Study on Active Noise Control System Using Parametric Array Loudspeakers

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Summary
In this paper, we propose an active noise control (ANC) system using parametric array loudspeakers (PALs). Conventional active noise control systems using ordinary loudspeakers as control sources may result in unwanted increment of sound pressure levels outside the target points (quiet zones). Moreover, a multiple-channel ANC system increases the computational complexity significantly as compared to a single-channel ANC system. On the other hand, the proposed ANC system can not only reduce unwanted acoustic noise levels at the desired locations but also suppress the increment in sound pressure levels at other locations because the PALs have a super-directivity feature. If interferences between different channels of the proposed ANC system are minimized, therefore each channel in this ANC system can be controlled independently. We have attempted to apply the proposed system in a factory where manufacturing equipments generate noise levels of over 90 dB. Due to the distribution and multiple-path propagations of noise sources, conventional ANC system cannot work effectively. In addition, the installation locations of the control sources are constrained for safety consideration. For these reasons, comparative experiments have been conducted to find the optimized locations to install PALs in a Case(1,2,2) ANC system. Recent results of the proposed ANC system are presented and remaining issues are discussed in this paper.

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1. Introduction
Acoustic noise problems are becoming increasingly serious in the process of industrialization. A lot of manufacturing equipments can generate noise levels of over 90 dB. Exposure to such intense sounds may cause physical and mental harms to people working nearby. The masking effect caused by the noises also hinders verbal communications between them.

As an effective approach to reduce unwanted noise, active noise control (ANC) [1]-[3] has been applied in various fields [4]. In a typical ANC system, an anti-noise wave with the same amplitude and opposite phase of the unwanted noise wave is generated from the control source. Based on the superposition principle of sound waves, the cancellation of the noise wave can be achieved at a specified location.

There are many affecting factors to consider when designing an ANC system, such as the control structure, the adaptive algorithm, the secondary source, and so forth. These affecting factors are closely associated with the practical performance of the designed system. Appropriate selections of them usually depend on the acoustic environment, where the ANC system is deployed [5]. Thus, a large amount of efforts have to be spent on experimental measurements.

When applied in a factory, the control points of an ANC system are located at vicinities of workers. Therefore, the secondary sources must be placed far from the control points due to the safety consideration. The distribution of multiple noise sources and their multiple-path propagations increase the complexity of the acoustic environment. Thus, conventional ANC systems face difficulty in converging to satisfactory performance in such an application scenario. We find that an ANC system using parametric array loudspeakers (PALs) as control sources [6]-[17] can be a feasible solution.

When PALs are used in the ANC system, it can not only reduce the noise level at the targeted locations, but also prevent spillover of the anti-noise wave to the other areas. It is because of the super-directivity of the PALs [9]. Moreover, if interferences between different channels of the proposed ANC system are minimized, the proposed ANC can independently control every channel. Thus, in our proposed ANC system, two PALs are deployed to independently control the noise levels near the left and right ears of a user. By this mean, the computational complexity of a multiple-channel ANC system is reduced since the cross-talk secondary path models are negligible.

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As aforementioned, the installation locations of the secondary sources are limited when the proposed ANC system is installed in factory. Therefore, it is important to find the optimized locations to install the PALs. We have examined various installation locations of the PALs with respect to the control point, where the error microphone is placed. Moreover, we demonstrate the influence of cross-talk in proposed Case(1,2,2) ANC system. The performance of the proposed ANC system is demonstrated through experiments and simulations. It has been confirmed that PALs outperformed omnidirectional loudspeakers in terms of being free from cross-talk in the Case(1,2,2) ANC system.

2. Active Noise Control System Using Parametric Array Loudspeakers

2.1. Factory Noise
Various types of industrial equipments have been introduced in manufacturing plants and factories owing to the development of industrial machinery. However, some manufacturing equipments in factories generate strong acoustic noises (over 90 dB SPL). Exposure to such intense sounds may cause physical and mental harms to people working nearby and prevent verbal communication between them. In addition, the noise sources are distributed in the factory workshop, and multiple reflections are caused by the ceiling, the floor, walls and equipments. Thus, acoustic environment in factory is extremely complex.

Figure 1 shows a typical time waveform of the factory noise measured in a factory along with its corresponding spectrum. It is noted that the envelope of the time-domain waveform varies with time, which shows the nonstationary nature of the factory noise. Periodic impulses are also observed in the waveform, as well as in the spectrum. Apparently, it is hard to categorize the factory noise as a broadband or narrowband noise. Therefore, we choose a hybrid ANC system which is a combination of the feedforward and feedback ANC system to reduce the factory noise.

2.2. Parametric Array Loudspeakers
Sound principle of a PALs is much different from that of an electrodynamic loudspeaker. The latter generates sound from a vibrating diaphragm, while the PALs utilizes the nonlinear acoustic effects in air. When two ultrasonic waves propagate together, a sound beam at their difference frequency is accumulatively formed. Thus, the spatial behavior of a PALs is more similar to an end-fire array of the ordinary loudspeakers.

Figure 2 shows an example of the PALs used in our studies, which are manufactured by Tristate limited. The audio input is modulated to an ultrasonic carrier by the driving circuit. After being transmitted from the ultrasonic transducer, reproduced audible sound is generated based on the self-demodulation effect due to the nonlinearity of air. The audible sound beam has a similar beamwidth as the ultrasonic carrier.

Hence, PALs have a super-directivity feature by inherited from an ultrasonic beam because the sound at high frequencies like ultrasonic has strong straightness. By using this feature of PALs, the proposed ANC system can not only reduce unwanted acoustic noise at targeted locations but also prevent spillover of the anti-noise wave to the other locations. Moreover, the proposed ANC system can independently control unwanted acoustic noise near each ear because interference between different channels of this system is minimized.
2.3. Hybrid ANC System

The hybrid ANC system generates the canceling signal on the basis of the outputs of both the reference and error sensors, which utilizes a combined structure of the feedforward and feedback ANC systems [18]–[20]. Figure 3 shows a block diagram of a single-channel hybrid ANC system with Filtered-x normalized least mean square (FXNLMS) algorithm which is the most popular. When the PALs are used as the secondary sources, the feedback path can be omitted, negligible level of control sound is picked up by reference microphone. The secondary signal $y(n)$ is a summation of the outputs of the feedforward noise control filter $W_F$ and the feedback noise control filter $W_B$ as shown in Fig. 3. The hybrid ANC system plays a dual role in canceling the primary noise using $W_F$, which is picked up by the reference microphone, and the residual noise component (or plant noise) using $W_B$, which is only picked up by the error microphone. Therefore, the hybrid ANC system possesses the merits of the feedforward and feedback ANC systems. It is good at reducing a mixture of the broadband and narrowband noises. Hence, the hybrid ANC system is expected to improve stability and high noise reduction performance in the proposed ANC system.

The algorithms used to update the noise control filters $W_F$ and $W_B$ are respectively expressed as

$$w_F(n+1) = w_F(n) + \frac{\alpha_F}{\beta_F + ||x(n)||^2} x(n)e(n), \tag{1}$$

and

$$w_B(n+1) = w_B(n) + \frac{\alpha_B}{\beta_B + ||r(n)||^2} r(n)e(n), \tag{2}$$

respectively. $w_F(n)$ and $w_B(n)$ are the tap-weight vectors of the feedforward noise control filter $W_F$ and feedback noise control filter $W_B$. $x(n)$ and $r(n)$ are the filtered reference signal vectors, respectively. Moreover, $\alpha_F$, $\alpha_B$, $\beta_F$, and $\beta_B$ are the step size and regularization parameters of the noise control filters $W_F$ and $W_B$, respectively. Furthermore, $e(n)$ is the error signal picked up at the error microphone.

2.4. Case(1,2,2) ANC System

A multiple-channel ANC system consists of multiple reference microphones, secondary sources and error microphones. According to the common naming rule, a Case(1,2,2) ANC system represents a this multiple-channel ANC system that uses one reference microphone, two secondary sources (PALs) and two error microphones. Figure 4 shows a block diagram of the Case(1,2,2) ANC system with FXNLMS algorithm. Anti-noise waves are transmitted from two secondary sources to reduce noise levels simultaneously at two control points. When PALs are used as the secondary sources, the cross-talk secondary path models are likely to be negligible.

The algorithm used to update the noise control filters in Fig. 4 is expressed as follows.

$$w_k(n+1) = w_k(n) + \sum_{m=1}^{\infty} \frac{\alpha}{\beta + ||x_{mk}(n)||^2} x_{mk}(n)e_m(n)$$

$$k = 1, 2, \tag{3}$$

where $w_k(n)$ are the tap-weight vectors of each noise control filters and $x_{mk}(n)$ are the filtered reference signal vectors, respectively. Furthermore, $e_m(n)$ are the error signals picked up at error microphones.
3. Experimental Results

We demonstrate the noise reduction performance of the proposed hybrid ANC system for factory noise and appropriate locations of secondary loudspeakers (PALs) through some experiments. Moreover, we examine the influence of cross-talk in both-channel control using the proposed Case(1,2,2) ANC system. The ANC algorithm is implemented on a DSP platform TMS320C6713DSP (Texas Instruments Co.). Table I shows the common experimental conditions. All measurements have been conducted in a soundproof room.

3.1. Noise Reduction Performance

The noise reduction performance of the proposed hybrid ANC system for factory noise was demonstrated through some experiments. The error microphone was placed close to the left ear of a head and torso simulator (HATS). Figure 5 shows the placement of a PALs with respect to the HATS in each experiment.

In the this study, the PAL was placed at the fiducial location, where the elevation angle $\theta$ and the horizontal angle $\phi$ were both set at 0°. The distance from the secondary source to the error microphone was $d = 1.5$ m. Fig. 6 shows the time waveform picked up by the error microphone (the microphone attached to the HATS) and a comparison of the spectra picked up by the error microphone before and after ANC system was turned on. It can be seen from Fig. 6 that the proposed ANC system can stably operate and reduce factory noise effectively about 10 dB more than 500 Hz.

3.2. Appropriate Locations of Secondary Loudspeakers

The most appropriate locations of the PALs were examined in the proposed hybrid ANC system. Different locations of the secondary source in terms of the elevation angle, the horizontal angle, and the distances from the secondary source to the error microphone, as shown in Figure 5, were examined.

Figures 7, 8, and 9 show some experimental results when the locations of the PALs were changed from the fiducial position. It can be observed from Figs. 7–9 that the proposed ANC system can reduce factory noise even if the PALs are placed higher than the control point and the distances between the PALs and the control point are more than 2.5 m. In summary, the PALs are suitable to be used as the secondary sources when the installation locations are constrained.

3.3. Both-Channel Control by Proposed Case(1,2,2) ANC System

Next, the noise reduction performance and influence of cross-talk of a Case(1,2,2) ANC system were demonstrated through the measurement experiments where two PALs were used as the secondary sources and the control points were located at the left and right ears of the HATS. Figure 10 shows a schematic diagram of this experiment of setup. The two PALs were placed symmetrically to the HATS, where the
horizontal angles were set at $\phi = \pm 30^\circ$. The elevation angles of the two PALs were kept at $0^\circ$. The distances from one secondary source to the corresponding control point were $d = 1.5$ m, and the distances from the noise source to the center of the two control points were $l = 2.0$ m.

Fig. 11 shows the comparison of the spectra picked up by the error microphones (the microphone attached to the HATS of left and right ear) before and after the proposed ANC system was turned on. It can be observed from Fig. 11 that the proposed ANC system can efficiently reduce factory noise about 15 dB more than 500 Hz. Furthermore, when the cross-talk secondary path models $\hat{S}_{12}$, $\hat{S}_{12}$ were removed, there was little to no change of noise reduction performance of this ANC system. It has been validated that the proposed ANC system can reduce unwanted acoustic noise even if the cross-talk secondary path models $\hat{S}_{12}$, $\hat{S}_{21}$ are removed. On the other hand, when considering the actual environment, we need to examine the effectiveness of a multiple-channel ANC system using multiple reference microphones (e.g. Case(2,2,2) ANC system).

4. Computer Simulation

We demonstrate whether the proposed Case(1,2,2) ANC system can reduce unwanted acoustic noise even if the cross-talk secondary path models $\hat{S}_{12}$, $\hat{S}_{21}$ are removed through the computer simulation. The computer simulation of the proposed ANC system was conducted in terms of convergence property when the Case(1,2,2) ANC system with and without the cross-talk secondary path models. The simulation conditions are the same as the experimental conditions in Table I. As the evaluation function, we defines the reduction as follows:

$$\text{Reduction} = 10 \log_{10} \sum \frac{(d_1^2(n) + d_2^2(n))}{\sum (e_1^2(n) + e_2^2(n))} \quad (4)$$

Therefore, we can compare the noise reduction ability using Equation (4) in the case of the cross-talk secondary path models $\hat{S}_{12}$, $\hat{S}_{21}$ are used and the cross-talk secondary path models are removed.

Figure 12 shows the noise reduction ability between the Case(1,2,2) ANC system with and without the cross-talk secondary path models. It can be seen from Fig. 12 that the proposed Case(1,2,2) ANC system where the cross-talk secondary path models are removed can reduce unwanted acoustic noise as same as the case where the cross-talk secondary path models are used. Hence, the proposed Case(1,2,2) ANC system can realize the reduction of computational complexity since the cross-talk secondary path models are negligible.
5. Conclusions

In this paper, we have proposed single-channel and multi-channel ANC systems using PALs as the secondary sources. The effectiveness and implementation of our proposed ANC system have been examined through experiments. It has been found that the effectiveness of the proposed hybrid ANC system is not affected when the PAL is placed higher than the control point or at a distance more than 2.5 meters from the control point. In other words, the proposed hybrid ANC system can reduce factory noise without being affected by the installation locations of PAL. Moreover, it has been validated that the cross-talk secondary path models are negligible in the proposed Case(1,2,2) ANC system because the PALs generate narrow sound beams.

However, there are remaining issues about the proposed ANC system which are stated as follows:

1) Study on a multiple-channel ANC system using multiple reference microphones (e.g., Case(2,2,2) ANC system)
2) Expansion of the quiet zones near the user’s ears using fixed coefficient filters
3) Subjective assessment for the proposed ANC system
4) Improving the algorithm for moving targets

In the near future, feasible studies will be conducted on the above remaining issues of the proposed ANC system in an actual factory.

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References