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Experimental design methodology for global active noise control in enclosed space

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The purpose of this paper is to propose an experimental design methodology for global active noise control in an enclosed space. We aim to control the noise caused by an internal noise source. Since each enclosed space has different acoustic characteristics, it is difficult to design different controllers suitable for each enclosed space. So, we decided to design a controller that could be used universally. The basic concept is the collocation of noise source and control speakers to generate a sound field opposite in phase to the noise source in a free field. For implementation of the proposed method, we propose a configuration method of control speakers and error microphones, and an active noise control algorithm. Also, to confirm the applicability of the proposed method, we design a controller in an anechoic chamber, which represents a free field condition, and perform active noise control in other enclosed spaces with the controller designed for the anechoic chamber. The experimental results show that the solution calculated in the free field condition can be used in other enclosed spaces without any modifications.

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Active noise control (ANC) is a method of reducing unwanted noise by using a control speaker to generate anti-phase sound. ANC has traditionally shown excellent control performance in noise control of ducts and headphones. Recently, interest in this method has been gradually increasing with commercialization in automobiles and wireless earphones. Most active noise control, including the technologies mentioned, is local active noise control. The control area of local active noise control is limited around the point like microphone; it is difficult to control large spaces. However, noise control for the enclosed spaces in which people live or work will require noise control in global areas, because people are always moving around. Among noises in enclosed space, we want to focus on internal noise caused by internal noise sources. There are two ways to implement global ANC of internal noise sources in enclosed spaces. One is to control the noise by an indirect path (reflection noise); the other is to control the noise by a direct path. Experimental results on indirect path noise control in enclosed spaces were reported by Warnaka et al.¹ and Ross². this area has been studied continuously, and research has expanded to global ANC in three-dimensional enclosed spaces³⁻⁷. However, because enclosed spaces have various sizes, shapes, and reflective properties of walls, this method involves

different solutions for the different spaces in which ANC is applied. Results also depend on arrangements of objects in the enclosed spaces; even finding solutions when objects are present can become very complicated. On the other hand, the second method involves collocation of noise source and control speakers to generate a phase sound field opposite to that of the noise source. Nelson et al. studied a theoretical approach to acoustic power minimization for global ANC in free field⁸. This theoretical approach was performed in the frequency domain. The simulation results showed that significant noise reduction could only be achieved if control sources were placed within a distance of one half wavelength of the noise source. Later, Nelson et al. showed that even stationary random noise sources can be controlled using acoustic power minimization through the Wiener filter solution⁹. We assumed that we would be able to control various enclosed spaces with a controller designed to minimize acoustic power in the free field condition. Based on this background, we proposed control speakers, a microphone configuration method, and the ANC algorithm for a global ANC system for acoustic power minimization. To confirm the feasibility of our system, we used the solution obtained in an anechoic chamber with proposed method in an ANC experiment performed in various enclosed spaces. The experiments were conducted in three enclosed spaces with different acoustic characteristics.

Results

In the experiment, we used a loudspeaker as noise source. Since the loudspeaker is close to a monopole in the low frequency range, and we can determine the input signal, it is suitable for confirming the experimental maximum performance of the proposed method. Originally, the frequency range of interest was determined by the spectrum of the noise source. However, we set an arbitrary frequency range of interest from 170Hz to 378Hz for this experiment. We used band limited white noise as the speaker input of the noise source. According to Eq. (1), the radius of the microphone array must be over 1m and set to 1m. The radius of the control speaker array must be less than 0.45m from the noise source; as in Eq. (3), and considering the size of the noise source, it was set at 0.12m, as close as possible to the noise source. According to Eq. (2), measurable degree of spherical harmonics was set at 7. We used the Gaussian sampling method and set up 128 microphones. The sound field of the loudspeaker(noise source) was measured using the determined microphone array; as expected, it was close to a monopole source. So, the maximum degree of the noise source was 0. According to Eq. (4), more than one control speaker must be used, and so we placed a sufficient number of control speakers (four) at the vertices of a regular tetrahedron. Figure 1 shows the experimental setting of the control speaker array and microphone array in the anechoic chamber.

With the determined control speaker and microphone configuration, the sound fields of the noise source and control speakers were measured in the anechoic chamber; a Wiener filter was obtained. Active noise control was performed in the anechoic chamber and three enclosed spaces using the Wiener filter obtained in the anechoic chamber. The three enclosed spaces were selected as spaces with different reverberation characteristics and classified by

reverberation time and relative size of the space. Size of anechoic chamber was 3.6 m (width) $\times$ 3.6 m (depth) $\times$ 2.4 m (height). Enclosed space 1's size was 3.2 m (width) $\times$ 5.5 m (depth) $\times$ 2.8m (height); reverberation time was 0.26s. Enclosed space 2's size was 6.1m (width) $\times$ 3.1m (depth) $\times$ 3.8m (height); reverberation time was 2.2s. Enclosed space 3's size was 6.6m (width) $\times$ 9.9m (depth) $\times$ 2.6m (height); reverberation time was 0.7s. For performance measurement, 9 microphones were placed near the noise source according to electronic noise measurement specifications (KS C IEC 60704-1: 2015); the experimental setting in each space is shown in Figure 2.

Figure 3 shows the ANC results for each space in the frequency range of interest. Noise has been reduced throughout the frequency ranges of interest in all spaces. It was also observed that the spectrum, which indicates the characteristics of the enclosed space, was evenly maintained after the noise was reduced. Table 1 shows the average dB reduction in the frequency range of interest at each microphone and the maximum, minimum, and average dB reduction at each space. There were slight deviations from the maximum and minimum noise reduction levels, but the mean values were similar. This shows that controllers designed in free field condition have similar control performance in other enclosed spaces.

Discussion

In this study, we proposed an experimental design methodology for global active noise control in enclosed spaces. We targeted noise caused by internal noise sources inside enclosed spaces. Enclosed spaces have different acoustic characteristics and it is difficult to design different controllers for different enclosed spaces. Therefore, we designed a controller that can be used universally in enclosed spaces. The controller we designed minimizes the acoustic power under free field condition. We also proposed configuration methods of the control speaker array and of the microphone array for acoustic power estimation. Using our proposed configuration method, the arrangement and number of control speakers and microphones can be obtained through continuously from the frequency range of interest. Loudspeakers were used as noise source to determine the experimental maximum performance of the proposed method. The frequency range of interest was arbitrarily set from 170 to 378Hz. Accordingly, four control speakers were placed at the vertices of a regular tetrahedron at distances of 0.12m from the noise source; using the Gaussian sampling method, microphones were placed at a total of 128 points at distances of 1m from the noise source. After designing the controller in an anechoic chamber, control performance in three enclosed spaces with different acoustic characteristics was compared. Although the controller was designed in an anechoic chamber, it was found that there was little difference in control performance in the anechoic chamber and in other enclosed spaces. About 12dB noise reduction was achieved in all spaces. These experimental results show that the controller designed in free field condition can be satisfactorily used in other enclosed spaces.

Methods

Configuration method of control speakers and microphones The ANC system consists of a reference sensor, control speaker, and error microphone¹⁰. The reference sensor is used to predict noise in the control area. The control speaker is used to generate sound of opposite phase to the noise. The error microphone is used to estimate the noise in control area. The reference sensor type and configuration depend on the characteristics of the noise source; we will not cover the configuration method of the reference sensor in this paper. In local ANC targeting point control, the error microphone is placed in the control area and the control speaker is placed in a causal position. However, in spatial control like global ANC, discrete placement of the control speakers and error microphones can cause spatial aliasing. Spatial aliasing affects the controllable and measurable frequency ranges and the radiation pattern. Spatial aliasing is an important consideration when placing control speakers and error microphones.

First, we are only interested in outgoing waves. So, we set the radius of the microphone array to be larger than half of the wavelength at which effects of evanescent waves are reduced by about 95 percent¹¹.

$$\frac{\lambda}{2} < r \quad (1)$$

Here, λ is the wavelength and r is the radius of the microphone array. Arrangement and number of microphones are determined by measurable radiation patterns and a sampling method. We used a spherical harmonic function as the basis of the radiation pattern. This function has already been used in areas of 3D sound field reproduction like ambisonics¹². The spherical harmonics degree indicates the complexity of the radiation pattern. Measurable spherical harmonics degree without spatial aliasing is determined by the radius of the microphone array and the upper frequency limit¹¹.

$$kr < N \quad (2)$$

Here, k is the wave number, r is the radius of the microphone array, and N is the measurable spherical harmonics degree. Once the measurable degree is determined, the number and arrangement of microphones are determined by the sampling method. Typical sampling methods include uniform sampling, equal-angle sampling and Gaussian sampling. We decided to use the Gaussian sampling method because it allows easy setup of the experimental equipment¹¹. The Gaussian sampling method requires $2(N + 1)^2$ number of microphones. The sound field of the noise source can be measured through such a microphone arrangement; the maximum degree of the spherical harmonics of the noise source can be estimated through spherical harmonics expansion¹³.

We decided to configure the control speakers at the vertexes of a platonic solid because this makes it easy to quantify the spatial aliasing issues and to control the 3-D space equally¹⁴⁻¹⁵. The upper limit of the radius is determined by the spatial aliasing frequency¹⁶.

$$f < \frac{c}{2a} \quad (3)$$

Here, f is the controllable frequency, c is the speed of sound, and a is the radius of the speaker array. This is the same argument as used by Nelson et al⁸. Number of control speakers was decided according to the noise source's maximum degree of spherical harmonics¹⁷. There must be at least as many control speakers as spherical harmonics to be controlled.

$$(N_M + 1)^2 \leq L \quad (4)$$

Here, N_M is the noise source's maximum degree of spherical harmonics and L is the number of control speakers. We can obtain the frequency range of interest according to the spectrum of the noise source. The proposed configuration method determines the number and arrangement of control speakers and error microphones with the above considerations and for the frequency range of interest. We can decide on the lower limit of the radius of the microphone array using the lower frequency limit, with Eq. (1), and the upper limit of the radius of the control speaker array using the upper frequency limit, with Eq. (3). Measurable spherical harmonics degree is decided according to the radius of the microphone array and the upper frequency limit, with Eq. (2). When the measurable spherical harmonics degree is determined, the arrangement and number of microphones are determined by the sampling method. Using this microphone configuration, the sound field of the noise source can be measured and this can be approximated through spherical harmonics expansion as a noise source having a maximum degree of spherical harmonics. The minimum number of control speakers is determined by the maximum degree of spherical harmonics, with Eq. (4); the control speaker array can be formed by arranging the control speakers at the vertexes of a regular polyhedron. Figure 4 shows the sequence of steps.

ANC algorithm Most ANC algorithms use the adaptive filtering method updated by signals measured by the error microphone in the control area. As mentioned above, our cost function is the acoustic power. The measurement of the acoustic power is performed on the spherical surface at the far field; it requires a large number of microphones.

$$J = \sum_{m=1}^M E [|p_{n,m} + p_{c,m}|^2] \quad (5)$$

Here, M is number of microphones, $p_{n,m}$ is the sound pressure by the noise source at the m^{th} microphone, $p_{c,m}$ is the sound pressure by the control speaker at the m^{th} microphone, and $E[\cdot]$ is the expected value. Using a large number of microphones during ANC is not practical. They must be placed on the spherical surface in the far field surrounding the noise source and this can interfere with movement or with life within the space. So, we decided to use the open-loop ANC algorithm and calculated the optimal control filter with a Wiener filter solution. The Wiener filter is obtained by preliminary experiments on the free field condition.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author Contributions

Y.P designed the research and organized the manuscript. I.J carried out the calculations and collected the data. All authors analyzed the theoretical results and contributed to the manuscript writing.

Competing interests

The authors declare no competing financial interests.

Figures and Figure Captions

(a) control speaker array

(b) microphone array

Figure 1. Experimental setting for controller design in anechoic chamber. (a) Control speaker array; (b) microphone array. Four control speakers were placed near noise source at vertex of regular tetrahedron and eight microphones (red circles) were rotated to measure acoustic power at a total 128 points according to Gaussian sampling method.

(a) anechoic chamber

(b) enclosed space 1

(c) enclosed space 2

(d) enclosed space 3

Figure 2. Experimental setting for control performance comparison. (a) Anechoic chamber. **(b)** Enclosed space 1 (small size, small reverberation time). **(c)** Enclosed space 2 (small size, large reverberation time). **(d)** Enclosed space 3 (large size). Red circle is noise source and control speaker array. Blue circles are nine microphones for ANC control performance evaluation according to electronic noise measurement specifications (KS C IEC 60704-1: 2015).

Figure 3. ANC control performance comparison experiment results. (a) Anechoic chamber; **(b)** Enclosed space 1 (small size, small reverberation time). **(c)** Enclosed space 2 (small size, large reverberation time). **(d)** Enclosed space 3 (large size). Blue lines indicate noise before ANC and red lines indicate noise after ANC. Nine microphones were placed according to electronic noise measurement specifications (KS C IEC 60704-1: 2015), as in Figure 2.

Figure 4. Flow chart of configuration method of control speakers and microphones. Once the frequency range of interest was determined by the spectrum of the noise source, the placement and number of control speakers and microphones can be determined according to the lower and upper frequency limits.

Table and Table Caption

	Anechoic chamber	Enclosed space1	Enclosed space2	Enclosed space3
mic 1	11.2dB	12.1dB	11.5dB	11.0dB
mic 2	11.2dB	11.2B	11.7dB	11.9dB
mic 3	11.6dB	13.0dB	11.8dB	12.2dB
mic 4	11.6dB	10.3dB	11.5dB	11.7dB
mic 5	11.1dB	11.0dB	11.6dB	11.4dB
mic 6	9.4dB	11.0dB	11.9dB	11.1dB
mic 7	12.4dB	11.2dB	11.3dB	13.3dB
mic 8	10.0dB	11.2dB	11.2dB	11.3dB
mic 9	15.6dB	14.5dB	12.5dB	14.6dB
Maximum	15.6dB	14.5dB	12.5dB	14.6dB
Minimum	9.4dB	10.3dB	11.2dB	11.0dB
Average	11.6dB	11.8dB	11.7dB	12.3dB

Table 1. Nine microphones were placed according to electronic noise measurement specifications (KS C IEC 60704-1: 2015). Table shows noise dB reduction at each microphone in frequency range of interest and maximum, minimum, and average noise dB reduction in each space.

Figures

(a) control speaker array

(b) microphone array

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