Attenuation Effects of Discrete Tone Using Adaptive Feedback Active Noise Control

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Abstract

The attenuation characteristics of a slit resonator that combined the adaptive feedback ANC system at a ventilation aperture of the package for leakage noise is investigated. The discrete tones radiated from an AC axial flow fan are controlled by DSP using Filtered-X Least Mean Square algorithm. The attenuation is found at the range of : $3\,\mathrm{dB}$-$14\,\mathrm{dB}$ with circular slit resonator, $2\,\mathrm{dB}$-$15\,\mathrm{dB}$ with elliptic slit resonator. Results of measurement show that the proposed system can achieve TNR(Tone to Noise Ratio) and PR(Prominence Ratio) under threshold effectively.

Key words: Noise Control, Adaptive Control, Slit Resonator, Discrete Tone, Tone to Noise Ratio, Prominence Ratio

1. Introduction

The packages of machines or electronic equipments are necessary to prevent the leakage noise. The leakage noise from machines has all audio frequency. Generally, it is desirable that the noise is controlled in all audio frequency. The simplest method for preventing the noise is to completely surround a machine by a package. But inner heat is not discharged. When a ventilator is made for discharging the inner heat, the noise is also emitted outside. So, the relation between heat balance and sound isolation is contradictory. The packages to reduce machinery noise must satisfy conflicting requirements for sound isolation and ventilation at the same time.

In order to satisfy the coexistence of ventilation and sound insulation, a circular slit resonator type silencer with ANC (active noise control) system is proposed(1),(2). However, the hardware that is DSP (digital signal processor) and the data acquisition system gives the noise attenuation quantity a limit. Thus, it is necessary to wait for the performance improvement of the hardware in order to ensure more sound attenuation. Recently the sound quality improvement has been studied by attenuating the sound of the specific frequency(3). In this paper, we propose a new silencer system for changing the sound quality of the fan noise. It is known that the improvement of the sound quality is possible by attenuating the discrete tone(3). In the experiment, the discrete tones that radiated from an AC axial flow fan are attenuated by the feedback active noise control. Metrics of the sound quality use TNR(tone to noise ratio) and PR(prominence ratio)(4). The sound is defined as an unpleasant sound when metrics exceed the threshold. The threshold is $6\,\mathrm{dB}$ for TNR and is $7\,\mathrm{dB}$ for PR. As the experimental results, it is clarified that the proposed system is capable of reducing TNR and PR from the threshold effectively.
2. Adaptive Feedback ANC

Figure 1 shows a schematic diagram of adaptive feedback ANC system\(^5\). ANC is implemented by Filtered-X Least mean algorithm. This graph is expressed in the Z-domain. As shown in the figure, D(z) is the primary noise, E(z) is the error signal, and U(z) is output signal of adaptive filter. W(z) is the adaptive digital filter which generates controlled sound. The transfer function of C(z) from control speaker to error microphone is approximated by $\hat{C}(z)$. Thus, we can estimate the primary noise $\hat{D}(z)$ as the next equation.

$$X(z) \equiv \hat{D}(z) = E(z) + \hat{C}(z)U(z) \quad (1)$$

The reference signal $x(n)$ is expressed in the time domain as follows.

$$x(n) \equiv \hat{d}(n) = e(n) + \sum_{m=0}^{M} \hat{c}_m(n-m) \quad (2)$$

where $\hat{c}$ are the coefficients of the $M$th order FIR filter $\hat{C}(z)$ used to estimate the C(z). The coefficients of W(z) are updated by using Filtered-X Least mean algorithm.

$$w_k(n + 1) = w_k(n) + \mu x'(n - k)e(n)$$

$$k = 0, 1, \cdots, K \quad (3)$$

3. Experimental Method

3.1. Slit resonator

Figure 2 shows the dimensions of a circular slit resonator and an elliptic slit resonator. The slit resonator consists of two panels, a spacer and loudspeakers. Two panels are made of acrylic resin 500mm x 500mm, 8mm in thickness and have a circular hole with $D_o = 175mm$ in center for ventilation. A spacer that has a circular hole with diameter $D_m = 410mm$ or an elliptic hole with a major axis $D_a = 410mm$ and a minor axis $D_b = 210mm$ in center is between their panels. Thickness of a spacer is 7mm. The spacer makes an air thin layer that is radially expanded with a very short axial length. The circular opening of the slit resonator, which is a ring-shaped source, completely surrounds the noise through ventilation aperture\(^6\). Honda et al. have theoretically clarified that the sound power of an axial fan can be minimized by the secondary sources on circumference of an axial fan\(^7\). The slit resonator with the concentric opening also surrounds the noise that passes through the ventilation. Therefore, it is considered that the slit resonator decreases the sound power of the discrete tone\(^2\). Loudspeakers are driven by the same control signal from DSP. When a slit resonator has a spacer with a circular hole, control sound is radiated from four loudspeakers. Four loudspeakers are placed in the
interval of 90-degrees. However, when a slit resonator has a spacer with an elliptic hole, two loudspeakers are placed on that of the major axis.

Figure 3 shows the transfer characteristic $\hat{C}(z)$ of secondary path. The transfer characteristic was measured by the time stretch pulse method\(^\text{(8)}\). $\hat{C}(z)$ is identified as FIR filter with 128 taps. It is indicated that the gain of the transfer function for the elliptic slit resonator is generally higher than that of the circular slit resonator. It means that the sound is transmitted in the high frequency, compared with the circular slit resonator.

### 3.2. Experimental system

The mounting arrangement of the axial flow fan is shown in figure 4. The axial flow fan used here had 5 blades and it was driven at a rotational speed at a range of from 1900 to 2850 rpm. Its maximum quiet pressure is 196 Pa, and maximum air flow rate is 11.2 $m^3/min$. 

![Graph of frequency characteristics of $\hat{C}(z)$](image)
Figure 4 shows that the slit resonator unit is attached on suction side of the fan. A lip of the slit resonator opening is covered with a mesh sheet of 0.1 mm thickness to suppress aerodynamic flow excitation. It was confirmed that the effect of the edge tone generated by the interaction of the air flow with the slit edge is small in this experimental condition. Specification of the fan is shown in Table 1.

The experimental setup is shown in Figure 5. Slit resonator is fixed in the wall of a test plenum. The test plenum dimensions are 900(w) x 900(H) x 900(D) mm, and the six sides were made of plywood (12 mm thickness), glass wool (20 mm thickness) and absorption sheet (1.5 mm thickness). A slider set up on the back wall regulated the air load. The window size for slider is 800(W) x 200(H) mm. The air flow quantity changes from 3.7 m$^3$/min to 10.7 m$^3$/min. The sound pressure level was measured at the error microphone.

3.3. Computer simulation

Computer simulations are performed to illustrate the effectiveness of the proposed system. Figure 6 shows the frequency spectrum of the noise that the actual fan radiates. Seven dis-

<table>
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<th>Table 1 Specification of fan</th>
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<tr>
<td>Model</td>
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<td>Type</td>
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<tr>
<td>Rated voltage</td>
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<tr>
<td>Speed</td>
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crete tones are observed. There are $f_1=225\text{Hz}$, $f_2=450\text{Hz}$, $f_3=675\text{Hz}$, $f_4=900\text{Hz}$, $f_5=1125\text{Hz}$, $f_6=1350\text{Hz}$, $f_7=1575\text{Hz}$. Using seven frequencies, the noise used in the simulation was defined like figure 7. This noise mixed seven sine waves with the Gaussian noise. The parameters used in the simulation are shown in table 2.

3.4. ANC Experiment

A single channel feedback ANC system consisting of an error microphone and the slit resonator is set up as shown in figure 5. As secondary sources which is the slit resonator, four loudspeakers are mounted into the circular membrane of the slit resonator. The secondary sources are controlled by single channel filtered-X LMS algorithm to give maximum reduction for the discrete tone at the error microphone. The error microphone is located on the rotational axial line 80 mm from the test plenum wall on the inflow side. A sampling frequency of 10 kHz and a FIR filter length of 250 taps were used for ANC. Specification of DSP is shown in table 3.

4. Results and Discussions

4.1. Attenuation Characteristics by Computer Simulation

The results of the computer simulation are shown in figure 8(a),(b),(c). Figure 8(b) is the result after ANC in using the circular slit, and figure 8(c) is the result after ANC in using the elliptic slit. The transfer function $\hat{C}(z)$ from the loudspeaker to the error microphone used the measured value. From the result of figure 8(c), the elliptic slit resonator has attenuated all discrete tones. However, it is proven that the attenuation of $f_6(1350\text{Hz})$ and $f_7(1575\text{Hz})$ is insufficient for the circular slit resonator in figure 8(b). This result shows that the elliptic slit resonator has good performance to the high frequency. The reason is considered to be that the

<table>
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<th>Table 2 Parameter for ANC simulation</th>
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<tr>
<td>Tap number of $\hat{C}(z)$</td>
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<tr>
<td>Tap number of $W(z)$</td>
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<tr>
<td>Sampling frequency</td>
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<tr>
<td>Step size</td>
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Table 3 Specification of DSP

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<tr>
<td>Frequency</td>
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</tr>
<tr>
<td>MIPS</td>
<td>25</td>
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<tr>
<td>Calculation accuracy</td>
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(a) ANC OFF(noise source)

(b) ANC ON(circular slit)

(c) ANC ON(elliptic slit)

Fig. 8 Results of adaptive feedback ANC simulations

4.2. Attenuation results by Experiment

From the result of the computer simulation, the composite system of the slit resonator and feedback ANC clarified that the discrete tone could be sufficiently attenuated. Figure 9(a) and (b) show the sound pressure spectra measured in the inflow side of the fan with the circular slit and the elliptic slit resonator units, with ANC turned on and off. The sound pressure level is measured at 80mm on the fan rotation axial line from the test plenum. The rotational speed of fan is 2700rpm and the slider is opened to give no load. The discrete tone radiated from the fan is also confirmed from $f_1$ to $f_7$.

In figure 9(a), the circular slit resonator obtained the noise attenuation from $3dB$ to $14dB$. Especially, the noise attenuation is very large at the fundamental frequency $f_1=225Hz$. The discrete tone of $f_3$ seem to be not sound attenuation according to the ANC’s effect but sound absorption by the resonance of the slit. It is because $f_3$ overlaps with the resonance frequency of the circular slit resonator. Two frequencies of $f_6$ and $f_7$ were not attenuated as well as the computer simulation.

In figure 9(b), the elliptic slit resonator obtained the noise attenuation from $2dB$ to $15dB$. The control effect of $f_7$ was not confirmed either in this case. However, the sound attenuation effect for $f_6$ was confirmed, and it is equal to the simulation.
5. Tone Quality Change by ANC

Figure 10 shows the relation between O.A.(A-weight) and air flow. The O.A. value slightly decreases in the side in which the flow quantity is large when the ANC is executed. Figures 11 shows the frequency spectrum of sound pressure at each flow quantity. In the low flow region $Q=3.7 m^3/min$, turbulent flow noise and wide-band noise by the counter flow increase $600 Hz$ or less(9). Therefore, the prominent discrete tone is not confirmed. In figure 11(b) and 11(c), the discrete tone becomes remarkable, as the flow quantity increase over $Q=6.8 m^3/min$. Therefore, O.A. value after ANC execution reduces $1 dB$~$2 dB$. Then, O.A. value after the ANC execution becomes a value in which the circular slit and the elliptic slit are also much the same.

The discrete tone analysis was carried out over flow quantity $Q=6.8 m^3/min$ in which the discrete tone spectrum remarkably appeared. It aimed at the first sound that had a large effect on the audibility, and then TNR and PR were evaluated in the first sound. The sound is defined
as a harsh sound, when the value of TNR and PR exceeds the threshold. Threshold of TNR is 6dB and that of PR is 7dB. And it is known that the improvement of the sound quality is possible by attenuating the discrete tones.

Figure 12 and figure 13 show TNR and PR for the circular slit resonator and the elliptic slit resonator as a function of the air flow, with ANC turned on and off. TNR and PR were evaluated on the first sound that affects the audibility. Results show that TNR and PR are larger than threshold over 8m³/min. ANC ON enables us to reduce TNR and PR under the threshold in all region of the air flow. Since the first sound in the critical band becomes remarkable, with the increase of the flow quantity, TNR and PR increase. TNR is higher than the threshold, when Q = 6.8 m³/min is exceeded. PR is also higher than the threshold over Q = 8.1 m³/min. It is proven that the air capacity which exceeds the threshold by analysis procedure differs. In the PR technique, the power of the critical band width including the first sound is compared with the average power of the neighbor critical band width. Therefore, in the power of the neighbor critical band at large flow rate area Q = 6.8 m³/min ~ 8.1 m³/min, it is considered that PR is evaluated small than the threshold. It is shown that TNR and PR are smaller in using the elliptic slit, compared with the circular slit. Figure 10 shows that the noise level of the elliptic slit is higher than the circular slit as a ANC OFF. It is indicated that the level of the wide-band noise with the elliptic slit is high. By the increase of the wide-band noise level, the discrete tone has been hidden in the inside, and the level of the discrete tone seems to relatively decrease. Therefore, tone quality improvement effect seemed to appear in ANC OFF. TNR and PR drastically decrease from the threshold after ANC ON, and it becomes the almost fixed value for the air flow.

6. Conclusion

The composite system with adaptive feedback ANC and the slit resonator was proposed. The effect for the discrete tone was clarified by the computer simulation and the experiment in order to indicate the usefulness of this system. As a result of the discrete tone analysis,
following points were clarified.

- As a result of the computer simulation, the higher gain of the transfer characteristic for the secondary path obtained, the more effective on the attenuation of the discrete tone obtained. The elliptic slit resonator is effective for the control of the discrete tone with the high order, because the gain of frequency characteristics is higher than that of the circular slit resonator.
- Experimental results by using five-blades axial flow fan, it is clarified that the elliptic slit resonator is effective for the attenuation of the discrete tone in the high frequency side.
- At the air flow $Q = 6.8\text{m}^3/\text{min} \sim 10.7\text{m}^3/\text{min}$ of the fan, O.A. value (A-weight) after the ANC ON is reduced 1dB or 2dB. TNR and PR are increased for the air flow, and it is drastically reduced after the ANC ON from the threshold defined as a harsh sound.

References


