design.

1. Theoretical Study

1.1 Noise reduction through muffler with air flow

Referring to Fig. 1, which illustrates a simple reactive type muffler without air flow, Fukuda has proposed the following approximate attenuation equation as shown by Eqs. (22) and (35) in Part 1[2].

$$Att = 20 \log_{10} | m \sin(k l) \sin(k l_0) | \quad \text{dB} \tag{1}$$

Where Att represents the difference of sound pressure level at the same relative positions with and without a muffler (cavity and tail pipe); $m=S/s$ is the ratio of cross-sectional areas of the cavity (S) and the pipe (s), k is wave length constant, i.e., $k=\omega/c=2\pi f/c$ (ω ; angular frequency, f; frequency, and c; sound velocity), and l and l_0 are the lengths of the cavity and the tail pipe respectively.

When there is a uniform air flow with the velocity of Mach number M, the sound velocity is given by Eq. (2), using the usual convention of + and − suffixs respectively for the forward and backward directions of the plane acoustic waves relative to the air flow.

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$$c_{+}=c(1+M), \qquad c_{-}=c(1-M) \tag{2}$$

The wave length constant is given by :

$$k_{+}=k/(1+M), \quad k_{-}=k/(1-M) \tag{3}$$

and the acoustic characteristic impedance is

$$Z_{0+}=Z_0(1+M), \quad Z_{0-}=Z_0(1-M) \tag{4}$$

where Z_0 corresponds to a case without air flow and is given by $Z_0=\rho c/s$ with ρ the density, and s the pipe cross-section.

The energy density can be expressed by

$$E_{+}=|p_{+}|^2/\rho c^2_{+}, \quad E_{-}=|p_{-}|^2/\rho c^2_{-} \tag{5}$$

For the expansion type muffler shown in Fig.1, we make the following assumptions

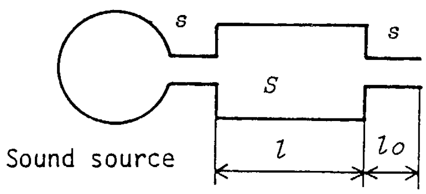


Fig. 1 Reactive muffler

that (i) plane acoustic waves propagate through the cavity with uniform air flow, (ii) the three pipes of inlet, cavity and outlet are connected in cascade and can be analyzed as a matrix and (iii) the continuity of pressure and of volume velocity are satisfied at each junction. Under these assumptions the following approximate equation can be derived.

$$Att = 20\log_{10}|m(1-M_{lo}^2)\sin(k_l l)\sin(k_{lo} l)| \quad \text{dB} \tag{6}$$

where M_{lo} is the Mach numer at the tail pipe ($M_{lo}< 1$), $k_l=k/(1-M_l^2)$, and $k_{lo}=k/(1-M_{lo}^2)$

In Eq. (6),

$$\sin(k_l l)\sin(k_{lo} l_0) < 1 \tag{7}$$

Therefore,

$$Att_{\max}=20\log_{10}|m(1-M_{lo}^2)| \qquad \text{dB} \tag{8}$$

The influence of air flow on the acoustic characteristics of the muffler is almost negligble at a low flow velocity less than several tens of meters per second.

1.2 Noise generation by a muffler with air flow

Let us assume that the power level $L_{w'}$ of the noise emanated from the open end without the muffler (see Fig. 2) is defined by

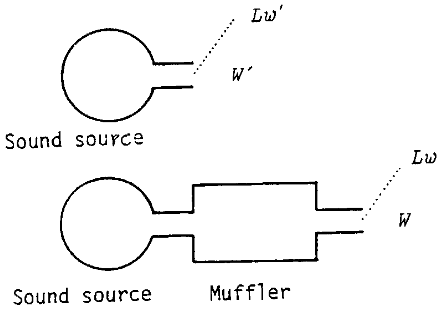


Fig. 2 Powers W, W' and power levels L_w, $L_{w'}$ of emanating noise

$$L_{w'} = 10 \log_{10} \frac{W'}{10_{-12}} \quad \text{dB} \tag{9}$$

From Eq. (9), the emanated power W' is calculated as follows :

$$W' = 10^{(L'w/10)-12} \quad \text{W} \tag{10}$$

When a muffler is present, the power level Lw of the emanated noise from the muffler tail pipe and emanated power W are given by :

$$Lw = 10 \log_{10} \frac{W}{10^{-12}} \quad \text{dB} \tag{11}$$

$$W = 10^{(Lw/10)-12} \quad \text{W} \tag{12}$$

Next, let us assume that no muffler is attached and the air flow noise is negligible at low velocity. In that case, the power level and emanated power of the noise generated at the open end will be represented by $L_{wl'}$ and $W_{l'}$ respectively. Furthermore, let us define the noise parameters $L_{wh'}$ and $W_{h'}$ for the case where a significant air flow noise is generated because of high velocity (all other conditions remaining the same). In addition, with a muffler attached, the foregoing parameteres are expressed by L_{wl}, W_l, L_{wh} and W_h, respectively. Also, the power ratio λ is defined as

$$W_l = \lambda\ W_r \qquad \text{W} \tag{13}$$

Using these definitions, the attenuation *Att* (dB) of the muffler is obtained from $L_{wl'}$—L_{wl}, i. e. :

$$Att = 10 \log_{10} \frac{1}{\lambda} \qquad \text{dB} \tag{14}$$

Therefore, λ is given by :

$$\lambda = 10^{-Att/10} \tag{15}$$

The emanated power W_h at high velocity is calculated using :

$$W_h = \lambda\ W_{h'} + W_f \qquad \text{W} \tag{16}$$

where W_f is the power of the initial air flow. From these equations, the secondary noise power level L_{wf} (dB) which emanates from the muffler due to the air flow is given by

$$L_{wf} = 10 \log_{10} (Wf/10^{-12}) \qquad \text{dB} \tag{17}$$

Consequently, the air flow sound pressure level L_f at a distance r from the open end is expressed by

$$L_f = L_{wf} - 10 \log A \qquad \text{dB} \tag{18}$$

where the propagating area A(m^2) is given by $4\pi r^2$ in a free space and $2\pi r^2$ in a semi-free space.

Furthermore, by assuming sound pressure levels of $L_{h'}$, $L_{l'}$, L_h and L_l corresponding to the power levels $L_{wh'}$, $L_{wl'}$, L_{wh} and L_{wl}, at the same relative position from the open end, the air flow sound pressure level L_f can be calculated as follows

$$L_f = 10 \log_{10} \mid 10^{Lh/10} - 10^{\{Lh' - (Ll' - Ll)\}/10} \mid \qquad \text{dB} \tag{19}$$

In other words, the frequency characteristics of the air flow sound pressure level L generated in the muffler can be calculated by obtaining the frequency characteristics of sound pressure levels with and without the muffler and air flow.

2. Experiment and Calculation

2.1 Air flow noise from muffler

When the flow velocity increases, what relationship will hold between air flow noise and muffler design? In answering this question the authors studied the fact of the generation of air flow noise from a muffler and the influence of the figure of the muffler.

Figure 3 illustrates the test setup. A blower (turbo-centrifugal type) was used for

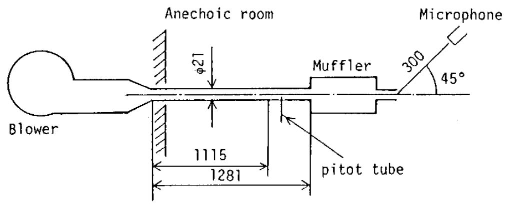


Fig. 3 Test setup

the noise source. The velocity was controlled by a throttle valve located at the blower inlet. The velocity was measured by a 0.7 diameter Pitot tube at 166mm upstream position from the cavity inlet, and the mean flow velocity was obtained. The noise was measured at a position 300mm away from the open end making an angle of 45 degrees with the pipe axis. The improvement in noise reduction was determined from the difference (*Att*) of the sound pressure levels (L_p) with and without a muffler.

Figure 4(a) indicates the frequency characteristics of an emanated noise L_p from a straight pipe with no muffler attached. Essentially no change in L_p is observed

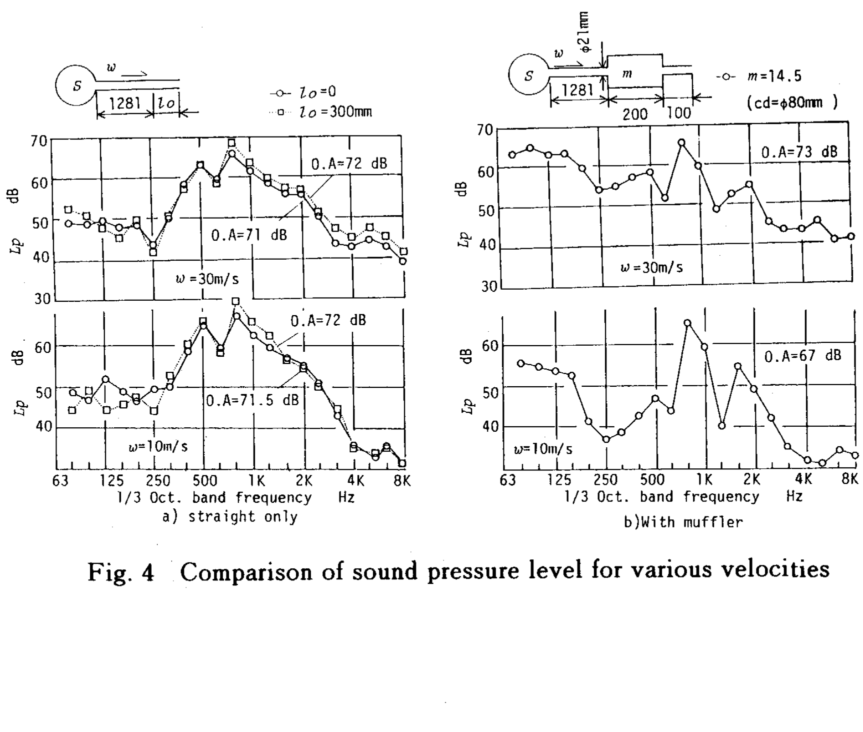


Fig. 4 Comparison of sound pressure level for various velocities

when the flow velocity is changed from 10m/s to 30m/s, except in the high frequency range. A large noise component is observed at 800Hz. This component corresponds to the 835Hz fundamental frequency of the blower impeller of the sound source.

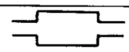
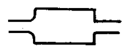
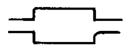
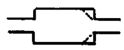
When the test setup is replaced with a pipe system containing a muffler as shown in Fig. 4(b), a significant noise increase is observed at a flow velocity of 30m/s in both the low frequency range around 250Hz and the high frequency range. This may be due to air flow noise generated by the muffler.

2.2 Effect of adapters on air flow noise

A number of adapters have been devised to prevent the air flow noise, assuming that this noise is generated mainly by the air turbulence caused by a sudden change in slope of the cavity inlet/outlet.

Table 1 presents the most types of mufflers.

Table 1 Mufflers with various adapters

Mufflers	Sketch	Remarks
I		No adapter
II		Bellmouth on inlet end
III		Bellmouth on tail pipe inlet
IV		Perforated conical plate on cavity outlet end

First of all, it needs to be investigated whether or not the acoustic characteristics of these mufflers change depending on the type of adapter used. Fig. 5(a) is a comparison between muffler I and a muffler with II + III + IV adapters in terms of improved noise reduction, using a loud speaker source. It can be seen that there is hardly any improvement in the noise reduction. Fig. 5(b) shows the difference between the sound pressure level at 10m/s and at 28m/s. When the adapter employing a blower as a sound source is used, as shown, it leads to less radiated noise from the open end in this figure. This may be the result of a noise supressive effect of the adapter on air flow.

2.3 Air flow noise inside the muffler cavity

It is important to identify the position where the secondary noise is generated by air flow within the muffler cavity.

Figure 6 shows the calculated air flow noise assuming a muffler of 300mm cavity length and a flow velocity of 28m/s, while neglecting air flow noise at any velocity less than 10m/s. Each adapter is the same as shown in Table 1. It is seen that, for both the low and high frequency ranges, the air flow noise becomes a significant fraction of the total.

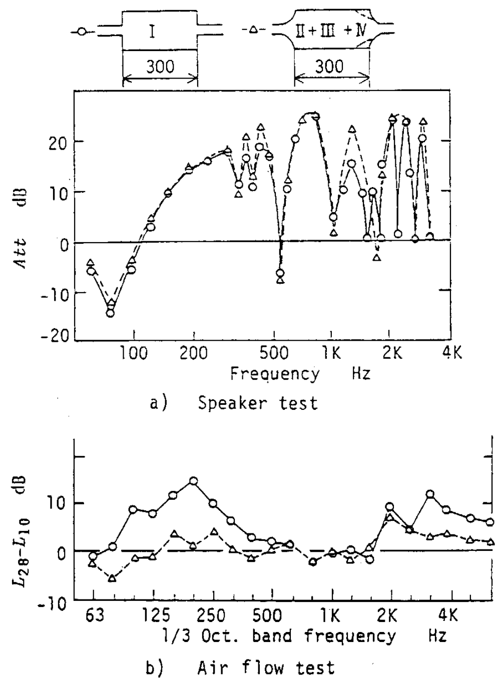


Fig. 5 Comparison between simple muffler and combined one with composite adapter

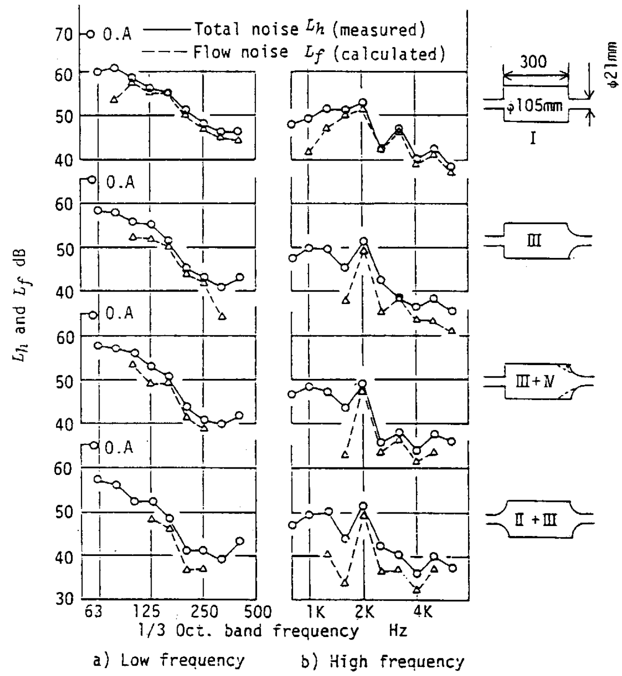


Fig. 6 Calculation of the air flow noise L_f from the total measured noise L_h (w=28m/s)

Figure 7 shows the generated noise at the cavity inlets ⓐ and ⓑ, obtained from the difference of air flow noise for the mufflers III and II + III. The same figure shows

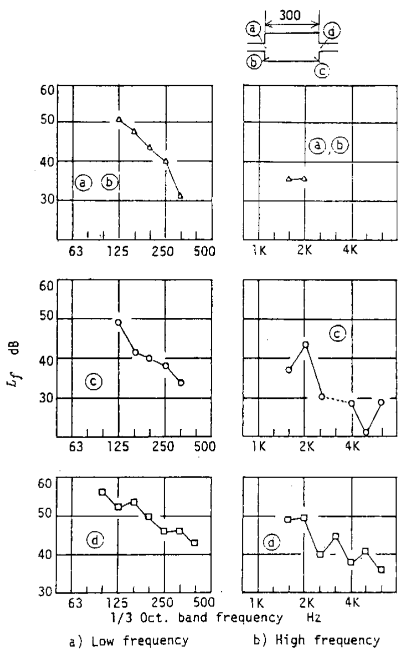


Fig. 7 Calculation of the air flow noise L_f at various positions inside the cavity (w=28m/s)

the generated noise at the cavity outlet corner ⓒ also calculated in the same way as for mufflers Ⅲ and Ⅲ + Ⅳ. Similar calculations are also shown for the tail pipe inlet ⓓ and mufflers Ⅰ and Ⅲ. Referring to these results, it is clear that, of all the positions generating noise, position ⓓ generates the largest flow noise in both the low and high frequency ranges.

2.4 Effect of cavity length on air flow noise

Figure 8 shows the frequency characteristics of air flow noise changing the

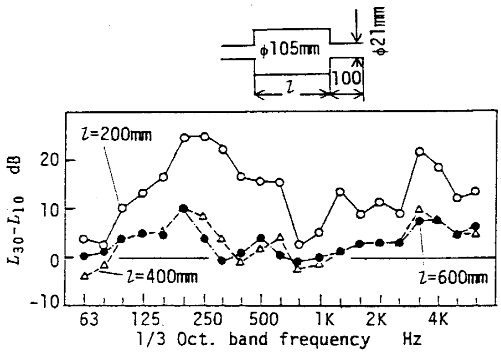


Fig. 8 Noise increase for different cavity lengths

cavity length from 200mm to 600mm. The ordinate indicates the difference between the sound pressure level at 10m/s and at 30m/s. It is noted that the noise increase due to air flow is extremely large at a cavity length of 200mm. In this case, there are two significant noise peaks, one in the low frequency range around 250Hz and the other in the high frequency range of 3~4kHz.

To verify these results, the authors measured the pressure distribution at the cavity wall as shown in Fig. 9. With a cavity length of 400mm, the jet stream occurs close to the wall surfaces at $x/l \fallingdotseq 0.7$ in this muffler. With a cavity length less than

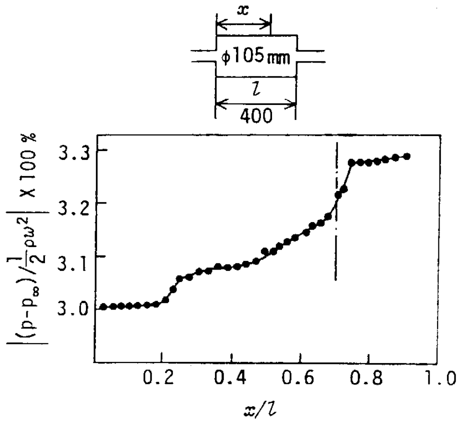


Fig. 9 Wall surface pressure distribution inside the cavity (w=28m/s)

300mm, it is estimated that the total jetting energy might actually impact the inlet part of the tail pipe.

In Fig. 9, p_∞ is the atmospheric pressure, p is the pressure inside the wall of the cavity and w is the velocity of the air flow in the inlet pipe.

3. Conclusions

This paper presents theoretical and experimental studies on reactive mufflers with air flow.

The results of the research are summarized as follows :

(1) The influence of air flow on the acoustic characteristics of the muffler is almost negligible at low flow velocity less than several tens of meters per second.

(2) The air flow noise generated inside the muffler is almost negligible at any velocity less than about 10m/s in the pipe. For flow velocity higher than about 30m/s, the noise becomes significant.

(3) The inlet part of the tail pipe is a position of the largest air flow noise generation inside the cavity. Large air flow noise is generated when a jet stream from the inlet pipe directly impacts the tail pipe. The generated noise increases as cavity length decreases.

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References

1) Davis, D. D., et al., NACA Tech. Rep., 1191 (1954).
2) Fukuda, M., Tech. Rep. of the Yamaguchi Univ., 3[2], pp. 79–91 (1983).