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NEAR-FIELD ERROR SENSING OF MULTI-CHANNEL ACTIVE NOISE CONTROL USING VIRTUAL SENSING TECHNIQUE

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This paper proposes a near-field error sensing method for multi-channel feedforward active noise control (MCFFANC). The proposed method is particularly useful in applications such as the active noise canceling window that can mitigate noise passing through an open window. In MCFFANC, the classic multiple-error LMS algorithm is derived for minimizing the sum of the squared errors, which is an appropriate approximation of the noise power when the error microphones are placed in the far field. However, owing to the room reverberation, the error microphones are preferably placed in the near field. Therefore, there is a mismatch between the algorithms and applications of MCFFANC. Near-field error sensing methods are desired in MCFFANC. For such purposes, this paper extends the single-channel virtual sensing technique to the multiple-channel case. The effectiveness of the proposed method is validated by an experimental setup of the active noise canceling window. An improved global reduction of noise is confirmed at far-field observation points.

Keywords: acitve noise control, multiple-error LMS algorithm, minimax algorithm, virtual sensing

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1. Introduction

In the 1930s, Lueg was first granted the patent on the “process of silencing sound oscillations", where a reference signal was used to generate a secondary sound that interfered with the primary noise [1]. This idea is now widely referred to as the feedforward structure of the active noise control (ANC). The feedforward ANC is often adequate to deal with the broadband noise, while the other type of ANC, namely the feedback ANC, is more efficient in reducing the narrowband noise [2]. ANC systems can also be classified by the number of channels [3]. The single-channel ANC is mostly deployed for the local cancellation of noise, since the quiet zone is typically formed within one tenth of the noise wavelength from the error microphone [4]. The multi-channel ANC is considered when the control area is relatively large [5].

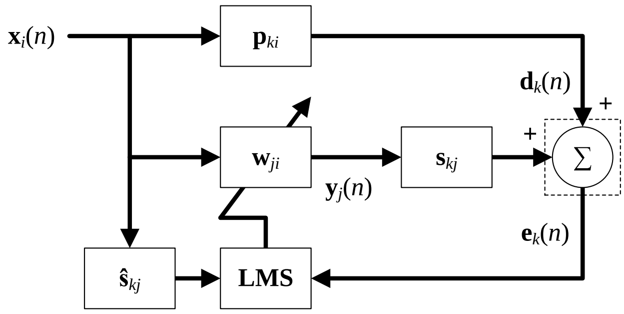

Figure 1: Block diagram of multi-channel feedforward active noise control.

The block diagram of a feedforward multi-channel ANC (FFMCANC) is shown in Fig. 1, consisting of *I* reference microphones, *J* secondary loudspeakers and *K* error microphones. Hence, this FFMCANC is also called a case (I, J, K) ANC system. $\mathbf{x}_i\,(n)$ and $\mathbf{y}_j\,(n)$ denote the reference signal vector of the *i*-th reference microphone and the control signal vector of the *j*-th secondary loudspeaker, respectively. The control filter $\mathbf{w}_{ji}\,(n)$ calculates the output of the *j*-th secondary loudspeaker based on the input from the *i*-th reference microphone. The error signal measured at the *k*-th error microphone is a summation of the primary noise and secondary sound as

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

where $d_k\,(n)$ is the noise signal received by the *k*-th error microphone; $*$ denotes the convolution; and the secondary path from the *j*-th secondary loudspeaker to the *k*-th error microphone is denoted as $\mathbf{s}_{kj}$. The multiple-error LMS (MELMS) algorithm updates the control filter coefficients by

$$\mathbf{w}_{ji}(n+1) = \mathbf{w}_{ji}\,(n) - \mu \sum_{k=1}^{K} e_k\,(n)\,\mathbf{x'}_{kji}\,(n), \tag{2}$$

where $\mathbf{x'}_{kji}\,(n) = \hat{\mathbf{s}}_{kj} * \mathbf{x}_i\,(n)$ is the filtered reference signal vector calculated based on the estimate of the secondary path $\hat{\mathbf{s}}_{kj}$ [6]. Hence, this algorithm is also called the multi-channel filtered-reference LMS (MCFxLMS) algorithm [7].

The MELMS or MCFxLMS algorithm minimizes the sum of the squared errors, which is an appropriate approximation of the noise power when the error microphones are placed in the far field [8]. However, many MCFFANC applications have to place the error microphones in the near field. For example, the noise canceling window distributes secondary loudspeakers across an open window to provide a quiet living environment while preserving the ventilation of the room [9]. According to Ise's boundary surface control principle, the active noise canceling window is feasible to generate an anti-noise field with inverted phase of the incidence noise field, so that the noise level in the room is globally reduced [10]. However, due to the room reverberation, the error microphones are preferably placed in the near field. Near-field error sensing methods are therefore desired in the noise canceling window, as well as in many other MCFFANC applications.

2. Multi-Channel Virtual Sensing Algorithm

Since 2015, Kajikawa's group has been working on a novel virtual sensing technique for single-channel and binaural ANC systems [11, 12]. This virtual sensing technique has different versions for feedforward and feedback ANC [13, 14]. In this paper, the single-channel virtual sensing technique for feedforward ANC is extended to the multi-channel case.

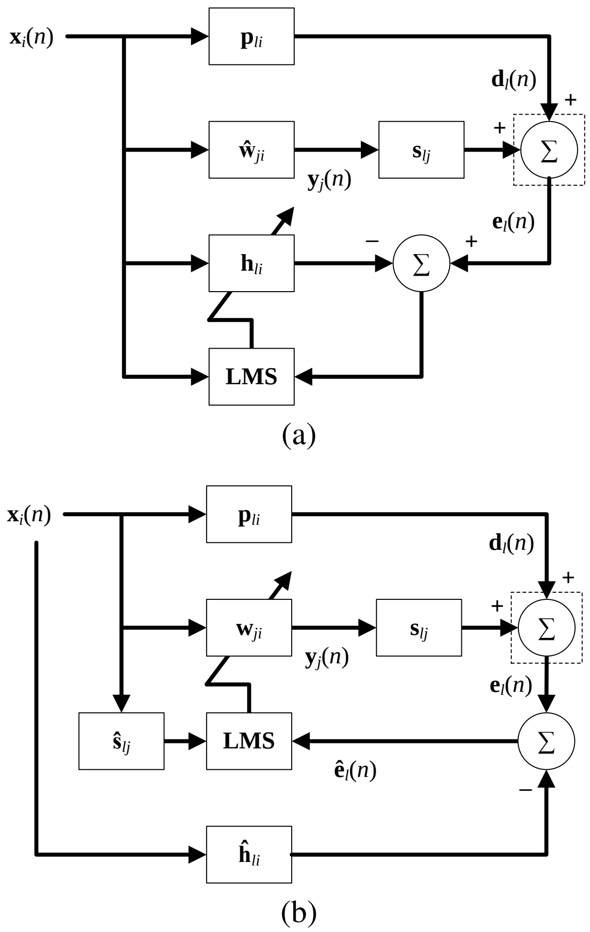

Figure 2: (a) Training the auxiliary filters in a multi-channel feedforward active noise control system; (b) training the control filters in a multi-channel feedforward active noise control system with pre-trained auxiliary filters.

As shown in Fig. 2, there are two stages in the multi-channel virtual sensing technique. The first stage is called the training stage. The control filters are converged to the optimal solution $\hat{\mathbf{w}}_{ji}$ when the far-field error signals are taken by the ANC controller. Those control filters lead to residual errors of the near-field error microphones, which are written as

$$e_l\left(n\right) = d_l\left(n\right) + \sum_{j=1}^{J} \mathbf{s}_{lj} * \hat{\mathbf{w}}_{ji} * \mathbf{x}_i\left(n\right). \tag{3}$$

Therefore, a group of auxiliary filters are trained to predict the residual errors based on the reference signals by

$$\mathbf{h}_{li}(n+1) = \mathbf{h}_{li}\left(n\right) + \mu' \left[e_l\left(n\right) - \sum_{l=1}^{K} \mathbf{h}_{li}\left(n\right) * \mathbf{x}_i\left(n\right) \right] \mathbf{x}_i\left(n\right), \tag{4}$$

where μ' is the stepsize of the LMS algorithm.

The second stage is called the control stage. In the control stage, the far-field error microphones are not taken by the ANC controller. The near-field error signals are preprocessed as

$$\hat{e}_l\left(n\right) = e_l\left(n\right) - \hat{\mathbf{h}}_{li} * \mathbf{x}_i\left(n\right). \tag{5}$$

The control filters will converge to generate the desired residual errors of the near-field error microphones by

$$\mathbf{w}_{ji}(n+1) = \mathbf{w}_{ji}(n) - \mu \sum_{l=1}^{K} \hat{e}_l(n) \mathbf{x}'_{lji}(n), \tag{6}$$

where $\mathbf{x}'_{lji}(n) = \hat{\mathbf{s}}_{lj} * \mathbf{x}_i(n)$ is the filtered reference signal vector calculated based on the estimate of the secondary path $\hat{\mathbf{s}}_{lj}$. The control stage can also be understood as active sound profiling or active noise equalization, while the purposes are different [15, 16].

3. Experimental Validation

An experimental setup of the active noise canceling window is built up as shown in Fig. 3. The primary noise source is enclosed in a cubic ($60 \times 60 \times 60$ cm^3). There is an opening on one side of the cubic. The size of the opening is 20×20 cm^2. Four secondary loudspeakers are distributed on the opening. The spacing between the secondary loudspeakers is 12.5 cm. Every 4 error microphones placed at the same distance from the opening surface are grouped together. In total, there are six groups of the error microphones.

In this experiment, the error microphones at a distance of 13 cm are referred to as the far-field error microphones. This is recommended in the design of the active noise canceling window [9]. Moreover, the error microphones at distances of 5 and 8 cm are chosen as the near-field error microphones for comparison. The rest of the error microphones are used to evaluate the global noise reduction performance.

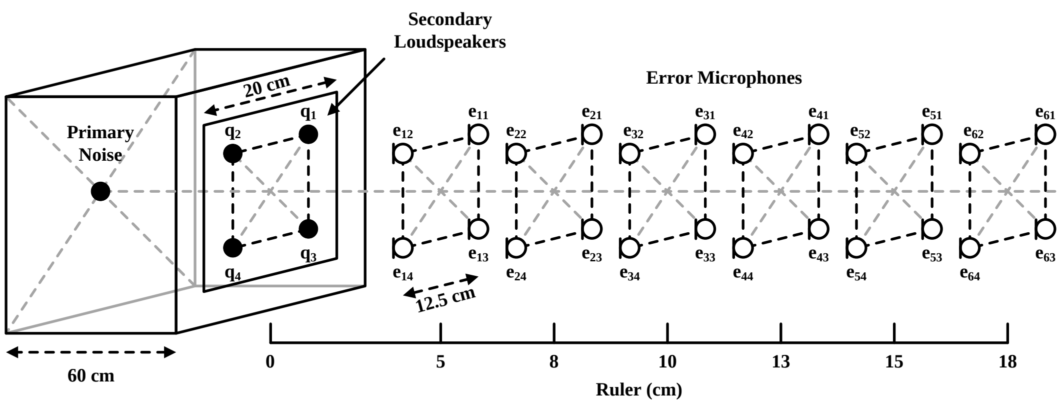

Figure 3: Experimental setup of a 4-channel active noise canceling window.

The sampling frequency of the ANC controller is 16 kHz. The primary noise is band-limited, ranging from 200 Hz to 2000 Hz. The secondary path models and control filters have the lengths of 200 and 400 taps, respectively. The auxiliary filters have the lengths of 200, 300 and 400 taps for comparison. The duration of each test lasts for 24 seconds.

Figure 4 shows the results when the error microphones placed at a distance of 5 cm are used as the near-field error microphones. Firstly, the observations are made at 5 cm. Without virtual sensing, the near-field error microphones lead to the best local noise reduction, while far-field error microphones lead to significant residual errors. When the virtual sensing technique is applied, the residual errors becomes closer to that of the far-field error microphones. The auxiliary filters are considered to have been accurately trained, when its length is 400 taps.

When the observations are made at 13 cm, the best local noise reduction is obtained by the far-field error microphones. The virtual sensing technique cannot achieve the same performance even with 400-tap auxiliary filters. Consequently, there are small gaps between the global noise reduction achieved by the near-field error microphones with virtual sensing technique and the global noise reduction achieved by the far-field error microphones. However, when the length of the auxiliary filters is 400 taps, the performance difference is almost negligible. The effectiveness of the proposed multi-channel virtual sensing technique is hence confirmed.

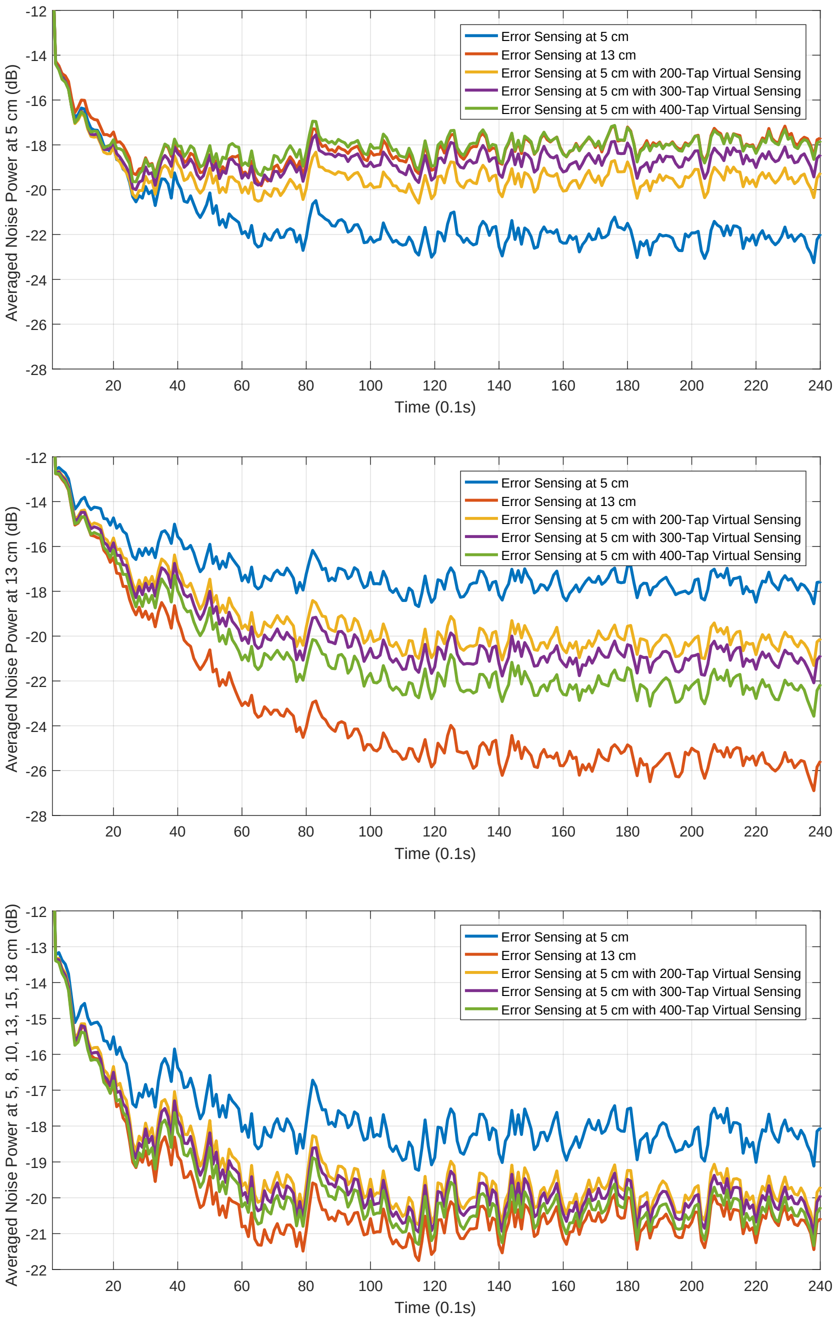

Figure 4: Comparative results when the error microphones are placed at a distance of 5 cm are chosen as the near-field error microphones.

Figure 5 shows the results when the error microphones placed at a distance of 8 cm are used as the near-field error microphones. In this case, the near-field error microphones are relatively closer to the far-field error microphones. When the observations are made at 8 cm, the performance difference between the near-field error microphones without virtual sensing and the far-filed error microphones is not so great as that in Fig. 4. Similarly, when the virtual sensing technique is applied, the residual errors are closer to that of the far-field error microphones. When the observations are made at 13 cm, the gaps between the local noise reductions of the near-field error microphones with virtual sensing technique and the local noise reduction of the far-field error microphones are still notable. However, when the length of the auxiliary filters is 400 taps, the near-field error microphones with the help of the virtual sensing technique can slightly outperform the far-field error microphones in terms of the global noise reduction.

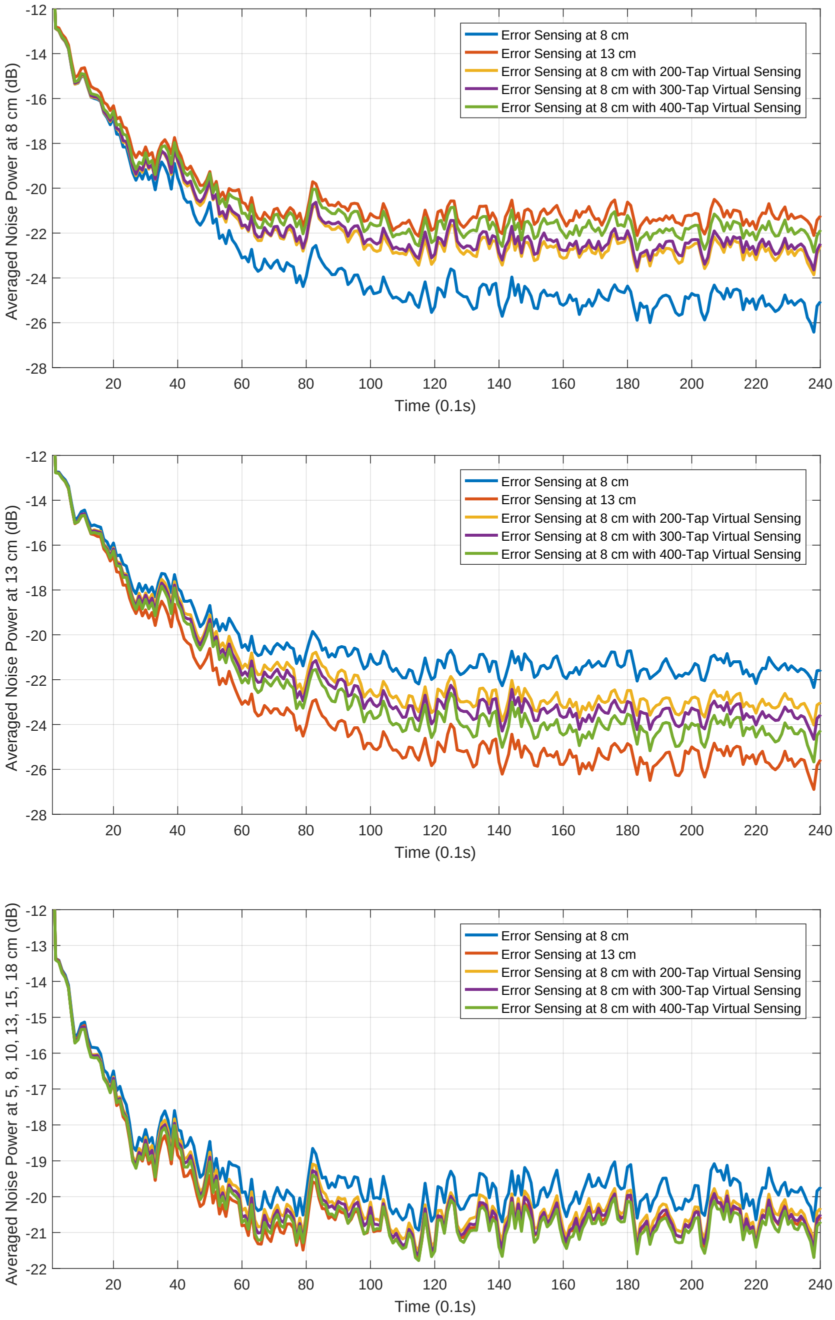

Figure 5: Comparative results when the error microphones are placed at a distance of 5 cm are chosen as the near-field error microphones.

4. Conclusions

This paper develops the near-field error sensing method for MCFFANC by introducing the multi-channel virtual sensing technique. In an experimental setup of the active noise canceling window, the proposed multi-channel virtual sensing technique is able to match the residual errors of the far-field error microphones when only near-field error microphones are taken by the ANC controller. However, the local noise reduction measured at the locations of the far-field error microphones are generally not reproducible by the near-field error microphones. Eventually, the near-field error microphones can be used with the virtual sensing technique to achieve equivalent global noise reductions as compared to the far-field error microphones.

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