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Active Control for Reduction of Noise Passing through Enclosure and Optimization of Microphone Position

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***Abstract*—**In this study, noise characteristics of structure were analyzed in an effort to reduce noise passing through an opening of an enclosure surrounding the structure that generates noise. Enclosures are essential measure to protect noise propagation from operating machinery. Access openings of the enclosures are important path of noise leakage. First, noise characteristics of structure were analyzed and feed-forward noise control was performed using simulation in order to reduce noise passing through the opening of enclosure, which surrounds a structure generating noise**.** We then implemented a feed-forward controller to actively control the acoustic power through the opening. Finally, we conducted optimization of placement of the reference sensors for several cases of the number of sensors. Good control performances were achieved using the minimum number of microphones arranged an optimal placement.

***Keywords*—**Active Noise Control, Feed-forward Control, Noise Attenuation, Position Optimization.

I. Introduction

With improvement of life standard, there is an increasing demand to live in a more pleasant environment away from noise. While necessity of reduction in living noises is being emphasized, industrial sites are showing increasing importance of enhancement in working environment through reduction of noise [1]-[2]. Machineries used in industries generate noise during operation, and emission of such noise to outside can be prevented by installing an enclosure nearby the structure. Enclosure installed nearby structures require partial opening to allow easy entrance of workers. However, since such opening can become a path through which internal noise is leaked outside, openable door is generally installed in the opening to open and close for works outside the enclosure. Here, if door is opened during operation of a machine, internal noise can be leaked outside and work efficiency can also be reduced due to inconvenience in opening and closing of the door. To resolve such problems, a sensor can be installed in the opening instead of openable door. Speaker installed inside the enclosure uses active noise control that generates control signals to reduce noise passing through the opening [3]-[6]. Construction of such active noise barrier can more effectively and certainly reduce noise.

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In this study, noise characteristics of structure were analyzed and feed-forward noise control was performed using simulation in order to reduce noise passing through the opening of enclosure, which surrounds a structure generating noise. In addition, position optimization of microphone was conducted for improvement of control performance, predicting control performance according to the number of microphones.

II. Optimization of Sound Power Using Feed-forward Control

During feed-forward control, sound pressure measured in microphone is defined as the sum of sound pressure by existing noise and sound pressure by control signal, as shown in Eq. (1).

$$\tilde{p} = \tilde{p}_p + \tilde{p}_s \tag{1}$$

Here, $\tilde{p}_p$ refers to sound pressure of microphone caused by internal noise, and $\tilde{p}_s$ is sound pressure of microphone caused by control source.

Eq. (1) can be expressed as Eq. (2) using transfer function and control source [7]-[8].

$$\tilde{p} = \tilde{p}_p + \overline{H}_s \tilde{q}_s \tag{2}$$

Here, $\tilde{q}_s$ is sound source generated by control speaker for control, and $\overline{H}_s$ is transfer function between control source and microphone.

Here, sound power of noise leaked outside through windows can be given as an objective function in Eq. (3).

$$J = \tilde{p}^H \tilde{p} \tag{3}$$

where $()^H$ denotes the complex conjugate transpose. And Eq. (3) can be expressed as below by substituting Eq. (2).

$$\begin{aligned} J &= \tilde{p}_p^H \tilde{p}_p + \tilde{q}_s^H \overline{H}_s^H \tilde{p}_p \\ &+ \tilde{p}_p^H \overline{H}_s \tilde{q}_s^H + \tilde{q}_s^H \overline{H}_s^H \overline{H}_s \tilde{q}_s^H \end{aligned} \tag{4}$$

With Eq. (4) as the objective function, Eq. (5) and Eq. (6) must be satisfied to minimize the function.

$$\frac{\partial J}{\partial \mathrm{Re}(q_s)} = 0 \tag{5}$$

$$\frac{\partial J}{\partial \mathrm{Im}(q_s)} = 0 \tag{6}$$

Here, control source $\tilde{q}_s$ satisfying Eq. (5) and Eq. (6) can be expressed as Eq. (7).

$$\tilde{q}_s = -(\overline{H}_s^H \overline{H}_s)^{-1} \overline{H}_s^H \overline{H}_p \tilde{q}_p \tag{7}$$

By substituting Eq. (4) into Eq. (7), minimized objective function can be obtained as in Eq. (8).

$$J_{\min} = \tilde{q}_s^H \overline{H}_p^H (I - \overline{H}_s (\overline{H}_s^H \overline{H}_s)^{-1} \overline{H}_s^H) \overline{H}_s^H \tilde{p}_p \tag{8}$$

Also, theoretical maximum noise attenuation is defined as Eq. (9) [9].

$$Attenuation(dB) = 10 \log_{10}(\frac{J}{J_{\min}}) \tag{9}$$

III. Active Noise Control for Reduction of Noise Passing through Enclosure

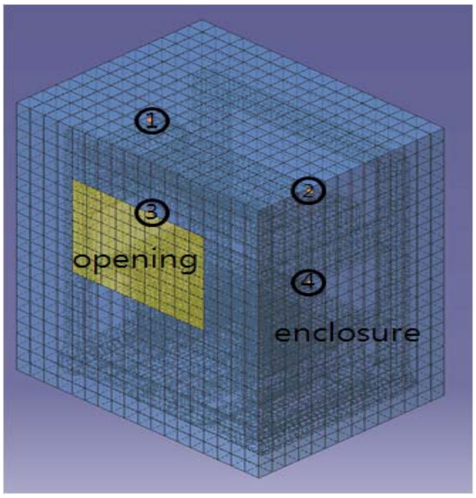

Fig. 1 Structural diagram of the machine and enclosure that perform active noise control

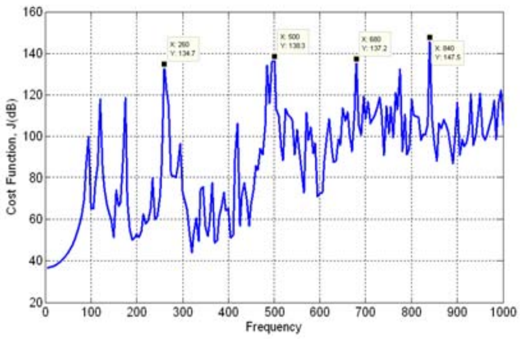

Fig. 2 Uncontrolled Cost Function [dB]

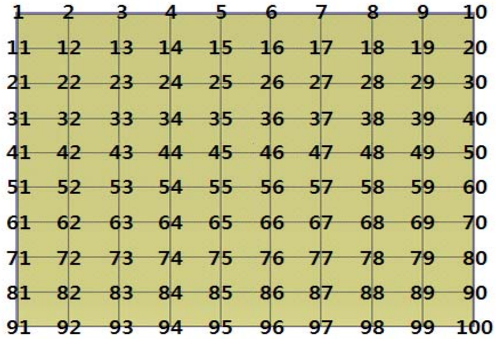

Fig. 3 Node number on the Field point

Fig. 1 is structural diagram of the machine and enclosure that perform active noise control. There is a machine that generates noise on the interior, and an enclosure with an opening surrounds the machine. Noise sources exist in positions 1 and 2 within the enclosure. The two sound sources were assumed to have identical amplitude and opposite phase. In addition, control speakers are installed for active noise control in positions 3 and 4. In order to reduce noise leaked outside through the opening located in the enclosure, microphones are installed at random positions of the opening. Control signal is generated by speakers using feed-forward control to minimize noise discharged through the opening.

Fig. 2 shows sound power at the opening between 0~1,000Hz with 5Hz interval, when internal noise is generated at positions 1 and 2 without control signal. As shown in the figure, high sound power values are found at 260Hz, 500Hz, 680Hz, and 840Hz. 100 node numbers were granted as in Fig. 3 to define microphones installed in the opening. In this study, commercial software called SYSNOISE was used to find transfer function between sound sources including control signal and between nodes in the opening. While fixing the position of noise and control speakers, study was conducted focusing on control performance according to the number and position of microphones in the opening.

A. Comparison of Control Performance According to the Number of Microphones

To compare control results according to the number of microphones, the number of microphones in the opening was differentiated as shown in Fig. 4. In the figure, red circles represent position of microphones. Control results according to each case are shown in Fig. 5, and attenuation after control is shown in Fig. 6.

As shown in Fig. 5, control performance at each frequency was found to differ according to change in the number of microphones. Attenuation for each peak value according to the number of microphones is shown in Table I. While control performance was dropped when control was performed with 4 microphones, similar control performances were shown in other cases.

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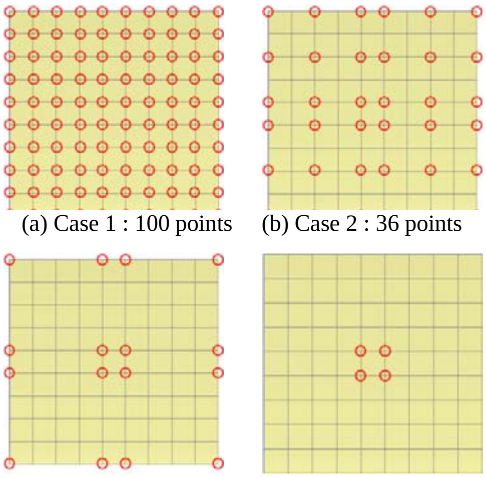


(a) Case 1 : 100 points (b) Case 2 : 36 points

(c) Case 3 : 16 points (d) Case 4 : 4 points

Fig. 4 Arrangements of microphones on the openings to evaluate the effect of the number of the sensors

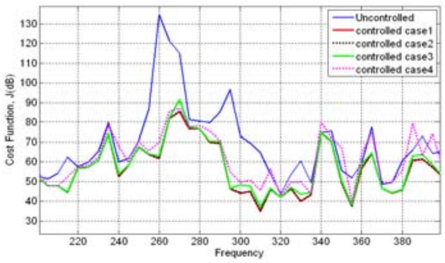


Fig. 5 Variation of cost functions with the number of microphones

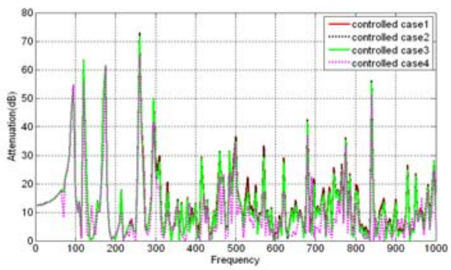


Fig. 6 Variation of attenuation with number of microphones

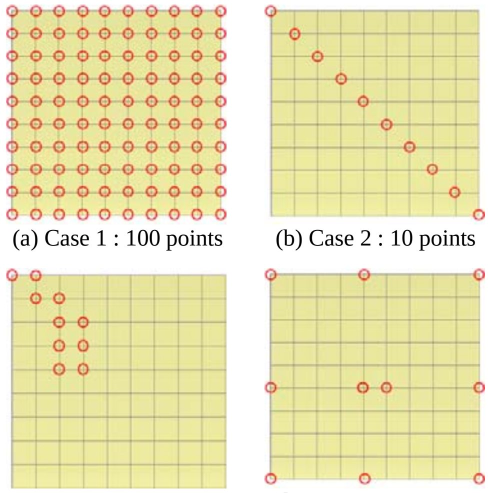
TABLE I
NOISE ATTENUATION AT PEAKS

CASE	260 HZ	500 Hz	680Hz	840 Hz
1	*72.88 dB*	*36.27 dB*	*42.44 dB*	*55.98 dB*
2	*72.70 dB*	*36.17 dB*	*42.17 dB*	*55.90 dB*
3	*71.63 dB*	*34.48 dB*	*41.56 dB*	*55.34 dB*
4	*64.79 dB*	*34.06 dB*	*37.05 dB*	*51.24 dB*

B. Control Performance According to Position of Microphones

When the number of microphones for feed-forward control is fixed, control was carried out on different arrangements of microphones as shown in Fig. 7 in order to compare control performance according to position of microphones. Control performance for each case is shown in Fig. 8, and attenuation after control is shown in Fig. 9. Table II shows attenuation at each peak value according to position of microphones.

With fixed number of microphones, control performance at each frequency was found to differ according to different positions of microphones.



(a) Case 1 : 100 points (b) Case 2 : 10 points

(c) Case 3 : 10 points (d) Case 4 : 10 points

Fig. 7 Arrangements of microphones to evaluate the effect of the location of the sensors

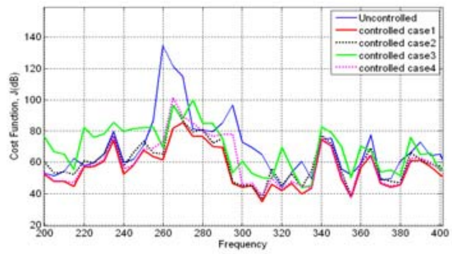


Fig. 8 Variation of the cost function with the location of the microphones

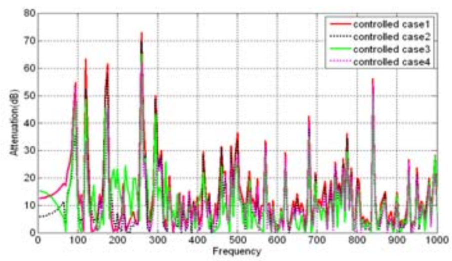


Fig. 9 Variation of attenuation with the location of the microphones

TABLE II
NOISE ATTENUATION AT PEAKS FOR POSITIONS OF MICROPHONE

CASE	260 HZ	500 Hz	680Hz	840 Hz
1	*72.88 dB*	*36.27 dB*	*42.44 dB*	*55.98 dB*
2	*69.31 dB*	*33.25 dB*	*38.10 dB*	*53.73 dB*
3	*64.95 dB*	*21.85 dB*	*34.91 dB*	*50.26 dB*
4	*61.76 dB*	*28.05 dB*	*40.62 dB*	*54.33 dB*

C. Selection of Sensor Position to Optimize Control Performance

Through the results verified earlier, control performance was found to increase with sufficient number of sensors. However in an actual experiment, there is limitation in the number of microphones. Possibility of experimental error also increases with increasing number of microphones. Accordingly, it is necessary to use a technique for effective attenuation of noise at specific frequencies, by positioning the least possible number of microphones in appropriate position. Number of cases was calculated in this study while differentiating the number of microphones used for active noise control between 2 and 4. After selecting position of microphones most effective in attenuation of noise at specific frequency, control results according to position were compared. Table III, IV, and V show optimal position of microphones and noise attenuation at each frequency when the number of microphones is 2, 3, and 4, respectively. In addition, number of repeated calculations at each frequency according to the number of microphones is shown in Table V. Optimal positions at different frequencies are similar despite difference in the number of microphone. Also, while number of repeated calculations is significantly increased with increase in the number of microphones, peak attenuation of noise was found to be similar, as shown in Fig. 10. Such result suggests that excellent control performance can be obtained with small number of microphones by placing them at appropriate positions.

TABLE III
POSITIONS OF MICROPHONE AND NOISE ATTENUATION AT PEAKS
(2 MICROPHONES USED)

FREQUENCY	NOISE ATTENUATION	OPTIMAL POSITION
260 Hz	*72.8635 dB*	*(62, 79)*
500 Hz	*36.1478 dB*	*(37, 56)*
680 Hz	*42.3607 dB*	*(11, 19)*
840 Hz	*55.9584 dB*	*(55, 77)*

TABLE IV
POSITIONS OF MICROPHONE AND NOISE ATTENUATION AT PEAKS
(3 MICROPHONES USED)

FREQUENCY	NOISE ATTENUATION	OPTIMAL POSITION
260 Hz	*72.8750 dB*	*(47, 62, 90)*
500 Hz	*36.2531 dB*	*(8, 37, 96)*
680 Hz	*42.4310 dB*	*(41, 66, 88)*
840 Hz	*55.9645 dB*	*(75, 77, 96)*

TABLE V
POSITIONS OF MICROPHONE AND NOISE ATTENUATION AT PEAKS
(4 MICROPHONES USED)

FREQUENCY	NOISE ATTENUATION	OPTIMAL POSITION
260 Hz	*72.8833 dB*	*(42, 48, 74, 78)*
500 Hz	*36.2646 dB*	*(21, 37, 83, 93)*
680 Hz	*42.4395 dB*	*(25, 41, 44, 77)*
840 Hz	*55.9763 dB*	*(49, 55, 68, 80)*

TABLE VI
ITERATION NUMBER FOR NUMBERS OF MICROPHONES

NUMBER OF MICROPHONES	ITERATION NUMBER
2	*4950*
3	*161700*
4	*3921225*

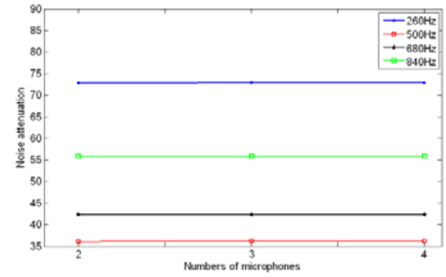


Fig. 10 Variation of the attenuation with the number of microphones

IV. CONCLUSION

In this study, noise characteristics of structure were analyzed in an effort to reduce noise passing through an opening of an enclosure surrounding the structure that generates noise. Feed-forward noise control was performed using simulation on frequencies that result in large noises based on noise characteristics of the structure analyzed. Attenuation effect for each single frequency was examined.

In addition, optimization of microphone position was carried out for improvement in control performance, and control performance was analyzed according to the number of microphones. While increasing number of microphones has large effect on attenuation of noise, it is difficult to create the control system with increased number of sensors in an actual experiment instead of simulation. Thus, maximum control effect must be obtained by placing small number of sensors at appropriate positions. Accordingly, optimal position of microphones was selected for different number of microphones, predicting maximum control effect.

A future study will be conducted to test control performance of microphones in optimal position through experimentation.

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