Improvement of Noise Reduction in a Panel Combined with Multiple Loudspeakers Using Active Noise Control

Tatsuya Murao*
* Meijo University, Department of Vehicle and Mechanical Engineering
1-501 Shiogamaguchi, Tempaku-ku, Nagoya, JAPAN
E-mail: mtatsuya@meijo-u.ac.jp Tel: +81-52-832-1151

Abstract— **This research proposes a method that combines a panel and loudspeakers to reduce noise across a wide frequency range by utilizing the characteristics of both. This device was plate of made by corrugated plastic panel and nine loudspeakers put on grid of arrangement at the panel, thus the performance of noise reduction levels depend on the material by mass law and the performance of speaker arrays of noise cancellation. However, the panel of lightweight are cannot shut out of middle frequency, meanwhile the speaker array also has limit of noise reduction for higher frequency range that was depend on the distance of each loudspeaker on boundary space if the device obtains of noise reduction zone at global space behind this array. Therefore, this research investigates the performance of this type of panel combined speaker array, that the panel of noise reduction performance are improved from combine arrangement. In the experiment, the panel of device are arranged on a boundary of wall in the small chamber (like a box of 2.4m×1.2m×1.34m). Moreover, the other configurations of panel and loudspeakers array which the arrangement of panel ware put on before or after of boundary of chambers, they also were checked by the same arrangement. In the noise reduction of performance with multiple filtered-x LMS was compared before and after using noise control system with loudspeaker array.**

I. Introduction

Noise mitigation for a residential environment or office space requires flexibility of arrangement to make multiple personal spaces, thus partitions like noise barriers are adopted in a common office. In those partitions as a panel, there are difficult to obtain much noise reduction for low and middle frequency range by the mass law [1], because partitions are usually thin or light wight for space-saving at a room. On the others hands, a duct had already applied the hybrid method active and passive noise control system in a lot of research [2-4]. In contrast, active noise control systems provide effective noise reduction in the low-frequency range [5]. Although, these systems require a specific arrangement of multiple loudspeakers to achieve spatial noise reduction, there is a theoretical limitation in achieving high-frequency noise reduction due to spatial aliasing caused by the arrangement of loudspeakers [6]. Moreover, loudspeakers also have a limit of the performance to generate low frequency range, because those were depended on the size of speaker diaphragm. Therefore, this research proposes a method that combines a panel and loudspeakers to reduce noise across a wide frequency range by utilizing the characteristics of both. In this panels, it was chosen a corrugated plastic panel as like a commonly used materials, because it was lightweight and a certain level of performance to insulate noise of high frequency ranges. Meanwhile, the array of loudspeakers embedded in the panel provides noise reduction for the mid and low-frequency ranges. In this experiment, nine loudspeakers are arranged in a grid on a panel, and the system is controlled using a modified multi-channel filtered-x LMS algorithm, which selects error signals based on that only short-distance error paths between the loudspeakers and microphones [7-8]. Therefore, the method reduces the computational load of multi-channel systems, which typically have high computational demands on the controller, but there is some degradation in noise reduction. Tianyou Li et al. have proposed BDFxLMS-BC [9], which overcomes the risk of instability in distributed methods and eliminates the estimation bias of distributed algorithms based on diffusion adaptation. Therefore, this research suggests that by using a nearby error microphone corresponding to an appropriate control sound source, it may be possible to achieve control while maintaining performance nearly equivalent to that of centralized control. In this examination, three type of arrangements that panel and speaker array unit were investigated and compare performances of noise reduction level with a small chamber (2.4m×1.2m×1.34m), which was divided two spaces on the space by partition with open 0.4m square. Thus, these devices are compared with each noise reduction levels. One of the arrangements is that loudspeaker array was embedded in a corrugated plastic panel, and other type of arrangements wares that speaker array was installed on the boundary of opening of partition at the center of chamber and panels put in front of the speaker array (as side of upstream by noise source) or behind of them (as like side of downstream). Consequently, each arrangement was affected the acoustic field of around near of the panel, however the panel of the device were more drastically decided the noise reduction of an active noise control devices.

II. ARRANGEMENT OF EXPERIMENTATION

Figure 1 shows a chamber to investigate performance of noise reductions by proposed devices. This chamber was 1.2 m ×2.4 m×1.53 m with Medium-density fiberboard (: MDF board) that is 21 mm thickness. In this chamber, a partition board with opening 0.4 m square set on center of inside. Moreover, the interior of the chamber was lined with sound-absorbing materials with the following specifications: polyester porous material with a density of 30 kg/m³.

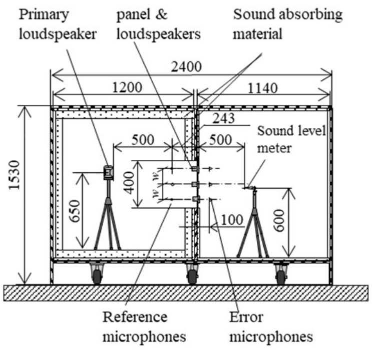

Fig. 1 An experimental arrangement in a chamber that separates two spaces through an opening equipped with a panel, speaker array, primary source, and microphones

One of the chamber compartments, which contains the primary loudspeaker (as shown in Fig. 1), was additionally lined with extra sound-absorbing material (10 mm thick with a density of 100 kg/m³) to insulate noise from another compartment of the chamber. Furthermore, nine reference microphones were placed in front of the opening (on the upstream side) to obtain reference signals, and nine error microphones were positioned behind the opening (on the downstream side) to capture error signals for the active noise control system. In another side of chamber, a sound level meter was placed behind the opening (on the downstream side) also. In this experimentation, a device that is combined a corrugated plastic and nine speakers set and control noise by loudspeakers' array.

III. PANEL AND SPEAKER ARRAYS

In this research, we evaluated the performance of a system in two configurations: (A) a device with the panel and speaker embedded into a single unit, and (B) a setup in which the panel and speaker were installed separately. The device in which nine loudspeakers (TBspeaker T1-1942SB) are embedded in a corrugated plastic panel with the following specifications: the panel measures 0.5 m square, weighs 120 g, and has a thickness of 4 mm as a corrugated board. The thickness of the plastic material is 0.04 mm, and the flute (span) is 4 mm. the two types of devices target to reduce noise that a corrugated plastic panel insulate higher frequency and middle frequency range, speaker array cancellate middle and low frequency range. On the other hands, an arrangement of the loudspeakers array for opening window that had showed performance as noise reduction with decentralized multi-channel Filtered-x LMS [8], therefore this experimentation also make a grid arrangement of loudspeakers at opening as an evaluation standard for noise reduction.

Figure 2 shows an arrangement to reduce noise for opening with nine loudspeakers array that are controlled by decentralized multi-channel Filtered-x LMS.

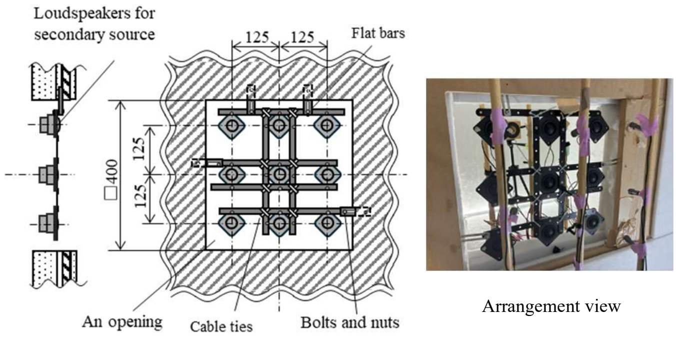

Fig.2 An arrangement of the device that nine speakers on the grid pattern were installed at opening. Loudspeakers are fixed on wall of partition board by flat bars, bolts, nuts, and cable ties.

Figure 3 shows that type A arrangement of panel and speakers. The type of device target to reduce noise that a corrugated plastic panel insulate higher frequency and middle frequency range, speaker array cancellate middle and low frequency range. In this case plastic panel are perforated 9 holes to embed 9 loudspeakers with bolts and nuts, moreover the unit of panel with loudspeakers are installed at opening with duct tape as figure 3.

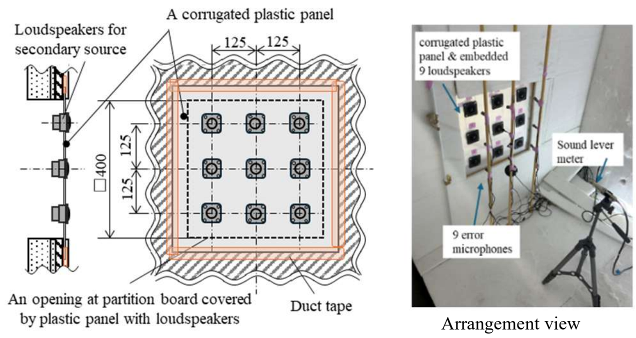

Fig.3 An arrangement of the device that nine speakers on the grid pattern were embedded on corrugated plastic panel.

Figure 4 shows another arrangement that the speaker array is individually set on the opening of the partition, and a corrugated plastic panel installed with duct tape on the side of downstream, when it is the same arrangement as shown in figure 2. In the arrangement of figure 4, the corrugated plastic panel is covered the opening at downstream side, meanwhile loudspeakers also are covered by this panel that the acoustic field including a panel coefficient directly, On the other hands, this corrugated plastic panel is a lightweight material thus it has not obtained noise reduction for low and middle frequency noise. Therefore, loudspeakers should be able to control middle and low frequency noise that was transmitted light wight materials panel. Table 1 shows three type of arrangement conditions.

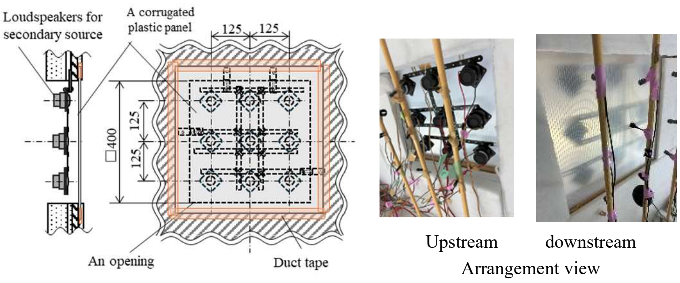

Fig. 4 An arrangement of the device that nine speakers on the grid pattern were installed at opening, and a corrugated plastic panel are covered at downstream of the opening of partition.

Tab.1 Device configurations of panels and loudspeakers

Condition name	Material of panel	Speakers' arrangement
Previous	N/A (open)	In opening
Type A	corrugated plastic	Embedded on panel
Type B	corrugated plastic	In front of panel

IV. THEORY OF NOISE REDUCTION BY SPEAKER ARRAY

It is prevalent that a speaker array to obtain noise reduction area in spatially (like as the waveform synthesis) by Huygens–Fresnel principle. In previous research, Bhan Lam, et.al. [4] investigated the physical limits on the performance of active noise control of open window, thus the relationship noises the limit of lower wavelength λ (m) (or upper frequency range) between the length of speaker span w (m) was that $w/\lambda < 0.5$.

In this our research, the length of each loudspeaker span was 125 mm. In this condition, the limitation of upper frequency become 1360 Hz for noise reduction spatially for normal and oblique incident sounds. Figure 5 illustratively shows the noise reduction zone created by the loudspeaker arrays for an obliquely incident plane wave. However, it is briefly expected that the noise reduction zone will narrow, as the phases of the primary and secondary sources increasingly misalign at greater distances between the two positions (as shown in Fig. 5).

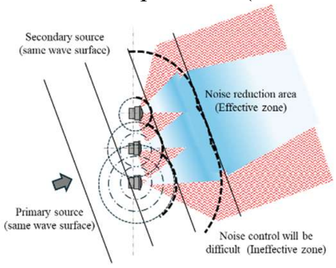

Fig.5 An example of noise reduction area by loudspeaker array illustratively, a wave surface of primary source can be synthesis by secondary source wave.

V. FILTERED-X LMS WITH 9 (1-1-N') CHANNEL SYSTEM

In this study, nine loudspeakers were controlled using a multi-input, multi-output (MIMO) filtered-x LMS algorithm [1]. However, an implementation of the full multi-channel filtered-x LMS algorithm imposed an excessive computational burden under the given system configuration. As a result, a high sampling frequency was required, since the distance between each reference microphone and its corresponding secondary loudspeaker needed to be minimized in order to satisfy the spatial conditions implied by the Huygens–Fresnel principle. Under this configuration, the system is capable of achieving a broad noise reduction zone for obliquely incident noise [5,6]. Accordingly, a sampling frequency of 16 kHz was adopted, which was deemed sufficient without being computationally prohibitive. The modified filtered-x LMS algorithm updates each adaptive filter using error microphone signals selected based on their short distance from the corresponding loudspeaker. There were installed 24 loudspeakers in a commonly window and investigated the decentralized multichannel filtered-x LMS algorithm by error signals by near field error microphones[8]. In this experimentation, an algorithm that is also chosen the near field microphones to update each loudspeaker is driven by only one adaptive finite impulse response (FIR) filter $w_{i=j}$ a and a single reference signal, as shown in Equation (1).

$$w_i(n+1) = w_i(n) - \mu \sum_{k=N}^{N'} c_{jk}(l) * x_i(n-l+1)\, e_k(n)$$

i: Number of reference signals, j: Number of secondary loudspeakers, k: Number of error signals, l: Number of FIR filter coefficients, N: Number of selections of error paths,
μ: Step size parameter, x: Reference signal, e: Error signal, $c_{jk}(l)$: FIR filter of secondary path. In this method, w_i will be updated by selective error paths which only near position from No.i secondary loudspeaker. In this case, we named loudspeaker numbers from 1 to 9 according to the order of the matrix arrangement as [1 2 3; 4 5 6; 7 8 9]. All of error paths were identified by LMS algorithm before controlling with filtered-x LMS. Table 2 shows the combinations that each adaptive FIR filter of w_{ij} $(i=j)$ was updated which secondary paths (from No.j loudspeaker to No. k error microphones) were chosen for Equation 1.

Tab.2 Combinations adaptive filter w_{ij} and selected secondary paths $c_{jk}(l)$ for updating Filtered-x-LMS in a grid arrangement of nine loudspeakers

Adaptive filter w_{ij} $(i=j)$ and secondary path $c_{jk}(l)$ to update equations for Filtered-x LMS algorithm from Equation (1)		
w_{11}: c_{1k} $k=1,2,4$	w_{22}: $c_{2k}, k=1,2,3,5$	w_{33}: $c_{3k}, k=2,3,6$
w_{44}: $c_{4k}, k=1,4,5,7$	w_{55}: $c_{5k}, k=2,4,5,6,7$	w_{66}: $c_{6k}, k=3,5,6,9$
w_{77}: c_{7k}, $k=4,7,8$	w_{88}: $c_{8k}, k=5,7,8,9$	w_{99}: c_{9k}, $k=6,8,9$

VI. RESULT OF EXPERIMENTATIONS

In this experimentation, a noise source was bandlimited random noise form 300 Hz to 1 kHz, because the size of loudspeakers was small to generate much intensity for low frequency. Thus, the upper frequency of this noise ware chose by a limitation of this arrange as 1307 Hz to obtain the enough effect using this system. Figure 6 to 14 shows the relative sound pressure level at error microphone No.1 to 9 as controlled points. Table 3 shows details of the conditions, which legend is which arrangement that opening (as shown Fig.2), Type A (as shown Fig.3) and Type B (as shown Fig.4).

Every figure shows relative sound pressure level (dB) of every type of condition at once. Solid lines show the condition that primary noise only, dashed lines show the condition that 9 loudspeakers are deriving for noise control (as shows "with ANC"), and chain gray lines shows the background noise. The other condition of arrangements ware named Type A and Type B, the former indicate the arrangement figure 3 and the latter indicate the arrangement figure 4.

Tab.3 Conditions of control system of active noise control and arrangements between corresponding each graph of legends

Conditions Source /Arrangement	Opening (Fig.2)	Type A (Fig.3)	Type B (Fig.4)
Primary noise only	— Red	— Orange	— Black
Under control (ANC)	--- Bule	--- Violet	--- Green
Background noise	- · - Gray		

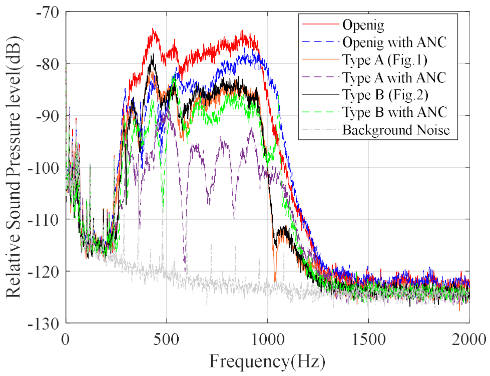

Fig.6 Relative sound pressure level at position No. 1 under every condition (as shown table 3)

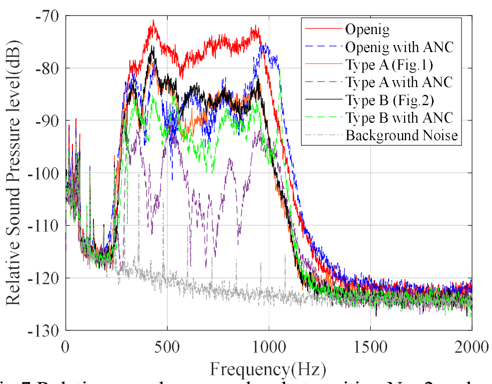

Fig.7 Relative sound pressure level at position No. 2 under every condition (as shown table 3)

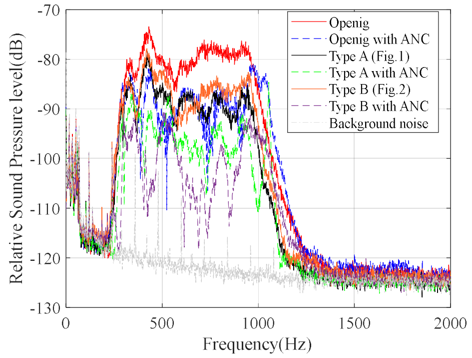

Fig.8 Relative sound pressure level at position No. 3 under every condition (as shown table 3)

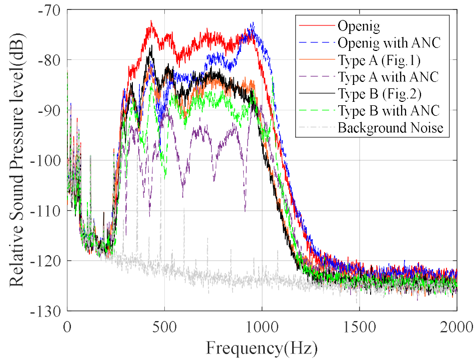

Fig.9 Relative sound pressure level at position No. 4 under every condition (as shown table 3)

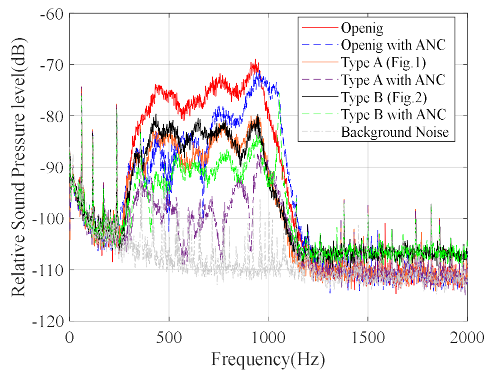

Fig.10 Relative sound pressure level at position No. 5 under every condition (as shown table 3)

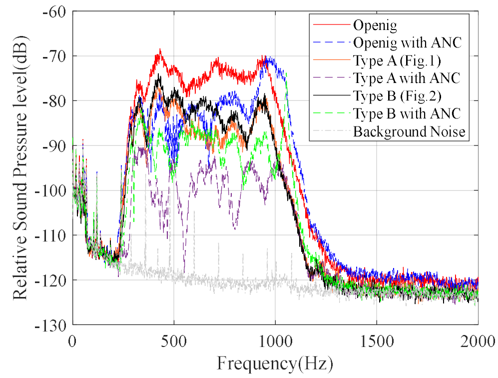

Fig.11 Relative sound pressure level at position No. 6 under every condition (as shown table 3)

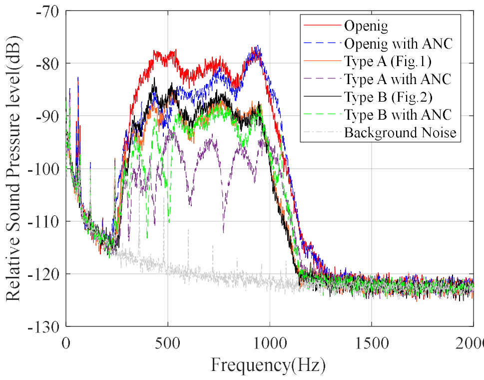

Fig.12 Relative sound pressure level at position No. 7 under every condition (as shown table 3)

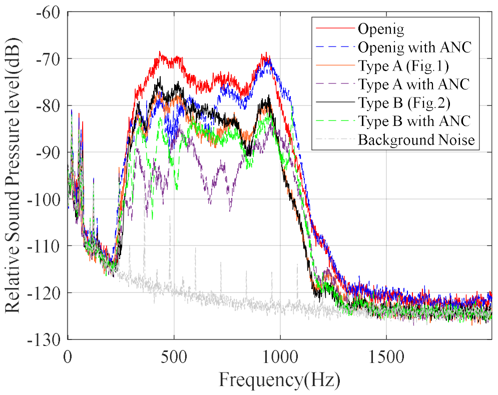

Fig.13 Relative sound pressure level at position No. 8 under every condition (as shown table 3)

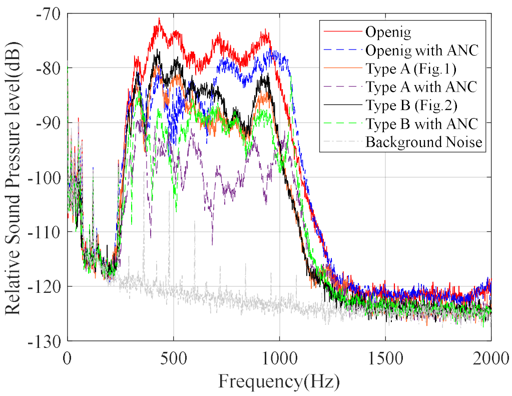

Fig.14 Relative sound pressure level at position No. 9 under every condition (as shown table 3)

Additionally, Figure 15 shows the sound pressure levels at the sound level meter positions, as indicated in Fig. 1. This measurement point was set using a sound level meter to confirm whether the devices were effectively controlling the zone behind the error microphones

The results under the condition where the speaker array was individually placed on the opening (as shown figure 2, and red solid line and bule dashed line in Fig. 6 to 14) obtained that all error microphones achieved noise reduction of approximately 5–15 dB in the frequency range from 300 Hz to 1 (kHz) in some cases.

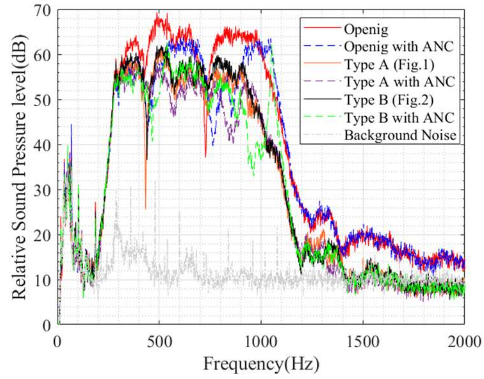

Fig.15 Sound pressure level at sound level meter under the every condition (as shown table 3)

However, A decline in noise reduction performance is observed as the frequency approaches 1 kHz.

The results the condition where the loudspeakers were embedded in the panel (as shown Figure 3, orange solid line and violet dashed line, indicated Type A) confirmed that all error microphones achieved noise reduction greater than 20 dB in the frequency range from 300 Hz to 1 kHz. In this arrangement (Type A) are obtained noise reduction by corrugated plastic panel around 1kHz frequency range.

However, at the sound level meter position, the amount of noise reduction was noticeably lower than that observed at the error microphones, although some frequency ranges still exhibited a measurable reduction.

The results under the condition where the speaker array was individually placed on the opening of the partition and a corrugated plastic panel covered the opening on the downstream side confirmed that all error microphones achieved noise reduction under 5~8 dB in the frequency range below 500 Hz in some cases. However, at the sound level meter position, the amount of noise reduction was noticeably lower than that observed at the error microphones.

VII. Conclusions

In this study, panel arrangements for noise reduction using loudspeaker arrays were proposed and investigated in terms of the resulting noise reduction levels when the device was placed at an opening in a partition. Three types of arrangement were confirmed the noise reduction level. A modified multi-channel filtered-x LMS control algorithm was used, in which only selected error paths were employed to update the adaptive filters in order to reduce the computational load on the controller.

The paths chosen were short distances from loudspeakers to error microphones only, to reduce the computational calculations conveniently and its corresponding error microphone. In one arrangement, nine loudspeakers were embedded in a corrugated plastic panel. In another arrangement, the loudspeaker array was positioned separately from a corrugated plastic panel. Consequently, the arrangement in which the loudspeakers were embedded in a corrugated plastic panel achieved a noise reduction of up to 20 dB over a wide frequency range from 300 Hz to 1 kHz. These results show an improvement in noise reduction performance compared to the previous type of device, such as the open-window active noise control system, particularly in the mid-frequency range between 500 Hz and 1 kHz by corrugated plastic panel as general passive noise control.

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