Basic Study on Active Acoustic Shielding*

Tatsuya MURAO** and Masaharu NISHIMURA***
**Department of Mechanical and Aerospace Engineering, Tottori University,
101, Minami 4-chome, Koyama-cho, Tottori-shi, Tottori-ken, 680-8552, Japan
E-mail: d12t1001h@edu.tottori-u.ac.jp
***Department of Mechanical and Aerospace Engineering, Tottori University,
101, Minami 4-chome, Koyama-cho, Tottori-shi, Tottori-ken, 680-8552, Japan
E-mail: mnishimura@mech.tottori-u.ac.jp

Abstract
Active acoustic shielding (AAS) is the system that can attenuate a sound passing through an open window. AAS is constructed from a number of AAS cells set in an array with having an approximately collocated microphone and speaker. Each AAS cell is individually controlled by a single-channel feedforward method. The concept of AAS was proposed by the authors and its feasibility was demonstrated in the previous report by performing some simple simulations and experiments. In this study, an AAS window with four AAS cells in a small open window was manufactured and installed in the door of a test room. Its noise-reducing performances were measured for noise from outside. The effects of multiple noise sources, moving noise sources and reflected sound in the room were also examined. As the results, the AAS window is demonstrated to be able to attenuate not only normal incident sound but also oblique incident sound in the frequency range from 500Hz to 1.5 or 2kHz. Moreover, noise reduction is obtained over a wide area in the room. Additionally the AAS window is also effective for multiple sound sources and moving sound sources.

Key words: Active Acoustic Shielding, Active Noise Control, Multiple Noise Sources, Moving Noise Sources, Reflected Sound

Nomenclature

\[ ATT(\omega) \] : Sound attenuation level [dB]
\[ c \] : Sound velocity [m/s]
\[ C_{\phi}(\omega) \] : Transfer function of error path
\[ d \] : Distance between the control speaker and the error microphone [m]
\[ f_s \] : Sampling frequency [Hz]
\[ f_c \] : Cut-off frequency of anti-aliasing filters [Hz]
\[ F(\omega) \] : Transfer function on howling canceller
\[ H(\omega) \] : Transfer function of control filter
\[ k \] : Wave number
\[ i \] : Imaginary unit
\[ p(\omega) \] : Complex sound pressure [Pa]
\[ P_0(\omega) \] : Complex amplitude of sound
\[ Q(\omega) \] : Sound strengths [ m²/s ]
\[ r \] : Distance from an AAS cell to the receiving point [m]
1. Introduction

Active noise control (ANC) has been developed and successfully applied to machines such as air conditioning ducts, engine mufflers, ear protectors, car cabins, noise barriers and so forth. However, to reduce random noise in large spaces, ANC requires a multichannel system that is too complicated and costly to be practically applied. The applications of ANC to three-dimensional spaces are restricted to reducing rather simple these of noise such as booming noise in cars and propeller noise in airplane cabins\(^{(1,2)}\). Therefore, a system for decentralized control has been proposed and developed, in which the boundaries of a sound field are controlled by distributed ANC units to reduce noise in the field\(^{(3-6)}\). In this system, the acoustic impedance of the walls, namely, the sound absorption, sound insulation or sound diffraction of the walls, is controlled by distributed active cells containing one microphone and one speaker each. The crosstalk components of each active cell are so small that the cells can be individually controlled. Thus, we can control a sound field by placing active cells with the same performance side by side. This system is very simple, and an active soft edge (ASE) system has already been practically used to reduce the sound diffraction of noise barriers\(^{(4)}\).

On the other hand, there is high demand for the development of open windows that can insulate sound by using ANC techniques. Ise proposed a sound field control method that controls the sound pressure and particle velocity at the boundary of the field\(^{(7)}\). However,
this system requires multiple channel control, making it too complicated to be practically used. The authors have been developing a decentralized control system that can reduce sound from visible sound sources such as traffic noise by using directional microphones and directional speakers (8). However its noise-reducing performance was unsatisfactory. Roure et al. also developed a noise shielding system for aircraft noise using directional devices (9). In this case, the quiet zone was small and the system was ineffective for sounds of oblique incidence.

With this research background, we proposed the concept of active acoustic shielding (AAS) and demonstrated its feasibility by performing some simple simulations and experiments (10). In this study, a small AAS window of size in 250mm × 250mm was manufactured and installed in the door of an anechoic room. The noise attenuation resulting from AAS was measured for the noise transmitted through the window from outside the room. The effect on the noise reducing performance was examined for oblique incident sound, multiple noise sources, moving noise sources and sound reflection in the room. (11)

2. Basic Concept of AAS

According to Huygens’ principle, a sound wave propagates by generating element waves at the wavefront and the intensity and direction of the sound wave are determined by the manner by which element waves are generated. If we can generate antiphase element waves with the same amplitude as the primary element waves at an arbitrary boundary plane, anti-sound waves will propagate behind the plane. Therefore, it is supposed that point sound sources distributed sufficiently closer to each other than the wavelength of the target sound can generate a wavefront of any shape by controlling their amplitudes and phases appropriately. This means that if we can make an active control system constructed with many noise controlling cells which have a collocated reference microphone and a control speaker individually and are distributed on an acoustic boundary such as a window at a sufficiently short distance from each other, the system can attenuate primary sound by generating an anti-phase sound relative to that measured by the reference microphone. We call this system “active acoustic shielding (AAS)”.

The basic concept of AAS is shown in Fig. 1. AAS cells are set in lines at an open window. An AAS cell has a reference microphone as close as possible in front of a secondary sound source. The signal measured by the reference microphone is inputted to the secondary source through a fixed filter $H(\omega)$. Namely, AAS cells are controlled by a feedforward method. The filter $H(\omega)$ is the same in every AAS cell. The transfer
function of the filter $H(\omega)$ is determined so that most of the sound transmitted through the window is removed. If necessary, a howling compensation filter $F(\omega)$ is set in the AAS cell. Because the reference microphone and secondary source are nearly collocated, not only normally incident plane waves but also obliquely incident plane waves, spherical waves and waves with arbitrary shapes are expected to be reduced by AAS using the same filter $H(\omega)$, according to Huygens’ principle. That means that AAS is expected to be effective for multiple primary sound sources and moving sources.

3. Simulation

Feasibility of the above concept of AAS was studied by simple simulations based on the assumption that reference microphones and secondary sources are perfectly collocated.

3.1 Simulation Model

Figure 2 shows the model used to simulate AAS. AAS cells are set on a control plane in lines that divide the free space. The reference microphone and secondary source of each AAS cell are assumed to be perfectly collocated.

Secondary sources are assumed to be point sources and their strengths are determined by multiplying the primary sound pressure signals at their positions by a fixed transfer function. The transfer function is determined for the sound pressure at the position of an error microphone so that it is perfectly cancelled when AAS is operating.

![Fig. 2 Simulation model of AAS](image)

Because the purpose of this simulation is to demonstrate the feasibility of the AAS system, the problem is simplified as follows. The primary sound is assumed to be a plane wave with an oblique incident angle to the control plane. The control plane is defined as the $yz$-plane at $x = 0$ and AAS cells are placed on that plane in lines at intervals of $w$ (l lines parallel to $y$-axis, $m$ columns parallel to $z$ axis) as shown in Fig. 2. The plane of the primary wave is parallel to the $z$ axis, and $\theta$ is the incident angle to the control plane. $\lambda$ is the wavelength of the primary sound. The error microphone’s position $e$ is $(d,0,0)$.

The complex sound pressure of the primary sound wave at $(x,y,z)$, $p_p(\omega;x,y,z)$, is written as follows. We refer to the complex amplitude of the sound wave as simply the sound pressure hereafter.

$$p_p(\omega;x,y,z) = P_p(\omega)e^{-i(k_x x + k_y y)} \quad (1)$$

$$k_x = k \cos \theta, \quad k_y = k \sin \theta \quad (2)$$
Here, \( P_p(\omega) \) is the amplitude of the incident sound wave, \( \omega \) is the angular frequency, \( k \) is the wave number and \( i \) is the imaginary unit. Therefore, the incident sound pressure at each AAS cell position \((0, mw, lw)\) is given as

\[
p_p(\omega, mw, lw) = P_p(\omega)e^{-imw\sin\theta} \quad (l, m : \cdots -2, 0, 1, 2). \tag{3}
\]

Secondary source strengths \( Q_{sw}(\omega) \) are determined by multiplying the primary sound pressure signals at their positions by fixed transfer function \( H(\omega) \). Then,

\[
Q_{sw}(\omega) = p_p(\omega; 0, mw, lw)H(\omega) = Q_{sw}(\omega)e^{-imw\sin\theta} \tag{4}
\]

\[
Q_{sw}(\omega) = P_p(\omega)H(\omega) \tag{5}
\]

Because the secondary sources are point sources, the contribution of the secondary source at \((0, mw, lw)\) to the sound pressure at the receiving point \((x, y, z)\) is given as follows.

\[
p_{sw}(\omega, x, y, z) = i\frac{\rho ckQ_{sw}(\omega)}{4\pi r_{lm}} e^{-ikr_{lm}} \tag{6}
\]

\[
r_{lm} = \sqrt{x^2 + (y - mw)^2 + (z - lw)^2} \tag{7}
\]

Here, \( \rho \) is the air density, \( c \) is the sound velocity and \( r_{lm} \) is the distance from the AAS cell at \((0, mw, lw)\) to the receiving point \((x, y, z)\). The sound pressure contribution from all the AAS cells is

\[
p(\omega, x, y, z) = \frac{i\rho ckQ_{sw}(\omega)}{4\pi} \sum_{l=-L}^{L} \sum_{m=-M}^{M} \frac{1}{r_{lm}} e^{-ik(xlw + mw\sin\theta)} . \tag{8}
\]

Here, \( 2M + 1 \) and \( 2L + 1 \) are the numbers of columns and lines of AAS cells, respectively. In this case, the total number of AAS cells is \((2M + 1)(2L + 1)\). Therefore, the sound pressure at receiving point \((x, y, z)\) is given by

\[
p(\omega, x, y, z) - p_0(\omega, x, y, z) + p_0(\omega, x, y, z) = P_p(\omega) e^{-ik(x, y, z)} + \frac{i\rho ckH(\omega)}{4\pi} \sum_{l=-L}^{L} \sum_{m=-M}^{M} \frac{1}{r_{lm}} e^{-ik(xlm + mw\sin\theta)} . \tag{9}
\]

Next, \( H(\omega) \) is determined as follows so that the sound pressure at the position of the error microphone \((d, 0, 0)\) is zero when AAS is operating and \( \theta = 0 \).

\[
H(\omega) = i \frac{4\pi e^{-i\omega d}}{\rho ck \sum_{l=-L}^{L} \sum_{m=-M}^{M} \frac{1}{r_{celm}}} \tag{10}
\]
Here, $r_{elm}$ is the distance from the AAS cell at $(0,mw, lw)$ to the error microphone at $(d,mw, lw)$. If $H(\omega)$ is fixed and given by Eq. (10), the noise reduction at the receiving point behind the control plane, $ATT(\omega, x, y, z)$, is obtained by the following equation in the case of an oblique incident primary sound wave.

$$ATT(\omega, x, y, z) = -20 \log \left( \frac{p_s(\omega, x, y, z) + p_s(\omega, x, y, z)}{p_s(\omega, x, y, z)} \right)$$

$$= -20 \log \left( \frac{e^{-ikd} \sum_{l=-L_{min}}^{L_{max}} \sum_{m=-M_{min}}^{M_{max}} \frac{1}{r_{elm}^{\omega \omega}} e^{-ik_r (r_{elm} + mw \sin \theta)}}{e^{-ik \cos \theta \sin \theta} \sum_{l=-L_{min}}^{L_{max}} \sum_{m=-M_{min}}^{M_{max}} \frac{1}{r_{elm}^{\omega \omega}} e^{-ik_{elm}}} \right)$$  \hspace{1cm} (12)

3.2 Simulation Results

For the noise reduction was calculated using Eq.(12) several conditions with $w = 0.125$ m, $L = 50$ and $M = 50$ fixed. Then AAS cells were distributed in the region satisfying $-6.25 \leq y \leq 6.25$ m and $-6.25 \leq z \leq 6.25$ m on the plane $x = 0$. The parameters $d$, $\lambda$ and $\theta$ were varied. The calculation results are illustrated in the form of noise reduction contours in the region satisfying $0 \leq x \leq 20$ m and $-10 \leq y \leq 10$ m on the plane $z = 0$.

3.2.1 Normal Incidence  ($\theta = 0$)

Figure 3 shows the results when $\theta = 0$ and $w / \lambda = 0.25$, which show the effect of carrying the parameter $d / w$.

![Noise reduction contours for different values of $d / w$ ($\theta = 0$, $w / \lambda = 0.25$)](image-url)

Fig. 3  Noise reduction contours for different values of $d / w$ ($\theta = 0$, $w / \lambda = 0.25$)
The white zones between the contours are regions with larger noise reduction greater than 20dB. It can be seen that large noise reduction is obtained behind the AAS plane. The zones with large noise reduction become narrower farther from the control plane. This is because the control plane is finite and has edges. The secondary sound field constructed by AAS consists of plane waves in the near field but spherical waves in the farther field. Zones with large noise reduction are also observed in farther zones. This is considered to be due to the fact that the AAS cells are finite and discretely placed. According to these figures, a distance of \( d/w = 1 \) from the control plane is sufficient for the error microphone. This means that a set of point sources can construct a plane wave at positions as for apart from the source plane as the interval between sources.

Figure 4 shows the results when \( \theta = 0 \) and \( d/w = 1 \) are fixed and \( w/\lambda \) is varied. These contours show that if \( w/\lambda \leq 0.75 \), large noise reductions is obtained in the case of \( \theta = 0^\circ \).

![Fig. 4 Noise reduction contours for different values of \( w/\lambda \) (\( \theta = 0^\circ \), \( d/w = 1 \))](image)

3.2.2 In the Case of Oblique Incidence (\( \theta \neq 0 \))

Figure 5 shows the results when \( w/\lambda = 0.25 \) and \( d/w = 1 \) are fixed and \( \theta \) is varied. It can be seen that large noise reduction is obtained up to \( \theta = 60^\circ \). According to further simulations, we found that if \( w/\lambda = 0.5 \), large noise reductions is obtained in the case of \( \theta \leq 60^\circ \).

![Fig. 5 Noise reduction contours for different values of \( \theta \) (\( d/w = 1 \), \( w/\lambda = 0.25 \))]
3.3 Summary of Simulations

In the above simulations it was found that if reference microphones and secondary sources are collocated, when a zone with large noise reduction is obtained behind the AAS plane under the conditions of \( \frac{w}{\lambda} \leq 0.5 \) and \( \theta \leq 60^\circ \), and that a distance of \( \frac{d}{w} = 1 \) from the control plane is sufficient for the error microphone. It is considered that AAS can also be effective when the incident wave is not only a plane wave but also a spherical wave or a more complicated wave.

4. Small Window with AAS

4.1 Fabrication of AAS Window

A small window with a 250mm × 250mm opening containing four AAS cells was manufactured as shown in Fig. 6. We call this window AAS window. In this study, the target frequency of the sound to be attenuated ranged from 500Hz to 2kHz. The configuration and dimensions of the AAS window are shown in the figure. A flat speaker was used as a secondary source because of its quick response. The reference microphone was set immediately behind the speaker box. The distance between the reference microphone and the speaker diaphragm is only 50mm. The distance is considered to be as short as that required for the collocation of the sound whose frequency is below 2kHz, because it is shorter than a quarter of the wavelength. This AAS cell is controlled by a feed-forward method as described below. In this case, the causality of the signals was proved to be satisfied in our previous report despite the short distance (10).

The distance between each cell center \( w \) is 125mm. This means that \( \frac{w}{\lambda} = 0.184 - 0.735 \) for the target frequency range. According to our previous report, the condition \( \frac{w}{\lambda} \leq 0.75 \) enables a quiet zone to develop behind the AAS plane in the case of sound with normal incidence. Clarification of the effect of oblique incidence is one of our research aims. The open area ratio of the AAS window is 68%.

![Fabricated AAS window](image)

Fig.6  Fabricated AAS window

4.2 Control of AAS Window

Each AAT-Cell is controlled individually by multiplying each measured reference signal by a fixed transfer function \( H(\omega) \) and inputting it to each secondary speaker as shown in Fig. 1. In the experiment \( H(\omega) \) was determined as follows.

Firstly, each error microphone was placed 100mm \( (d/w \approx 1) \) behind each AAS cell as shown in Fig. 7, and the system was controlled by the 4(1-1)-4 filtered-X-LMS algorithm shown in Fig. 8. This is equivalent to the algorithm with no cross filters in the ordinary
4-4-4 multiple filtered-X-LMS algorithm. A characteristic of this system is that each secondary source can be actuated only by its own reference signal. \( H_1(\omega) \) to \( H_4(\omega) \) were adaptively converged by an error-scanning method to minimize the mean square of every error signal. Secondly, after confirming that each transfer function is similar, a representative transfer function is selected and inputted to each AAS cell. Then each AAS cell has the same transfer function.

In this experiment, the sampling frequency of the controller \( f_s \) is 48kHz and the cut-off frequency of anti-aliasing filters \( f_c \) is 20 kHz. The filter tap lengths of \( H_i(\omega) \) and the error path filter \( C_j(\omega) \) are 220 and 120, respectively. The causality of the signals was satisfied and each transfer function \( H_i(\omega) \) converged to similar function as stated below. The howling compensation filter \( F_i(\omega) \) was not necessary.

### 5. Performance Tests of AAS Window

#### 5.1 Test Arrangement and Procedure

The manufactured AAS window was installed in the door of a small anechoic room (2.4mW × 2.4mL × 2.4mH) as shown in Fig. 9. First, a primary source was set at a distance of 500mm in front of the AAS window and adaptive control was performed using the 4(1-1)-4 filtered-X-LMS algorithm. After the control had converged, the transfer functions \( H_i(\omega) \) were fixed and the error microphones were removed.

Sound pressure spectra at the fixed points a-d shown in Fig. 9 were measured with and without ANC (ANC ON and OFF). 1/3-octave-band sound pressure level contours and sound attenuation level contours were drawn on the horizontal plane (1m x 1m) at the height of the AAS window center, as shown in Fig. 9, in accordance with the results of microphone traverse measurements.

Experiments were performed for the following five cases.

Case 1: A primary source was set at a distance of 500mm and normal to the AAS window.

Case 2: A primary source was set at a distance of 500mm and an oblique angle of 30degree to the AAS window.

Case 3: The above two incoherent primary sources were activated simultaneously.

Case 4: A primary source was moved on the line parallel to and 1m apart from the AAS window.
Case 5: Some sound reflection boards were set on the inside walls of the anechoic room to increase sound reflection.

In every case, frequency-restricted random noise from 500Hz to 2kHz was used for the primary noise. For Case 2-5, the same fixed transfer function $H(\omega)$ was used for every AAS cell which was determined in Case 1.

![Test setup](image)

(a) Outside view
(b) Plane view

Fig. 9  Test setup

5.2 Test Results

5.2.1 Transfer Function $H_i(\omega)$

Figure 10 shows the impulse responses and transfer functions of the four filters $H_i(\omega) \ (i = 1-4)$ which were converged by 4(1-1)-4 filtered-X-LMS algorithm in Case 1. Because they were nearly the same, their average value $H(\omega)$ was adopted as the fixed filter to every AAS cell thereafter.

![Converged filters in Case 1](image)

(a) Impulse response
(b) Gain
(c) Phase

Fig. 10  Converged filters in Case 1

5.2.2 Case 1

Figure 11 shows the sound pressure spectra at the fixed points under the conditions of ANC ON and OFF in Case 1 (normal incidence). In these figures, the sound spectra under two conditions of ANC ON are plotted. One is the case that the converged filter itself $H_i(\omega)$ was adopted for each AAS cell and the other is the case that the same averaged
filter \( H(\omega) \) was adopted for each AAS cell. Both results are similar and 10 -15dB noise reduction was obtained in the target frequency range (500Hz-2kHz) over a wide area of the test room. This demonstrates that the use of the same fixed filter gives satisfactory noise-reducing performance as predicted when discussing the basic concept. Hereafter, we show the results under the condition of using the same fixed filter.

This result was consisted with the result of simulation, because the value of \( \frac{w}{\lambda} \) is under 0.75 in the frequency region of this experiment.

Figure 12 shows 1/3-octave-band sound pressure level contours and sound attenuation level contours at typical frequencies. This figure shows that a large amount of noise reduction is obtained in almost all areas at 800Hz. Although there are some with increased noise zones at 1.6kHz, the high sound pressure is reduced in the main zone and the AAS window is also effective at this frequency.
5.2.3 Case 2

Figure 13 shows sound pressure spectra at the fixed points under the conditions of ANC ON and OFF in Case 2 (30deg oblique incidence). Nearly the same noise reduction is obtained in the frequency range from 500Hz to 1.5kHz as that in Case 1. However no noise reduction is obtained at frequencies higher than 1.5kHz. This is considered to be because \( \frac{w}{\lambda} \) is 0.5 above 1.5kHz\(^{(10)}\). Fig. 14 shows 1/3-octave-band sound pressure level contours and sound attenuation level contours at a typical frequency 800Hz. There are some zones of high sound pressure in the oblique direction under the condition of ANC OFF. However, the sound pressure in these zones is effectively reduced by ANC. Similar effects were also obtained at other frequencies.

![Fig. 13](image13.png)

**Fig. 13** Sound pressure spectra at fixed points under the condition of ANC ON and OFF in Case 2

![Fig. 14](image14.png)

(a) SPL contour

(b) SPL contour

(c) Sound attenuation level contour

**Fig. 14** Typical 1/3-octave-band sound pressure level and sound attenuation level contours in Case 2 using the same fixed filter \( H(\omega) \)

5.2.4 Case 3

Two primary sources were activated simultaneously with two incoherent frequency-restricted random noise signals in Case 3. One was set at a distance of 500mm and normal to the AAS window and the other was set at a distance of 500mm at an oblique angle of 30deg to it. Measured sound spectra at point a in Case 3 are shown in Fig. 15 along with those in Cases 1 and 2 for comparison. In the case of multiple sound sources, the sound spectra are the sum of those in each single sound source, both with and without ANC. This means that this AAS window is also effective for multiple sound sources.

Figure 16 shows 1/3-octave-band sound attenuation level contour at frequencies of 800Hz, 1.25kHz and 1.6kHz. These figures show that a large amount of noise reduction is obtained in almost all areas at 800Hz. Although there are some zones with increased noise at 1.6kHz, the high sound pressure is reduced in the main zone and the AAS window is also effective at this frequency.
5.2.5 Case 4

A primary source was moved on the line parallel to and 1m apart from the AAS window in Case 4. The speed of the source was set to 0.9m/s and 1.8m/s. Figure 17 shows the typical measured time variation of the 1/3-octave-band sound pressure levels at point a when the speed of the primary source is 0.9m/s. Similar results were obtained when the speed was 1.8m/s. These results demonstrate that the AAS window is also effective for moving noise sources.
5.2.6 Case 5

Finally, some sound reflection boards were set on the inside walls of the anechoic room to increase sound reflection in Case 5. The primary source was set at the same position as in Case 1. Figure 18 shows the sound spectra at points a and b under the conditions of ANC ON and OFF compared with those in Case 1. Although the spectra have some peaks and dips in Case 5 because of the sound reflection, satisfactory sound attenuation was obtained. Figure 19 shows 1/3-octave-band sound pressure level contours and sound attenuation level contours at various frequencies. These figures show that a large amount of noise reduction is obtained in almost all areas at 800Hz. It was considered that the reflection sound wasn’t influenced the noise reducing performance.

![Sound pressure spectra at fixed points under the condition of ANC ON and OFF in Case 1 and Case 5](image)

**Fig. 18** Sound pressure spectra at fixed points under the condition of ANC ON and OFF in Case 1 and Case 5

![Typical 1/3-octave-band sound pressure level and sound attenuation level contours in Case 5 using the same fixed filter](image)

**Fig. 19** Typical 1/3-octave-band sound pressure level and sound attenuation level contours in Case 5 using the same fixed filter $H(\omega)$

Additionally, the effect of speech in the room on the AAS window was examined. Normal speech did not affect the performance of the AAS window. This is considered to be because the reference microphones are set outside the window and the control filters are fixed.

6. Discussions

Figure 11 shows that AAS is effective in the frequency range below 2kHz in the case of normal incidence. In this case, 2kHz stands for $w/\lambda \approx 0.75$. Moreover, Figure 13 shows that AAS is effective below 1.5kHz in the case of oblique incidence. 1.5kHz stands for $w/\lambda \approx 0.5$. These results roughly coincide with the results of Chapter 3. We add to say that the lower limit of noise reduction (500Hz) depends on the speaker’s ability.

In these experiments, the distance between the reference microphone and the control
speaker, $s$, was 50mm. This distance also gives the restriction of noise reduction in the high frequency region, in the case of oblique incidence, when the fixed filters are used. The fixed filter is optimized in the case of normal incidence. However it is not optimum for obliquely incident sound, because the time delay of the sound wave travelling from the reference microphone’s position to the control speaker’s position is different from that of normal incident sound. This causes phase mismatch especially in the high frequency range. This phase mismatch is about 10°deg in the case of 1.5kHz and $\theta = 30$°deg when the distance ‘$s$’ is 50mm. The smaller the distance ‘$s$’ is, the better the noise reduction is, for the obliquely incident sound. However too small distance ‘$s$’ destroys the signal causality. We adopted very high sampling frequency to solve this problem. Normally sampling frequency of 5kHz is considered to be enough for controlling the sound below 2kHz. We used 48kHz as the sampling frequency to shorten the anti-aliasing filter delay and the digital delay. It was proved that the distance ‘$s$’ could be shortened down to 25mm in the previous work\(^8\). In the experiments shown in Chapters 4 and 5, 50mm was adopted for the distance ‘$s$’ to satisfy the causality law with enough margin.

We used a fixed filter for the control filter. It was realized by setting error microphones adjacent to control speakers. The transfer function of the error path can hardly be affected by the temperature change, if the distance of the error path is enough short compared with the sound wavelength. Moreover the transfer function can also hardly be affected by the reflection condition of the room because the direct sound from the control speaker is rather dominant compared with the reflected sound. AAS with fixed filters has many merits. The system is very simple and it can remove error microphones when operating. Conversations and noises in the room do not disturb the AAS performance.

In our experiments, it was possible to use the same fixed filter for each AAS cell. It is supposed to be accomplished because of the symmetrical positions of four AAS cells. This enables mass production of AAS cells.

7. Conclusions

The concept of active acoustic shielding (AAS) was proposed and its feasibility was studied by simulations and experiments. An AAS window was manufactured and installed in the door of an anechoic room. Its sound attenuation performances were examined for several types of sound sources. The following conclusions were obtained.

1. The simulations demonstrated that if reference microphones and secondary sources were collocated, a zone with large noise reduction was obtained behind the AAS plane when $w/\lambda \leq 0.5$ and $\theta \leq 60$°deg, and that a distance of $d/w = 1$ was sufficient from the control plane to the error microphone.

2. The AAS window was demonstrated to be able to attenuate not only normal incident sound but also oblique incident sound in the frequency range from 500Hz to 1.5 or 2kHz. Moreover, noise reduction was obtained over a wide area in the room.

3. The AAS window was also effective for multiple sound sources and moving sound sources.

4. Sound reflection and human speech in the room did not a severely affect the sound attenuation performance of the AAS window.
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