DUAL ACTIVE NOISE CONTROL WITH COMMON SENSORS

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ABSTRACT

In public spaces, it is important to reduce ambient noise and surrounding conversation sounds for smooth conversations. Since partitions are often installed at bank counters and shared offices to separate the space from the surrounding area, active noise control can be applied to these partitions. In this paper, we propose a dual active noise control (ANC) that can reduce unwanted sound simultaneously in two spaces separated by the partition while using common sensors. In the proposed dual ANC, one sensor acts as a reference sensor in one system and as an error sensor in the other system. We theoretically clarify signal processing mechanisms to realize simultaneous noise reduction. Simulation results indicate that the proposed dual ANC can achieve more than 6 dB noise reduction simultaneously in the two spaces and the film-like speaker is more suitable for secondary sources to improve the noise reduction performance.

Index Terms— dual active noise control, ANC partition, film-like speaker, public ANC

1. INTRODUCTION

Personal audio is attracting attention as a way to enjoy personal sounds and conversations in public spaces where many unspecified people gather, such as banks and shared offices. Active noise control (ANC) [1–3], which controls noise with sound, has been studied as a method to realize such personal audio. As one of the applications of ANC in public spaces, ANC partitions [4, 5], which introduce ANC function into partitions, have been studied. ANC partitions are capable of controlling speech and noise that diffracts through the partition from adjacent spaces.

Here, attempts to control incoming sound from adjacent spaces with ANC have been made with respect to the control of noise coming from windows [6–8] and the control of sound transmission from adjacent rooms [9]. However, these studies only consider the arrival of noise in one direction, where the sound from the adjacent space is controlled within the space of interest. On the other hand, in the ANC partition, the space is divided into two adjacent spaces (space A and space B) by a partition, and the diffracted sound from space A needs to be controlled in space B and the diffracted sound from space B needs to be controlled in space A. In other words, the arrival of noise in both directions must be considered simultaneously.

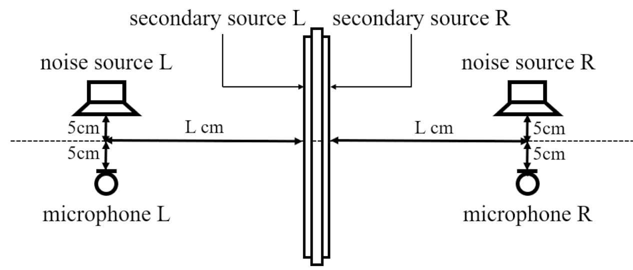

Fig. 1. ANC partition for simultaneous control of adjacent spaces

Methods for controlling multiple spaces simultaneously include multi-channel ANC [10–13]-based multi-zone control [14, 15] and decentralized control [16–19]. However, all of them are very different from the situation in ANC partitions, as they control noise in multiple areas in the same space and have unwanted noise in common. A similar application to the ANC partition is seat-by-seat active sound profiling in a car cabin [20, 21]. However, active sound profiling does not require a reference microphone because the reference signal (the audio or speech signal to be reproduced) is electrically available internally. On the other hand, in an ANC partition, a reference microphone must be installed in the space adjacent to the space to be controlled.

Fig. 1 shows the schematic diagram of the ANC partition in which the noise source L in the left space is detected by the microphone L and used as a reference signal to reduce the noise diffracted from the source L to the right space. The microphone R in the right side space is used as an error microphone to monitor the error signal. If we focus on the noise source R in the right side space, the roles of microphones L and R are reversed. In other words, the microphones L and R are simultaneously responsible for detecting the reference signal to achieve the noise control in one space and the er-

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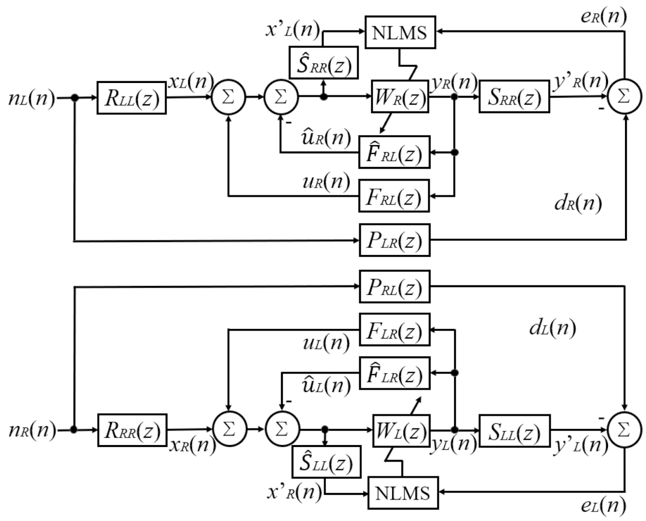


Fig. 2. Block diagram of feedforward ANC with feedback neutralization in tuning stage.

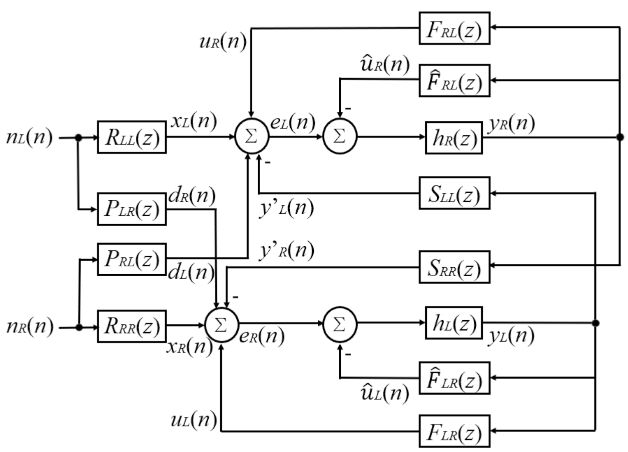


Fig. 3. Block diagram of dual feedforward ANC in control stage.

ror signal that is the residual noise coming from the other space at that point. In this paper, we propose a dual active noise control system with common sensors that simultaneously control two adjacent spaces as shown in Fig. 1, using two microphones that play the roles of both reference and error microphones.

In this paper, we show how to realize dual active noise control. The effectiveness of the dual active noise control is verified through numerical simulation experiments using the actual acoustic path characteristics. In addition, the influence of the acoustic feedback is explained theoretically and demonstrated through numerical simulations using film-like speakers (introduced in [4]) and dynamic speakers as secondary sound sources.

2. SIMULTANEOUS CONTROL OF ADJACENT SPACES BY DUAL ACTIVE NOISE CONTROL USING A COMMON SENSOR

In order to achieve simultaneous control using common sensors, the dual active noise control proposed in this paper performs simultaneous control in two adjacent spaces through two stages: a tuning stage to design the noise control filters and a control stage to actually control the noise.

2.1. Tuning Stage

Fig. 2 shows the block diagram of the tuning stage. In the figure, P_{LR}, P_{RL} are the primary paths from noise sources L and R to microphones R and L, respectively; R_{LL}, R_{RR} are the reference paths from noise sources L and R to microphones L and R, respectively; S_{LL}, S_{RR} are the secondary paths from noise sources L and R to microphones L and R, respectively, and F_{LR}, F_{RL} are the acoustic feedback paths from secondary sources L and R to microphones R and L, respectively. Also, $\hat{S}_{RR}, \hat{S}_{LL}, \hat{F}_{LR}$, and $\hat{F}_{RL}$ are the corresponding secondary path models and feedback neutralization filters, respectively. In the tuning stage, the noise control filters are designed by radiating the noise one side at a time in each partitioned space in Fig. 1. The noise control filters W_R and W_L in Fig. 2 are updated by the Filtered-x NLMS algorithm as follows

$$\mathbf{w}_L(n+1) = \mathbf{w}_L(n) + \frac{\alpha}{\beta + \|\mathbf{x}'_R(n)\|^2}\mathbf{x}'_R(n)e_L(n), \quad (1)$$

$$\mathbf{w}_R(n+1) = \mathbf{w}_R(n) + \frac{\alpha}{\beta + \|\mathbf{x}'_L(n)\|^2}\mathbf{x}'_L(n)e_R(n), \quad (2)$$

where α and β are the step size parameter and regularization factor, respectively. Note that W_L is a noise control filter to reduce the sound at microphone L using microphone R as a reference microphone, and W_R is a noise control filter to reduce the sound at microphone R using microphone L as a reference microphone. If

$$F_{RL}(z) = \hat{F}_{RL}(z), \quad (3)$$

$$F_{LR}(z) = \hat{F}_{LR}(z), \quad (4)$$

then the noise control filters W_L and W_R converge

$$W_{L,o}(z) = \frac{P_{RL}(z)}{R_{RR}(z)S_{LL}(z)}, \quad (5)$$

$$W_{R,o}(z) = \frac{P_{LR}(z)}{R_{LL}(z)S_{RR}(z)}. \quad (6)$$

2.2. Control Stage

Next, the block diagram of the dual active noise control in the control stage is shown in Fig. 3. In Fig. 3, the filter coefficients of the noise control filters W_L, W_R designed in the tuning stage are given to the noise control filters H_L, H_R as fixed coefficients. If, in Fig. 3, the acoustic feedback paths $F_{RL} = \hat{F}_{RL} = 0, F_{LR} = \hat{F}_{LR} = 0$, the z-domain representations of the error signals $e_L(n)$ and $e_R(n)$ are (for simplicity of notation, (z) is omitted)

$$E_L = P_{RL}N_R + R_{LL}N_L - S_{LL}H_LE_R, \quad (7)$$
$$E_R = P_{LR}N_L + R_{RR}N_R - S_{RR}H_RE_L. \quad (8)$$

Substituting (8) into (7), we get

$$E_L = (P_{RL} - S_{LL}H_LR_{RR})\,N_R + (R_{LL} - S_{LL}H_LP_{LR})\,N_L + S_{LL}H_LS_{RR}H_RE_L. \quad (9)$$

Thus,

$$(1 - S_{LL}H_LS_{RR}H_R)\,E_L = (P_{RL} - S_{LL}H_LR_{RR})\,N_R + (R_{LL} - S_{LL}H_LP_{LR})\,N_L. \quad (10)$$

Let $H_L = W_{L,o}, H_R = W_{R,o}$ and substituting (5) and (6), the first term on the right-hand side becomes 0, and

$$\left(1 - \frac{P_{RL}P_{LR}}{R_{RR}R_{LL}}\right)E_L = \left(1 - \frac{P_{RL}P_{LR}}{R_{RR}R_{LL}}\right)R_{LL}N_L. \quad (11)$$

Therefore,

$$E_L = R_{LL}N_L = X_L. \quad (12)$$

In the same way, we have

$$E_R = R_{RR}N_R = X_R. \quad (13)$$

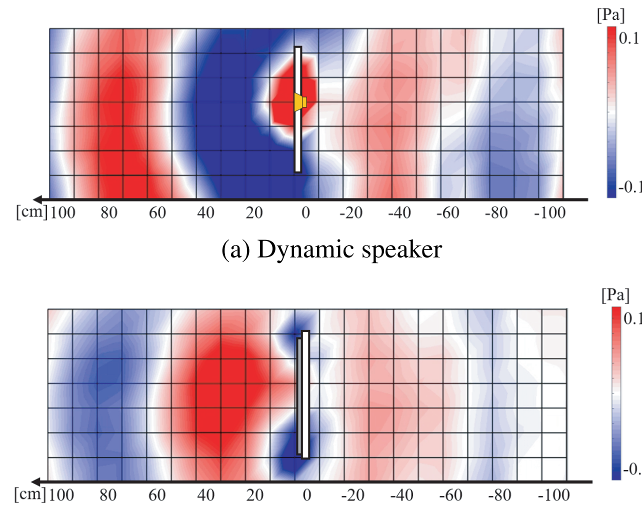
Therefore, only the near-end sounds (necessary sounds) X_L and X_R remain, and the unwanted diffracted sound can be properly controlled.

On the other hand, when the acoustic feedback path exists, solving for the error signals $e_L(n)$ and $e_R(n)$ in the same way, we obtain

$$E_L = \frac{S_{LL}(R_{RR}R_{LL} - P_{LR}P_{RL})}{S_{LL}(R_{RR}R_{LL} - P_{LR}P_{RL}) - F_{RL}P_{LR}R_{LL}}X_L, \quad (14)$$

$$E_R = \frac{S_{RR}(R_{LL}R_{RR} - P_{RL}P_{LR})}{S_{RR}(R_{LL}R_{RR} - P_{RL}P_{LR}) - F_{LR}P_{RL}R_{RR}}X_R. \quad (15)$$

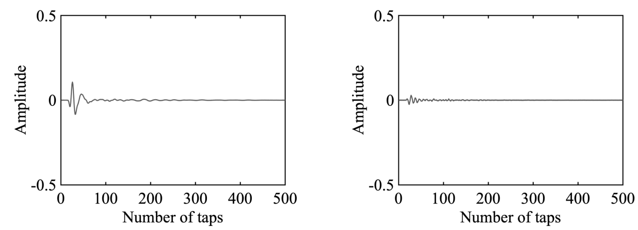
Therefore, it can be seen that when an acoustic feedback path exists, the near-end sounds X_L and X_R increases in proportion to the magnitude of the acoustic feedback path, even if a feedback neutralization filter is introduced. Therefore, it is necessary to make the acoustic feedback path as small as possible, which indicates that the selection of the loudspeaker for the secondary sound source is important.



(a) Dynamic speaker

(b) Film-like speaker

Fig. 4. Sound fields formed by secondary source mounted on partition.



(a) DS

(b) FS

Fig. 5. Impulse responses of acoustic feedback path in dynamic speaker (DS) and film-like speaker (FS).

3. SECONDARY SOURCE AND ITS EFFECT TO ACOUSTIC FEEDBACK PATH

Based on the discussion in the previous section, it is very important to reduce the influence of the acoustic feedback path from the secondary sound source in the dual active noise control where the ANC partition is used to control two adjacent spaces simultaneously. Fig. 4 shows the propagation of sound waves from the partition to the front and back when a dynamic speaker and a film-like speaker are installed in the partition. As can be seen from Fig. 4, the sound pressure of the sound wave propagating backward is higher for the dynamic speaker than for the film-like speaker. This means that the film-like speaker will have a smaller acoustic feedback path when placed in a partition than the dynamic speaker.

To confirm this, the impulse responses of the acoustic feedback path are shown in Fig. 5, where the dynamic and film-like speakers are used as secondary sources for the ANC partition. These impulse responses were measured at L=60 cm in Fig. 1. As can be seen from Fig. 5, the peak value in the impulse response of the acoustic feedback path is much larger for the dynamic speaker than for the film-like speaker. Therefore, as expected from the radiated sound pressure distribution in Fig. 4, the film-like speaker is a suitable secondary source for the dual active noise control using common sensors proposed in this paper because the influence of the acoustic feedback path is small.

4. EVALUATION OF PROPOSED DUAL ACTIVE NOISE CONTROL

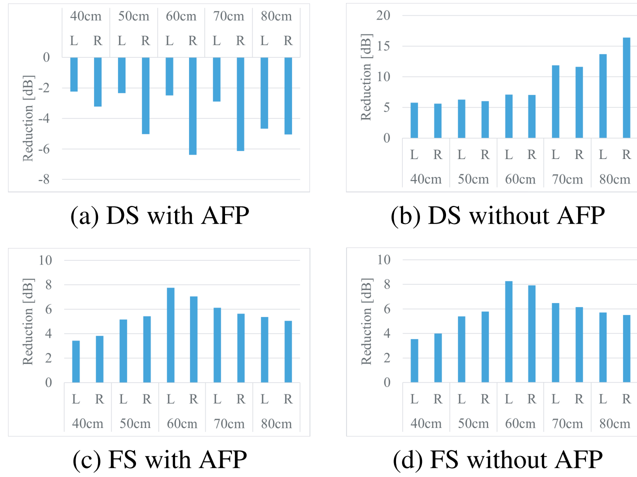
In the previous section, we have shown that dual active noise control can control both spaces simultaneously. It was also theoretically shown that the smaller the acoustic feedback path, the higher the noise reduction effect. In this section, we demonstrate the effectiveness of the proposed dual active noise control and the effectiveness of using film loudspeakers through simulations using the measured transmission paths.

4.1. Simulation Condition

The impulse responses of all paths in Fig. 2 and Fig. 3 were measured by varying the distance L between the partition and the microphone from 40 cm to 80 cm under the installation condition of Fig. 1. The impulse responses are used to evaluate the noise reduction at both microphones through simulation. In the simulation, we first design the noise control filters W_L, W_R in the tuning stage of Fig. 2, and then apply the filter coefficients to the H_L, H_R in the control stage of Fig. 3. In the simulation, the sampling frequency is 6000 Hz and the tap lengths of all transmission paths and filters are 500. In the simulations, we compare the reduction effect of using dynamic speakers and film-like speakers as secondary sound sources. In addition, we examine the effects of the presence and absence of the acoustic feedback path to verify the theoretical considerations in the previous section.

4.2. Simulation Results

Fig. 6 shows the reduction effect of the proposed dual ANC with and without the acoustic feedback path, respectively, when the dynamic and film-like speakers are used as secondary sound sources. Fig. 6 shows that noise reduction is achieved for both dynamic and film-like speakers when there is no acoustic feedback path. In the case where dynamic speakers are used as the secondary noise source, the noise reduction effect increases as the microphone moves away from the partition. As can be seen in Fig. 4, this is because the sound pressure of the dynamic speaker is higher around $70 \sim 80$ cm and the causality constraint is satisfied by the distance between the noise source and the secondary source. On the other hand, for the film-like speaker, the causality constraint results in a decrease in noise reduction around $40 \sim 50$



(a) DS with AFP (b) DS without AFP

(c) FS with AFP (d) FS without AFP

Fig. 6. Noise reduction of using dynamic speaker (DS) and film-like speaker (FS) with and without acoustic feedback path (AFP) in case where the distance between each microphone and partition is changed from 40 cm to 80 cm.

cm, but the further the microphone is from the partition, the better the noise reduction.

In the presence of the acoustic feedback path, the residual error increases with the magnitude of the acoustic feedback path, even if the feedback neutralization filter is used as discussed in the previous section, so the noise reduction is greatly degraded for dynamic speakers with a large influence of the acoustic feedback path. On the other hand, when the film-like speakers are used as secondary sound sources, there is almost no change in the noise reduction because the influence of the acoustic feedback path is small as discussed in the previous section.

5. CONCLUSION

In this paper, we proposed a dual active noise control system that simultaneously controls two adjacent spaces separated by a partition, and verify its effectiveness through simulation. In the proposed dual active noise control, a single microphone installed in each of the two spaces can detect both the reference signal and the residual error. It was shown that simultaneous control is theoretically possible and that the noise reduction effect is degraded when the acoustic feedback path is large. The simulation results verified the theory and demonstrate that the noise reduction can be achieved stably and simultaneously in two spaces by using film-like speakers as secondary sound sources, which are less affected by the acoustic feedback path. In this paper, we used a single-channel configuration with one microphone in each space to be controlled, but for a more realistic configuration, a multi-channel configuration with two microphones in each space should be realized using the dual active noise control.

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