Multi-channel Active Noise Control Using Parametric Array Loudspeakers

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Abstract—In this paper, a multi-channel active noise control (ANC) using parametric array loudspeakers (PALs) is proposed to solve the noise problem in a factory. The PAL is a type of directional loudspeaker making use of the nonlinear acoustic effects. There are two advantages when PALs are used as the secondary sources in a multi-channel ANC system. First, noise levels can be reduced at the targeted locations, while the sound pressure levels at the other locations are not affected. Second, the cross-talk secondary path models can be removed, because the sound field reproduced by one PAL has negligible interference with the other PALs. When the proposed ANC system is implemented with fixed coefficient noise control filters, the computational complexity is further reduced. Based on a real-time implementation in a digital signal processor (DSP), experiment results are obtained to demonstrate the performance of the proposed ANC system.

I. INTRODUCTION

Noise pollution is a global concern in the development of a sustainable world. For example, in a factory, the workers have to suffer from the noise levels over 90 dB, which are generate by the manufacturing equipment. Exposure to the excessive noises can cause cardiovascular effects on the workers. Meanwhile, verbal communications are masked by the noises. Necessary protective measures are demanded to eliminate these safety hazards.

Active noise control (ANC) has been proven to be an effective approach to reduce the noise level at a targeted location [1]–[4]. In a conventional single-channel ANC system, an anti-noise wave is generated from the control source (a.k.a. the secondary source) to have the same amplitude but opposite phase of the unwanted noise wave. Based on the superposition principle of sound waves, cancellation of the noise wave can be achieved at a specified location. There are many affecting factors in an ANC system, such as the control structure, the adaptive algorithm, the secondary source, and so forth. They are closely associated with the practical performance of the ANC system. Appropriate selections of these affecting factors depend on the acoustic environment where the ANC system is deployed [5].

When a conventional ANC system is installed in a factory, the control point is given by the vicinity of a worker, and the secondary source must be placed near the worker to maximize the performance. However, this configuration hinders the mobility of the worker. Moreover, the acoustic environment in a factory is very complicated. There are a lot of noise sources distributed all over the space, as shown in Fig. 1. In this case, an ANC system using parametric array loudspeakers (PALs) as control sources [6]–[14] are suggested to be a better solution. The PAL is a type of directional loudspeaker making use of the nonlinear acoustic principle. When the PALs are used in an ANC system, not only are noise levels at the targeted locations reduced, but also spillovers of the anti-noise waves to the other areas are limited. Moreover, there are negligible interferences between the sound fields reproduced by the PALs. Thus, in a dual-channel ANC system, two PALs can be deployed to independently control the noise levels near the left and right ears of a user. The computational complexity of this ANC system is reduced by removing the cross-talk secondary path models.

As aforementioned, the secondary sources must be placed to be far away from the workers, when the proposed ANC system is installed in a factory. In our previous paper [15], the optimized locations to install the PALs have been experimentally studied. Thereafter, the computational complexity of the real-time implementation is the main focus of this paper. Two implementations of the proposed ANC system using adaptive and fixed coefficient noise control filters are compared. The noise reduction performance and the influence of the cross-talk secondary path models are examined.

II. ACTIVE NOISE CONTROL SYSTEM USING PARAMETRIC ARRAY LOUDSPEAKERS

A. Factory Noise

As shown in Fig. 1, there are plenty of equipment on the production line in a factory. They are distributed all over the space, and each of them has its own spectral characteristics. Multiple reflections are caused by the ceiling, the floor, walls...
and equipment. Thus, the reference microphone of an ANC system picks up a mixture of many noise waves and multiple-path reflections.

Fig. 2 shows the time waveform and frequency spectrum of a recorded factory noise. The envelope of the time waveform shows the nonstationary nature of this factory noise. Periodic impulses are observed in both the time waveform and the frequency spectrum. This factory noise can be treated as a broadband noise, so a feedforward ANC structure is selected in our proposed system.

B. Parametric Array Loudspeakers

The sound principle of the PALs is apparently different from that of the electrodynamic loudspeakers. The electrodynamic loudspeakers generate sounds from vibrating diaphragms, but the PALs take advantage of nonlinear acoustic effects to create audible sounds from the ultrasound. When two ultrasonic waves propagate in the same direction, a sound beam at their difference frequency is accumulatively formed [16].

Figs. 3 and 4 show a commercial product of the PAL made by TriState and a block diagram of the sound principle of a PAL, respectively. The audible sound input is modulated on an ultrasonic carrier in the driving circuit, which integrates a modulator and a power amplifier. The modulated signal is then transmitted from the ultrasonic emitter. The sideband of the modulated ultrasonic carrier nonlinearly interacts with the ultrasonic carrier during propagating in air. The difference frequencies between them accumulatively form the desired audible sound output. This procedure is also known as the self-demodulation effect [17].

The self-demodulated wave consists of all the frequency components of the audible sound input, but some harmonic and intermodulation distortions are often noted [18]–[20]. On the other hand, the self-demodulated wave exhibits a similar directivity as the ultrasonic carrier. The PALs are advantageous in the transmission of sound beams. Thus, the proposed ANC system using PALs as secondary sources can not only reduce noise levels at targeted locations but also prevent spillovers of the anti-noise waves to the other locations. Moreover, the proposed ANC system can control the individual noise reduction near each ear thanks to the super-directional sound beams generated from the PALs [15].

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

According to the common naming rule, a single-channel ANC system consisting of only one reference microphone, one secondary source and one error microphone is called a Case(1,1,1) ANC system. Similarly, a Case(1,2,2) ANC system represents a multiple-channel ANC system that uses one reference microphone, two secondary sources and two error microphones. In a Case(1,2,2) ANC system, anti-noise waves are transmitted from two secondary sources to reduce noise levels at two control points simultaneously.

Fig. 5 shows a block diagram of the Case(1,2,2) ANC system with filtered-x normalized least mean square (FXNLMS) algorithm. When PALs are used as the secondary sources, the
cross-talk secondary path models are likely to be negligible. The algorithm used to update of the noise control filters in Fig. 5 is expressed as

\[ w_k(n + 1) = w_k(n) + \sum_{m=1}^{2} \alpha \beta \left| e_m(n) \right|^2 x_{mk}(n), \]

(1)

where \( k = 1 \) or \( 2 \) is the index of the secondary source; \( m \) is the index of the error microphone; \( w_k(n) \) is the tap-weight vector of the \( k \)th noise control filter; \( x_{mk}(n) \) is the \( m \)th reference signal vector filtered by the \( k \)th noise control filter; and \( e_m(n) \) is the error signal picked up by the \( m \)th error microphone.

D. Implementation of ANC System with Fixed Coefficient Filters

The computational complexity of a multi-channel ANC system is much higher than a single-channel ANC system. To use PALs as the secondary sources can help to the computational complexity of the cross-talk secondary path models. To further simplify the multi-channel ANC system implementation, the fixed coefficient noise control filters are introduced. In this implementation, the noise control filters, which are conventionally realized by adaptive filters, are replaced by fixed coefficient filters. The coefficients of the fixed coefficient filters are determined in an offline training. To implement an ANC system with fixed coefficient noise control filters is only feasible when the application environment changes trivially.

For example, in a single-channel feedforward ANC system, the optimal transfer function of the noise control filter \( W^\alpha(z) \) is expressed as

\[ W^\alpha(z) = \frac{P(z)}{S(z)}, \]

(2)

where \( P(z) \) and \( S(z) \) are the transfer functions of the primary and secondary paths, respectively. If the primary and secondary paths are unchanged in practice, the optimal noise control filter \( W^\alpha(z) \) can be determined by (2) in advance. Figs. 6 and 7 show the block diagrams of modeling the primary and secondary paths, respectively. In both Figs. 6 and 7, an adaptive algorithm is used and the converged model coefficients are saved. The primary and secondary path models are subsequently applied in the block diagram shown in Fig. 8 to obtain the optimal noise control filter. The computed coefficients are used in the fixed coefficient filter and implemented on a digital signal processor (DSP) platform. By making the training process offline, the computational complexity of an ANC system is contributed mostly from the convolution between the noise control filter and the reference signal.
TABLE I
EXPERIMENT CONDITIONS.

<table>
<thead>
<tr>
<th>Noise type</th>
<th>Factory noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap length of noise control filter</td>
<td>400</td>
</tr>
<tr>
<td>Tap length of secondary path model</td>
<td>200</td>
</tr>
<tr>
<td>Update algorithm of noise control filter</td>
<td>NLMS</td>
</tr>
<tr>
<td>Step size parameter</td>
<td>0.005</td>
</tr>
<tr>
<td>Regularization parameter</td>
<td>$1.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>12000 Hz</td>
</tr>
<tr>
<td>Cutoff frequency of low-pass filter</td>
<td>2500 Hz</td>
</tr>
</tbody>
</table>

Fig. 9. Implementation of the proposed Case(1,2,2) ANC system.

III. EXPERIMENT RESULTS

In this section, the noise reduction performance and influence of cross-talk secondary path models are demonstrated in the proposed Case(1,2,2) ANC system. Moreover, the effectiveness of the proposed Case(1,2,2) ANC system implemented with fixed coefficient filters is examined. The control unit is a DSP platform TMS320C6713DSP (Texas Instruments Co.). Table I shows the common experiment conditions. Fig. 9 shows the implementation of the proposed Case(1,2,2) ANC system. All the measurements were conducted in a soundproof room.

Fig. 10. Arrangement of the proposed Case(1,2,2) ANC system.

Fig. 11. Time waveform of error signal picked up by the left error microphone.

Fig. 12. Time waveform of error signal picked up by the right error microphone.
A. Noise Reduction Performance and Influence of Cross-talk

The control points of the proposed Case(1,2,2) ANC system were located at the left and right ears of the HATS. Fig. 10 shows a schematic diagram of the experiment 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°. The distances from one secondary source to its corresponding control point were \( d = 1.5 \text{ m} \), and the distances from the noise source to the center of the two control points was \( l = 2.0 \text{ m} \).

Figs. 11 and 12 show the time waveforms of the error signals picked up by the left and right error microphones, respectively. Fig. 13 shows the comparison of the spectra of the error signals in three cases when: (1) ANC is turned off; (2) ANC is turn on; (3) ANC is turned on, but the cross-talk secondary path models are removed. It is observed that the proposed multi-channel ANC system can stably reduce the factory noise by 15 dB at the frequency band above 500 Hz. Furthermore, when the cross-talk secondary path models 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 are removed.

B. Implementation of Proposed Case(1,2,2) ANC System with Fixed Coefficient Filters

The effectiveness of the proposed Case(1,2,2) ANC system implemented with fixed coefficient filters was demonstrated through experiments. The same experiment arrangement as the previous section was used. The coefficients of the noise control filters \( W_1 \) and \( W_2 \) were obtained in advance. They were saved in memory from the previous experiments after the adaptive algorithm had been turned on for 30 seconds. The saved coefficients of the noise control filters were adopted in the proposed Case(1,2,2) ANC system implemented with fixed coefficient filters.

Fig. 14 shows the comparison of the error signals picked up by the left and right error microphones. Fig. 15 shows the comparative results of three cases when: (1) ANC is turned off; (2) ANC is turn on; (3) ANC is turned on, but the cross-talk secondary path models are removed. It is observed that the proposed Case(1,2,2) ANC system implemented with fixed coefficient filters can reduce factory noise in all the control points. It is also found that the noise reduction performance at right error microphone location is better, because the PAL on the right channel has a larger reproduced sound pressure level than the PAL on the left channel. Furthermore, the error microphones are removed when the proposed Case(1,2,2) ANC system implemented with fixed coefficient filters, since there is no need of error signals to update the coefficients of the noise control filters.

Hence, the proposed Case(1,2,2) ANC system using PALs as the secondary sources can be implemented with fixed coefficient noise control filters to save the computational complexity and yet achieve satisfactory noise reduction performance. Moreover, the proposed Case(1,2,2) ANC system implemented with fixed coefficient filters can realize the quiet zones at the specified locations that error microphones are removed.

IV. CONCLUSIONS

In this paper, a multi-channel ANC system using PALs as the secondary sources has been proposed. The noise reduction performance of the proposed multi-channel ANC system has been demonstrated through experiments. It has been found that the cross-talk secondary path models can be removed in the proposed Case(1,2,2) ANC system which almost no compromise on noise reduction performance. Moreover, it has been validated that the proposed Case(1,2,2) ANC system can be implemented with fixed coefficient noise control filters to further reduce the computational complexity.

In the future, we will demonstrate the proposed multi-channel ANC system using multiple reference microphones to correspond to complicated noise environment. In addition, we will examine the proposed multi-channel ANC system using more error microphones to expand the quiet zones at the desired locations. In these case, the implementation of the proposed multi-channel ANC system with fixed coefficient filters becomes more important to reduce the computational complexity. Moreover, subjective assessments are planned to be carried out in the real factory environment.
Fig. 14. Comparison of time waveform of error signal when the proposed Case(1,2,2) ANC system with fixed coefficient filters is used.

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