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RESEARCH ARTICLE

Head-Mounted Multi-Channel Feedforward Active Noise Control System for Reducing Noise Arriving From Various Directions

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ABSTRACT A head-mounted active noise control (ANC) system based on the single-channel ($1 \times 1 \times 1$) feedforward control has been studied as a noise reduction method in complicated noise environments such as factories in which various machines are located that generate unwanted noises. However, it is difficult to reduce the noise arriving from various directions because the causality constraint cannot be satisfied. To solve this problem, we developed a head-mounted ANC system based on the multi-channel ($2 \times 1 \times 1$) feedforward control. This ANC system has two reference microphones that satisfy the causality constraint. Therefore, the proposed head-mounted ANC system achieves the expansion of noise reducible range of $0 - 100^\circ$ compared to that of the conventional head-mounted ANC with the range of $0 - 60^\circ$. In this paper, we examine the effectiveness of the newly developed head-mounted ANC system. In the experiments, we evaluate the effectiveness of placing two reference microphones on noise reduction performance in the case of various arrival direction of the unwanted noise. Experimental results demonstrate that the proposed system increases the noise reducible range and improves the noise reduction performance for two noise sources. In addition, we theoretically prove the effectiveness of the proposed system.

INDEX TERMS Multi-channel ANC system, feedforward control, FPGA, causality constraint, head-mounted ANC system.

I. INTRODUCTION

Acoustic noise problems are becoming more serious with the increasing use of industrial equipment. In particular, workers in factories may suffer from noise-induced hearing loss because they are exposed to the noise generated by manufacturing equipment for prolonged duration. Active noise control (ANC) [1], [2], [3], [4] has been studied as a means of solving such acoustic noise problems. ANC reduces noise on the basis of the superposition principle, i.e., an anti-noise with the same amplitude and opposite phase is generated and combined with an unwanted noise.

An ANC system can be realized as a feedforward or feedback system. A feedforward ANC system has the potential to reduce unwanted acoustic noise such as broadband noise by detecting the noise at a reference microphone [2], [5], [6]. On the other hand, a feedback ANC system is only effective for narrowband noise because it internally estimates noise [7], [8], [9]. In this paper, we focus on a feedforward ANC system because factory noise has broadband components.

The headrest ANC system [10] can be used to reduce factory noise. Conventionally, the error microphones are placed in the headrest position of the headrest ANC system, which struggles the degradation of the noise reduction performance at the user's ears. This is because the zone of quietness is created near the error microphone [11]. Hence, the headrest ANC system [10] has utilized remote microphone to reduce

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the unwanted noise at the user's ears. However, this system needs to identify the transfer function of the remote microphone when the user's head moves. In [12], the head tracking system has been adopted to the headrest ANC system to solve the degradation of the noise reduction performance of the ANC system caused by head movement.

Another way to reducing factory noise is to utilize a head-mounted ANC system [13], [14]. This system is more compact than a general feedforward ANC system and does not interfere with the worker's tasks. In addition, the error microphone and secondary loudspeaker are mounted close to the user's ears and the head tracking system is not required. The realization of a compact feedforward ANC system requires the distance between the reference and error microphones to be shortened and for the causality constraint [15], [16] to be satisfied simultaneously. Before a noise arrives at the error microphone, it is necessary for the reference microphone to collect noise and for the anti-noise to have been emitted from the secondary source. This is called the causality constraint. The causality constraint can be satisfied by an ANC system using an oversampling technique, which can reduce the delay in the production of anti-noise; this process includes anti-aliasing filters, smoothing filters, amplifiers, an analogue-to-digital converter (ADC), a digital-to-analogue converter (DAC), transducers, and digital signal processing. However, ordinary digital signal processor (DSP) systems may not be able to satisfy the causality constraint because of the limitation of the computation time. Hence, a field-programmable gate array (FPGA) has been used to realize a feedforward ANC system with an oversampling technique [17], [18]. The FPGA can perform computations faster than a DSP owing to parallel processing and a high sampling rate. By using the FPGA and an oversampling technique, a head-mounted feedforward ANC system can be designed.

A head-mounted ANC system based on feedforward control has been studied for a single-channel ($1 \times 1 \times 1$) system, which has one reference microphone, one error microphone, and one secondary sound source [19], [20]. However, it is difficult to reduce the noise arriving from various directions because the causality constraint cannot be satisfied. This feedforward ANC system can reduce noise only when the reference microphone detects the noise signal before the noise reaches the point where it is reduced. We believe that noise reduction in all directions can be realized by increasing the number of reference microphones. We therefore construct a head-mounted ANC system based on $2 \times 1 \times 1$ feedforward control, which has two reference microphones, and examine the noise reduction performance for two noise sources placed at different positions surround a user. To evaluate the effectiveness of this system, we conducted two experiments. In the experiments, we evaluate the effectiveness of placing two reference microphones on noise reduction performance in the case of various arrival direction of the unwanted noise. First, we evaluated the noise reducible range in the case of one noise source. Second, the noise reduction performance in the case of two noise sources was compared with that for a head-mounted single-channel ($1 \times 1 \times 1$) ANC system. Finally, the optimal filter conditions are derived, and the effectiveness of the proposed system is also theoretically investigated.

This paper is organized as follows. In Sect. II, the feedforward ANC system and its causality constraint are explained. In addition, we explain how to implement the head-mounted single-channel ($1 \times 1 \times 1$) ANC system and the head-mounted $2 \times 1 \times 1$ multi-channel ANC system. Then, experimental results are given in Sect. III and a conclusion is given in Sect. IV

II. HEAD-MOUNTED FEEDFORWARD ANC SYSTEM

A. FEEDFORWARD ANC SYSTEM AND ITS CAUSALITY CONSTRAINT

A feedforward ANC system consists of a reference microphone, an error microphone, and a secondary loudspeaker. To update the noise control filter in the feedforward ANC system, the filtered-x normalized least mean square (FXNLMS) algorithm [4] is most commonly used. A block diagram of the feedforward ANC system with the FXNLMS algorithm is illustrated in Fig. 1. In Fig. 1, R is a reference path between the noise source and the reference microphone, S is a secondary path between the secondary source and the error microphone, and P is a primary path between the noise source and the error microphone. In the FXNLMS algorithm, the secondary path model $\hat{S}$ is identified in advance and used to operate the ANC system. The updating algorithm of the noise control filter W is expressed as

$$w(n+1) = w(n) + \frac{\alpha}{\|x'(n)\|^2} x'(n)e(n), \tag{1}$$

where $w(n)$ is a filter coefficient vector of the noise control filter, α is a step-size parameter, $x'(n)$ is a filtered reference vector, and $e(n)$ is an error signal obtained at the error microphone.

The total delay of the reference path R, the noise controller, and the secondary path S should be shorter than the delay of the primary path P. In other words, before the noise arrives at the error microphone, it is necessary for the reference microphone to collect the reference noise and for the anti-noise to have been from the secondary source. This is called the causality constraint, and if the causality constraint is violated, the causality constraint is violated, and the ANC performance remarkably deteriorates. The causality constraint requires to satisfy the following inequality:

$$D_P > D_R + D_C + D_S, \tag{2}$$

where D_P is the delay of the primary path, D_R is the delay of the reference path, D_C is the delay of the computation performed to generate the anti-noise, and D_S is the delay of the secondary path.

B. ANC SYSTEM USING OVERSAMPLING TECHNIQUE

To realize a compact feedforward ANC system, it is necessary to shorten the distance between the reference and error

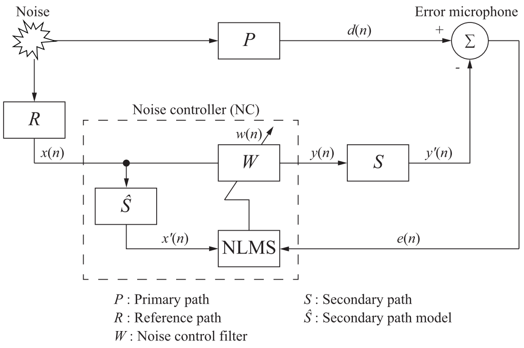


FIGURE 1. Block diagram of a single-channel (1 × 1 × 1) ANC system.

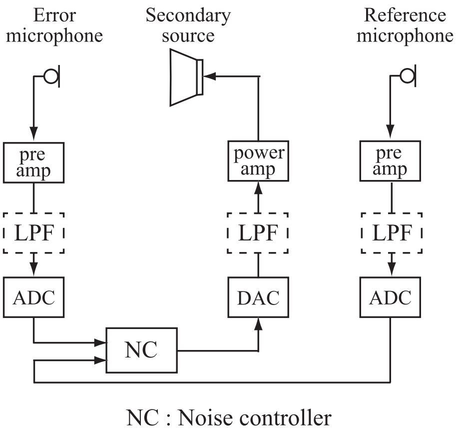


FIGURE 2. Block diagram of ANC system using oversampling technique.

microphones. However, since the ordinary feedforward ANC system has a large processing delay, the distance between the reference microphone and the error microphone should be sufficiently long to satisfy the causality constraint. To reduce the processing delay, an ANC system using an oversampling technique has been proposed [17], [18]. A block diagram of the ANC system using the oversampling technique is shown in Fig. 2. The block NC in Fig. 2 represents the noise controller, as shown by the dashed line in Fig. 1. An ordinary ANC system has a processing delay because anti-aliasing filters and a smoothing filter are employed as analogue low-pass filters (LPFs). On the other hand, since the ANC system using the oversampling technique can remove the need for anti-aliasing filters and a smoothing filter by increasing the sampling frequency, it can reduce the processing delay in the hardware. Therefore, the ANC system with the oversampling technique can shorten the distance between the reference and error microphones. However, ordinary hardware such as a DSP may not have sufficient processing speed. It is therefore necessary to use a specialized FPGA for this system.

C. IMPLEMENTATION OF FPGA

An FPGA is a flexible device that can freely change internal logic circuits. It consists of an array of programmable logic blocks and a hierarchy of reconfigurable interconnects that allow the blocks to be "wired together" in the same way that many logic gates can be interwired in different configurations. The interwired information is stored in the internal static random access memory (SRAM) and the FPGA can configure any logic circuit by changing the contents of the SRAM. Furthermore, some FPGAs can operate with higher sampling frequency than ordinary DSPs. Hence, we can shorten the distance between the reference and error microphones using the FPGA so that a head-mounted ANC system with a feedforward structure can be realized as shown in Fig. 3.

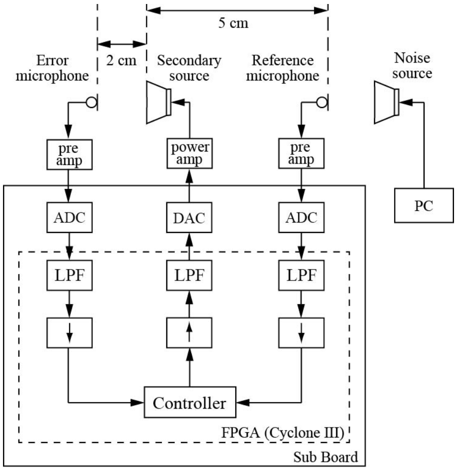


FIGURE 3. Brief diagram of implementation of head-mounted 1 × 1 × 1 multi-channel feedforward ANC system on FPGA.

D. HEAD-MOUNTED SINGLE-CHANNEL (1 × 1 × 1) ANC SYSTEM

It has been demonstrated that an ANC system with the oversampling technique implemented in the FPGA can reduce the distance between the reference and error microphone to 5 cm [19]. Therefore, it is possible to construct a head-mounted ANC system as shown in Figs. 4, 5, and 6. This head-mounted ANC system utilizes the personal field loudspeaker (PFR-V1, SONY). As shown in Fig. 5, the reference microphone is placed at the side of the loudspeaker. As shown in Fig. 6, the error microphone is placed at the frame in ear canal. Since this system does not cover the user's ears, the user does not feel a sense of restriction, and conversation is not disturbed. Also, the head-mounted ANC system does not have a passive effect of the ear cup since it does not have ear cups. Furthermore, since the left and right channels are separated by the head of the user, crosstalk between the two channels is sufficiently small and both channels can be independently realized with comparatively low computational complexity. However, the head-mounted single-channel (1 × 1 × 1) ANC system shown in Figs. 4, 5, and 6 cannot reduce the noise arriving from various directions because some directions cannot satisfy the causality constraint. It is considered that noise reduction in all directions can be realized by increasing the number of reference microphones.

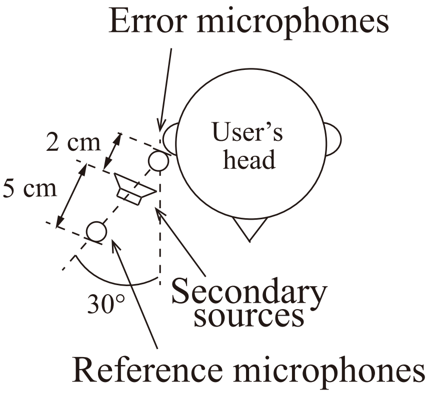


FIGURE 4. Head-mounted single-channel (1 × 1 × 1) ANC system.

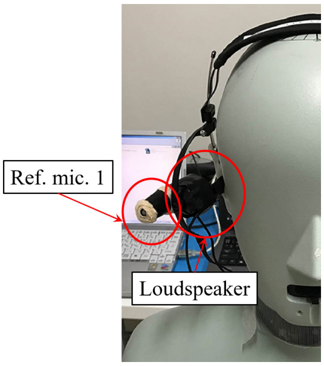


FIGURE 5. Setup of head-mounted single-channel (1 × 1 × 1) ANC system.

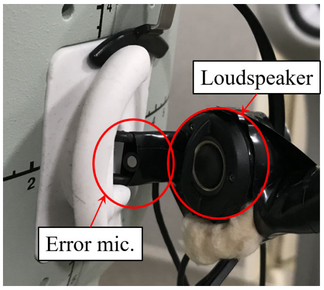


FIGURE 6. Setup of error microphone and secondary loudspeaker on head-mounted single-channel (1 × 1 × 1) ANC system.

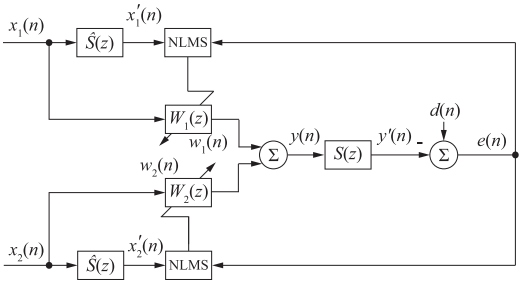


FIGURE 7. Block diagram of the 2 × 1 × 1 multi-channel ANC system.

E. HEAD-MOUNTED 2 × 1 × 1 MULTI-CHANNEL ANC SYSTEM

We have proposed a head-mounted 2 × 1 × 1 multi-channel ANC system to improve the noise reduction performance for various directions of arrival. This system is a multi-channel ANC system using two reference microphones, one secondary source, and one error microphone. Figure 7 shows a block diagram of the 2 × 1 × 1 multi-channel ANC system. The error microphone is placed at the same position of headmounted 1 × 1 × 1 ANC system shown in Figs. 4 and 6. Hence, the headmounted 1 × 1 × 1 ANC system is different from the headmouted 1 × 1 × 1 ANC system in terms of additional reference microphone. In this system, signals acquired by two reference microphones are passed through the corresponding control filters, and their outputs are added together. Then, the combined signal is generated from the secondary source. The noise control filters $w_1(n)$ and $w_2(n)$ are updated using the shift NLMS algorithm [21], whose update equations are expressed as

$$w_1(n+1) = w_1(n) + \frac{\alpha x_1'(n)e(n)}{N(\|x_1'(n)\|^2 + \|x_2'(n)\|^2)}, \tag{3}$$

$$w_2(n+1) = w_2(n) + \frac{\alpha x_2'(n)e(n)}{N(\|x_1'(n)\|^2 + \|x_2'(n)\|^2)}, \tag{4}$$

$$N(q) = \begin{cases} 2^i & (2^{i-1} < q \le 2^i) \\ 2^0 & (q \le 2^0) \end{cases} \tag{5}$$

where $x_1'(n)$ and $x_2'(n)$ are filtered reference signal vectors. $N(q)$ approximates q to a power of 2. By setting the normalization term to $N(q)$, the division can be represented by an i bit shift operation and it is easy to implement the NLMS algorithm in an FPGA.

The implemented model of the head-mounted 2 × 1 × 1 multi-channel feedforward ANC system is shown in Figs. 8 and 9. In this system, reference microphone 2 is placed to the rear and right of reference microphone 1 in the direction of 90° from reference microphone 1. This is because the noise reducible range of the head-mounted single-channel (1 × 1 × 1) ANC system is from 0° to 60° [19]. As a result, the noise reducible range of the proposed ANC system can be expanded.

III. EXPERIMENTAL RESULTS

To evaluate the effectiveness of the proposed head-mounted ANC system, we conducted two experiments. In the following experiments, we evaluate the effectiveness of placing two reference microphones on noise reduction performance in the case of various arrival direction of the unwanted noise. First, we evaluated the noise reducible range in the case of one noise source. Second, the noise reduction performance in the case of two noise sources was compared with the head-mounted single-channel (1 × 1 × 1) ANC system. Hereafter, the head-mounted single-channel (1 × 1 × 1) ANC system and 2 × 1 × 1 multi-channel ANC system are referred to as the conventional system and the proposed system, respectively. The common experimental conditions are shown in Table 1. The white noise is band-limited along the reproducible frequency

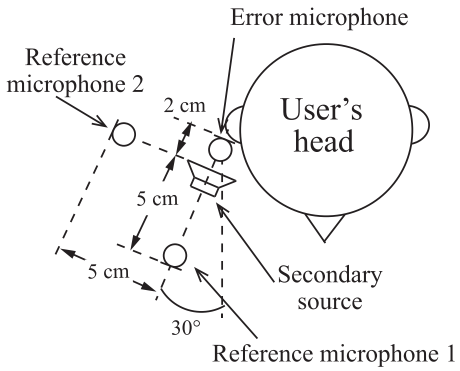


FIGURE 8. **Implemented model of head-mounted 2 × 1 × 1 multi-channel feedforward ANC system.**

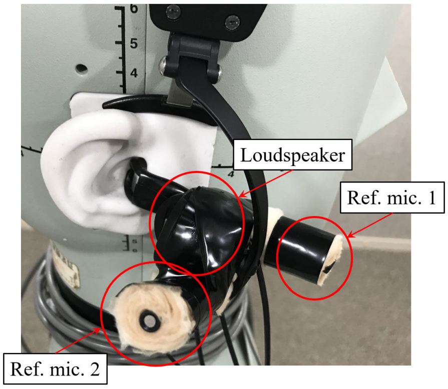


FIGURE 9. **Setup of head-mounted 2 × 1 × 1 multi-channel feedforward ANC system.**

TABLE 1. **Common experimental conditions.**

Noise source	White noise (600 – 10000 Hz)
Sampling frequency	100 kHz
Tap length of noise control filter	4000
Tap length of secondary path model	4000
Step size parameter of NLMS α	0.0005

of the secondary source. We conducted experiments in a soundproof room (width: 3.1 m, depth: 2.9 m, height: 2.1 m), and the average sound pressure level of unwanted noise was about 80 dB at the error microphone. We mounted a head-mounted ANC system on a head and torso simulator (HATS). We utilized an FPGA produced by Altera, that has a high sampling rate (1 MHz) and performs parallel processing. The implementation of the proposed head-mounted $2 \times 1 \times 1$ multi-channel ANC system is shown in Fig. 10.

A. EXPERIMENT 1: NOISE REDUCIBLE RANGE IN THE CASE OF ONE NOISE SOURCE

First, we evaluated the noise reducible range of the proposed system in the case of one noise source. The experimental arrangement is shown in Fig. 11. The noise source was placed at positions of −20° to 120°. The error spectra at the error microphone position for each noise direction are shown in Fig. 12. It can be seen from Fig. 12 that when the noise source positions are 0° and 60°, the noise reduction performances of both systems are almost the same. On the other hand, when the noise source positions are 80° and above, the proposed system can reduce the target noise, whereas the conventional ANC system cannot reduce the noise. This is because the proposed ANC system has two reference microphones and expands the range in which the causality constraint is satisfied. Therefore, the noise reducible range can be expanded by the proposed ANC system.

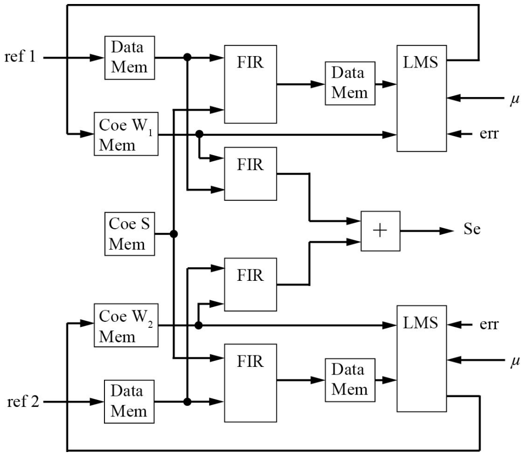


FIGURE 10. **Implementation of head-mounted 2 × 1 × 1 multi-channel feedforward ANC system on FPGA.**

To examine the reason for the above results, the difference in the arrival distance from the noise source to each microphone is shown in Table 2. From Fig. 12 and Table 2, it can be seen that noise reduction is possible when the difference in the arrival distance is over 5 cm. The angular range satisfying this condition depends on the arrangement of the microphones used in the system. In the conventional system, it is from 0° to 60°. On the other hand, the proposed system can expand the range from 0° to 100° by using reference microphones 1 and 2. Hence, the head-mounted $2 \times 1 \times 1$ multi-channel ANC system has a wider the noise reducible range than the head-mounted single-channel ($1 \times 1 \times 1$) ANC system. However, the amounts of noise reduction for both the $1 \times 1 \times 1$ and $2 \times 1 \times 1$ ANC systems decrease on noise arriving direction of 120°. This is because the reference microphone 1 cannot satisfy the causality constraint and the noise reduction performance degrades. This result depicts that the noise reduction performance on the noise arrival direction over 120 ° may be improved by placing the additional reference microphone on the opposite side of the reference microphone 1. Also, the causality constraint is not satisfied for both reference microphones in the case of arrival direction of the unwanted noise over 120° in this experiment. Therefore, the ability of noise reduction may degrade in both the conventional and proposed ANC systems. Here, as shown in Fig. 12 (d), the amplitude after applying ANC system is greater than that before applying ANC system around 3−4 kHz. This is because the frequency components of the unwanted noise

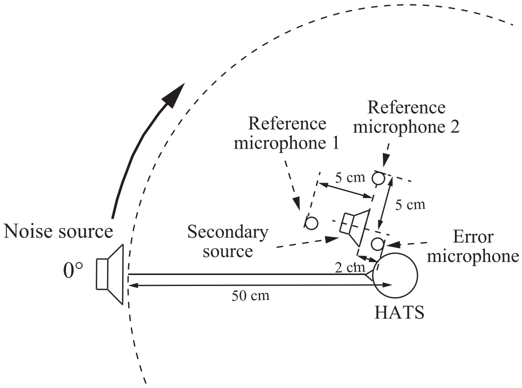


FIGURE 11. Experimental arrangement in the case of one noise source.

TABLE 2. Difference in the arrival distance from noise source to each microphone.

Noise angle [°]	−20	0	20	40	60	80	100	120
Err-Ref1 [cm]	3.37	5.25	6.59	7.02	6.27	4.31	1.61	−1.22
Err-Ref2 [cm]	−3.37	−1.88	−0.08	1.87	3.69	4.97	5.35	4.72

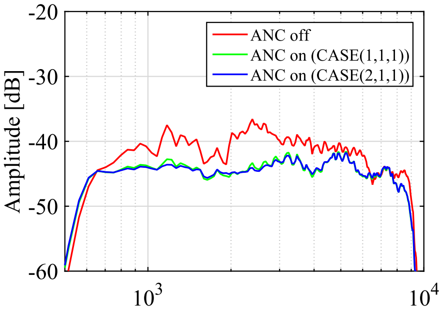
at 3-4 kHz might be very small at the error microphone position. Then, the noise control filter updates to forcibly reduce the small unwanted noise, and the antinoise becomes new disturbance and the noise level increases.

B. EXPERIMENT 2: NOISE REDUCTION PERFORMANCE IN THE CASE OF TWO NOISE SOURCES

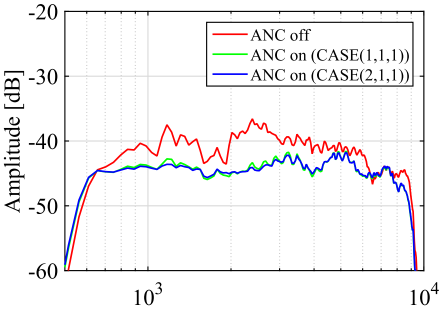
Next, the noise reduction performance of the proposed system in the case of two noise sources is compared with that of the conventional system. The experimental arrangement is shown in Fig. 13. The white noises used as target noises are independently generated. The error spectra at the error microphone position are shown in Fig. 14. It can be seen from Fig. 14 that the noise reduction performances of the proposed and conventional systems are similar when the noise sources are located at 0° and 40°. On the other hand, the proposed system can reduce the target noises when the noise sources are located at positions where the noise reduction performance of the conventional system deteriorates. When the noise source position is 20° and 60°, the noise reduction performance of the conventional system deteriorates despite both noises being within the noise reducible range clarified in the previous section. To investigate the cause of this deterioration, we derive the optimal filters for the conventional and proposed systems.

C. OPTIMAL FILTERS FOR SINGLE-CHANNEL ($1 \times 1 \times 1$) AND $2 \times 1 \times 1$ MULTI-CHANNEL ANC SYSTEMS IN THE CASE OF TWO NOISE SOURCES

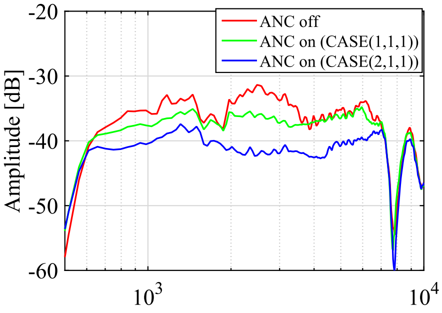
Next, we derive optimal filters for the single-channel ($1 \times 1 \times 1$) and $2 \times 1 \times 1$ multi-channel ANC systems in the case of two noise sources. Figure 15 shows a block diagram of the single-channel ($1 \times 1 \times 1$) ANC system including reference paths from the two noise sources to the reference microphone. In Fig. 15, $P_1(z)$ and $P_2(z)$ are the responses of the primary paths from the two noise sources to the error microphone, $R_{11}(z)$ and $R_{21}(z)$ are the responses of the reference paths from the respective noise sources to the reference microphone, and $S(z)$ is the response of the secondary path from the secondary source to the error microphone. The



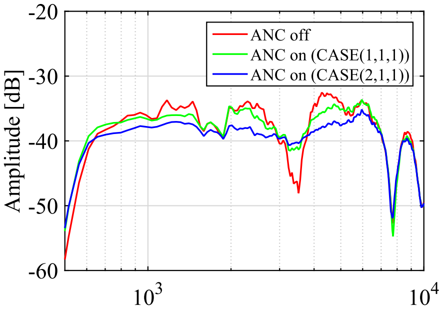
(a) Noise source at 0°



(b) Noise source at 60°



(c) Noise source at 80°



(d) Noise source at 120°

FIGURE 12. Error spectra in the case of one noise source.

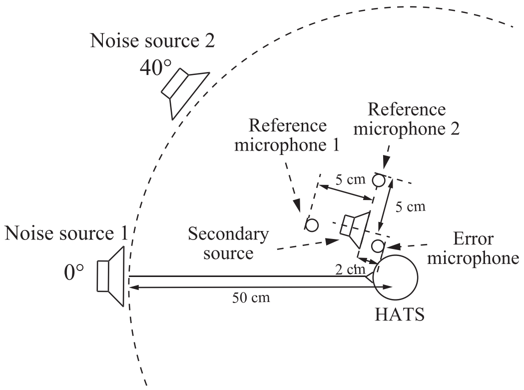


FIGURE 13. Experimental arrangement in the case of two noise sources.

z-transform of the reference signal $X_1(z)$ detected by the reference microphone is expressed as

$$X_1(z) = V_1(z)R_{11}(z) + V_2(z)R_{21}(z), \tag{6}$$

where $V_1(z)$ and $V_2(z)$ are the z-transforms of the target noise signals $v_1(n)$ and $v_2(n)$, respectively. The z-transform of the desired signal $D(z)$ at the error microphone is expressed as

$$D(z) = V_1(z)P_1(z) + V_2(z)P_2(z). \tag{7}$$

The error signal $E(z)$ is expressed as

$$\begin{aligned} E(z) &= D(z) - Y'(z) \\ &= D(z) - X_1(z)W_1(z)S(z). \end{aligned} \tag{8}$$

The noise control filter $W_1(z)$ is designed to minimize $E^2(z)$. The square of the error signal is given as

$$\begin{aligned} E^2(z) = D^2(z) &- 2D(z)X_1(z)W_1(z)S(z) \\ &+ X_1^2(z)W_1^2(z)S^2(z). \end{aligned} \tag{9}$$

Therefore, the gradient of the noise control filter is expressed as

$$\frac{\partial E^2(z)}{\partial W_1(z)} = 2X_1(z)S(z)\{X_1(z)W_1(z)S(z) - D(z)\}. \tag{10}$$

The optimal filter is obtained when (10) becomes zero, which is satisfied when

$$X_1(z)W_1^o(z)S(z) - D(z) = 0. \tag{11}$$

Therefore,

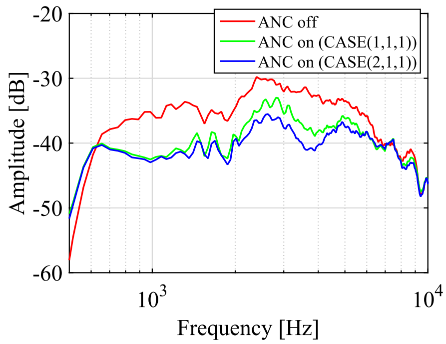
$$\begin{aligned} &V_1(z)\{R_{11}(z)W_1^o(z)S(z) - P_1(z)\} \\ &\quad + V_2(z)\{R_{21}(z)W_1^o(z)S(z) - P_2(z)\} = 0. \end{aligned} \tag{12}$$

To completely eliminate the target noises $V_1(z)$ and $V_2(z)$, the optimal filter $W_1^o(z)$ should simultaneously satisfy

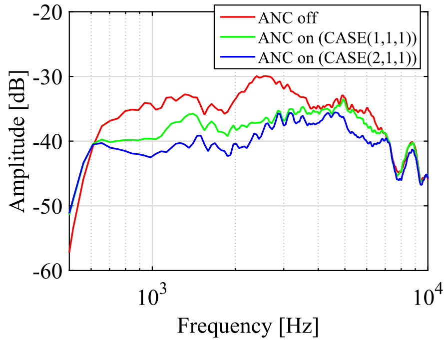
$$W_1^o(z) = \frac{P_1(z)}{S(z)R_{11}(z)}, \tag{13}$$

$$W_1^o(z) = \frac{P_2(z)}{S(z)R_{21}(z)}. \tag{14}$$

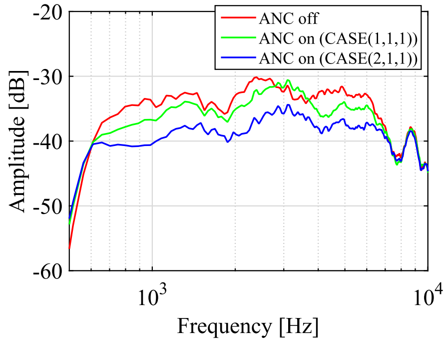
To satisfy both (13) and (14), $P_1(z) = P_2(z)$ and $R_{11}(z) = R_{21}(z)$ must be satisfied. However, this is a special situation where two noises symmetrically arrive at the reference microphone and the error microphone. Therefore, it is proved that it is difficult to obtain the optimal filter for the single-channel (1 × 1 × 1) ANC system except for in special cases.



(a) Noise sources at 0° and 40°



(b) Noise sources at 20° and 60°



(c) Noise sources at 40° and 80°

FIGURE 14. Error spectra in the case of two noise sources.

Figure 16 shows a block diagram of the 2 × 1 × 1 multi-channel ANC system including reference paths from the two noise sources to the reference microphones. Using the same derivation procedure as for the single-channel (1 × 1 × 1) ANC system, the gradients of the noise control filters are expressed as

$$\begin{aligned} \frac{\partial E^2(z)}{\partial W_1(z)} &= 2X_1(z)S(z)\{S(z)X_1(z)W_1^o(z) \\ &\quad + S(z)X_2(z)W_2^o(z) - D(z)\}, \end{aligned} \tag{15}$$

$$\begin{aligned} \frac{\partial E^2(z)}{\partial W_2(z)} &= 2X_2(z)S(z)\{S(z)X_1(z)W_1^o(z) \\ &\quad + S(z)X_2(z)W_2^o(z) - D(z)\}. \end{aligned} \tag{16}$$

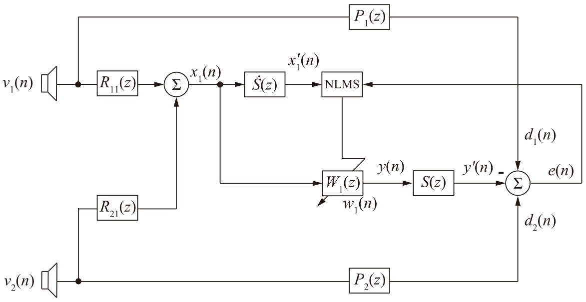


FIGURE 15. Block diagram of the single-channel (1 × 1 × 1) ANC system including reference paths from the two noise sources to the reference microphone.

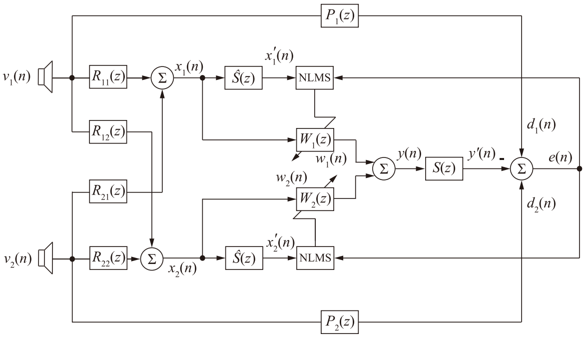


FIGURE 16. Block diagram of the multi-channel (2 × 1 × 1) ANC system including reference paths from the two noise sources to the two reference microphones.

The optimal filters are obtained when (15) and (16) become zero, which is satisfied when

$$S(z)X_1(z)W_1^o(z) + S(z)X_2(z)W_2^o(z) - D(z) = 0. \qquad (17)$$

Therefore, the optimal filters $W_1^o(z)$ and $W_2^o(z)$ are obtained by

$$W_1^o(z) = \frac{R_{12}(z)P_2(z) - R_{22}(z)P_1(z)}{S(z)\{R_{12}(z)R_{21}(z) - R_{11}(z)R_{22}(z)\}}, \qquad (18)$$

$$W_2^o(z) = \frac{R_{11}(z)P_2(z) - R_{21}(z)P_1(z)}{S(z)\{R_{11}(z)R_{22}(z) - R_{21}(z)R_{12}(z)\}}. \qquad (19)$$

From (18) and (19), the 2 × 1 × 1 multi-channel ANC system has optimal filters that can be obtained in all cases because they contain paths from both noise sources to each microphone. Therefore, it was theoretically proved that the proposed ANC system can reduce target noises more effectively than the conventional ANC system.

IV. CONCLUSION

In this paper, we developed a head-mounted ANC system based on the 2 × 1 × 1 multi-channel feedforward control in order to realize noise reduction for noise from various directions. The head-mounted single-channel (1 × 1 × 1) ANC system cannot reduce the noise arriving from various directions because the causality constraint cannot be satisfied. To solve this problem, we proposed a head-mounted multi-channel ANC system. In this paper, we examined the effectiveness of this system as a basic study toward the multi-channel expansion of head-mounted ANC systems. First, we evaluated the noise reducible range of the proposed system by changing the noise source position. It was found that, the proposed system improved the noise reducible range compared with that of the conventional system. Next, the noise reduction performance of the conventional and proposed systems in the case of two noise sources was compared. From the experimental result, the noise reduction performance of the proposed system was superior to that of the conventional system in the case of two noise sources. Finally, the optimal filters for the single-channel (1 × 1 × 1) and 2 × 1 × 1 multi-channel ANC systems in the case of two noise sources were derived. It was found that in the case of two noise sources, the optimal filter for the single-channel (1 × 1 × 1) ANC system cannot be obtained except for special geometrical arrangements. On the other hand, the optimal filters for the 2 × 1 × 1 multi-channel ANC system can be always obtained. From the above results, the effectiveness of the proposed system was demonstrated. Moreover, the robustness on the noise reduction performance may be improved by placing the additional reference microphone on the opposite side of the reference microphone 1.

In the future, we will further expand the head-mounted ANC system and demonstrate its effectiveness for noise arriving from all directions. In the conditions for various noise directions, the proposed head-mounted ANC system cannot reduce the unwanted noise at left and right ears. Hence, we will investigate the two-channel version of the proposed head-mounted ANC system. Moreover, we will conduct the evaluation on the noise reduction performance in the case of increase of the reference microphone and the diffuse noise condition. For example, we will adopt the sound source localization technique [22] and the feedforward ANC system with microphone array [23], [24], [25] to achieve the robustness of the arrival direction of the unwanted noise. For reducing the computational complexity due to microphone array processing, we will investigate the head-mounted ANC system with low computational complexity based on [26]. Moreover, the subband ANC system is effective to reduce the computational complexity, for example, ANC headphone proposed in [27]. Hence, we will try to adopt the subband adaptive digital filter into the proposed ANC system.

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