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Mixed-error approach for multi-channel active noise control of open windows

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ABSTRACT

This paper presents an attempt to reduce the computational complexity, while achieving acceptable level of noise reduction in a multi-channel active noise control (MCANC) system for mitigating noise passing through open windows. The reference signals are sensed at the back of the secondary loudspeakers. The existing approach to reduce the computational complexity has already used only one reference signal in each feedforward channel. As the number of error microphones is also important to ensure global noise reduction of the MCANC system for open windows, the main idea of this paper is to preprocess the error signals so that the number of inputs to the controller is further reduced. When the preprocessing is a simple summation, it is called the mixed-error approach. The number of inputs related to the error signals is eventually reduced to 1 after the mixed-error approach is applied. Simulation results demonstrate that the optimum control filters derived under general conditions can lead to similar global noise reduction to those derived based on the mixed-error approach. Experimental results confirm that in a 4-channel MCANC system applied to a 0.2 m by 0.2 m open window, the performance of global noise reduction is not compromised by the mixed-error approach.

1. Introduction

Active noise control (ANC) techniques have been widely used in many noise mitigating applications [1,2], such as reducing tonal noise in an aircraft cabin [3], cancelling airflow noise in a duct [4], treating engine noise in vehicles [5]. ANC techniques are favorable when dealing with low-frequency noise, whereby passive noise control techniques may fail to provide efficient noise reduction [6]. Most of the ANC applications focus on the local cancellation of noise in a small region, exemplified by noise cancelling headphones. Within one tenth of the noise wavelength from the error microphone location, a reduction of 10 dB in the noise level is typically obtained [7]. However, there is a recent trend of extending the control region to achieve global noise reduction by multi-channel active noise control (MCANC) systems [8–13].

In previous studies, we have proposed the concept to achieve global noise reduction in a room by deploying an MCANC system at the opening window [14–17]. Each feedforward channel of this MCANC system consists of a reference microphone and a secondary loudspeaker, as depicted in Fig. 1. The reference microphones face outwards, while the secondary loudspeakers face inwards. The feedforward channels are configured uniformly in the middle of the open window. According to Ise's boundary surface control principle, the sound field in an enclosed space can be controlled by adjusting the sound pressure and particle velocity on the surface of the space [18,19]. Therefore, the MCANC system for open windows is feasible to generate the anti-noise field with inverted phase of the noise field, so that the noise level in the room is globally minimized.

There are several design parameters of the MCANC system for open windows. Firstly, the size of the secondary loudspeaker may block natural ventilation. It also affects the lower effective frequency bound of the system, as small-sized loudspeakers usually cannot generate low-frequency sound at sufficiently high levels [17]. Secondly, the separation between the secondary loudspeakers determines the spatial aliasing condition, which provides the upper effective frequency bound of the system. Thirdly, the distance from the reference microphone to the secondary loudspeaker limits the maximum processing time as a result of the causality constraint of feedforward ANC systems, whereby the driving signal

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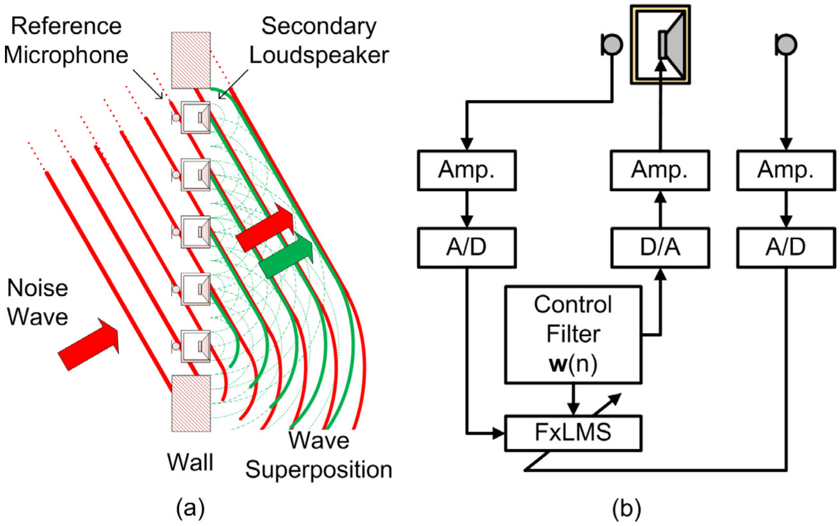

Fig. 1. MCANC system to mitigate noise passing through an open window: (a) illustration of wave superposition; (b) block diagram of a single-channel feedforward ANC system.

of the secondary loudspeaker has to be generated before the actual noise wave reaches the position of the secondary loudspeaker. On the other hand, a shorter distance from the reference microphone to the secondary loudspeaker is more favorable to carry out the decentralized MCANC algorithms that are much less complicated than the centralized MCANC algorithm [15–17]. In those decentralized MCANC algorithms, the control signal of each secondary loudspeaker is generated based on only one reference signal that is sensed by the nearest reference microphone. This is also known as the collocated implementation. When the distance from the reference microphone to the secondary loudspeaker is relatively longer, the decentralized MCANC algorithms are less effective for the moving noise source and multiple noise sources [14]. A compromise between the processing time and performance of the decentralized MCANC algorithms is to adopt a high sampling frequency. However, the high sampling frequency results in high computational complexity, due to the fact that the filter tap length is increased to maintain the frequency resolution.

In this paper, we propose to use the mixed-error approach to reduce the computational complexity, while achieving acceptable level of noise reduction in the MCANC system for open windows. The mixed-error approach simplifies the MCANC system to parallel single-channel feedforward ANC systems, whereby each single-channel feedforward ANC system takes the summed output of an error microphone array as the error signal [20]. The mixed-error approach has the merit of very low computational complexity as compared to the complete implementation of the MCANC system. When the summation of the error microphones' outputs is carried out by an analog mixer, the number of analog-to-digital convertors (ADCs) is also greatly reduced. There are previous works carrying out the mixed-error approach in feedback ANC systems [21–23]. It is of interest to compare the mixed-error approach with the mixed-reference approach, as in feedback ANC systems both approaches are coupled. However, in the MCANC system for open windows, the collocated implementation already uses only one reference signal in each channel. The mixed-reference approach cannot further reduce the computational complexity in the collocated implementation of the MCANC system. Furthermore, a weighted summation appears to be a more generic theoretical framework for such mixed-error and mixed-reference approaches [23], since the sensitivity of every microphone may not be exactly the same in practice.

2. MCANC algorithms

The MCANC system, shown in Fig. 2, includes I reference microphones, J secondary loudspeakers, and K error microphones, which is also called the $I \times J \times K$ MCANC system. The reference signal vector of the i-th reference microphone is denoted as

$$\mathbf{x}_i(n) = [x_i(n), x_i(n-1), \ldots, x_i(n-L+1)]^T, \tag{1}$$

where L is the tap length for both the control filters and secondary path models. The control filter that calculates the output of the j-th secondary loudspeaker based on the input from the i-th reference microphone is denoted as

$$\mathbf{w}_{ji}(n) = \left[w_{ji}^{(0)}(n), w_{ji}^{(1)}(n), \cdots, w_{ji}^{(L-1)}(n)\right]^T. \tag{2}$$

The output of the j-th secondary loudspeaker is denoted as

$$\mathbf{y}_j(n) = [y_j(n), y_j(n-1), \ldots, y_j(n-L+1)]^T, \tag{3}$$

where

$$y_j(n) = \sum_{i=1}^{I} \mathbf{w}_{ji}^T(n)\mathbf{x}_i(n). \tag{4}$$

Therefore, the error signal measured at the k-th error microphone is a summation of the noise and anti-noise signals as

$$e_k(n) = d_k(n) + \sum_{j=1}^{J} \mathbf{s}_{kj}^T \mathbf{y}_j(n), \tag{5}$$

where $d_k(n)$ is the noise signal received by the k-th error microphone. Moreover, the secondary path from the j-th secondary loudspeaker to the k-th error microphone is denoted as

$$\mathbf{s}_{kj} = \left[s_{kj}^{(0)}, s_{kj}^{(1)}, \ldots, s_{kj}^{(L-1)}\right]^T. \tag{6}$$

In order to update the control filters, the multi-channel FxLMS algorithm is adopted as

$$\mathbf{w}_{ji}(n+1) = \mathbf{w}_{ji}(n) - \mu \sum_{k=1}^{K} [e_k(n)\mathbf{r}_{kji}(n)], \tag{7}$$

where the filtered reference signal vector is written as

$$\mathbf{r}_{kji}(n) = [r_{kji}(n), r_{kji}(n-1), \ldots, r_{kji}(n-L+1)]^T. \tag{8}$$