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Virtual sensing technique for a multi-reference and multi-error active noise control system

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ABSTRACT

This paper investigates the virtual sensing technique for a multi-reference and multi-error active noise control (ANC) system. Our previous study has validated the effectiveness of virtual sensing technique for the multi-channel feedforward ANC system with only one reference signal. In this paper, two reference signals are implemented. The numbers of control filters and auxiliary filters are doubled accordingly. A comparison is carried out between the condition when 4 physical error microphones are used to model 8 virtual error microphones and the condition when 8 physical error microphones are used to model 4 virtual error microphones. It is demonstrated that when the number of physical error microphones are not less than the number of secondary loudspeakers, the virtual sensing technique remains effective.

Key word: Feedforward active noise control; Multi-channel active noise control; Virtual sensing

1. INTRODUCTION

Generally, there are two basic ways to abate noise. They are passive noise control (PNC) and active noise control (ANC) (1). PNC can reduce high-frequency noise efficiently. However, the efficiency of PNC decreases when the noise frequency is low, due to the relatively high cost and complexity in deployment. ANC utilizes loudspeakers to generate an anti-noise wave, which has the same amplitude and opposite phase of the noise wave. By doing so, ANC is ideally suited to reduce low-frequency noise, complementing PNC (2).

The use of microphones in ANC systems classifies them into two categories. The ANC systems using microphones to collect both reference and error signals are called feedforward ANC systems. In contrast, the ANC system using microphones to provide merely the error signals is called a feedback ANC system. In the feedback ANC system, reference signals are thought to be calculated based on error signals and internal models (3). Feedforward ANC systems are better at reducing broadband noise and easier to be stabilized than feedback ANC systems (4).

ANC systems are also categorized by the number of loudspeakers, namely secondary loudspeakers. When one secondary loudspeaker is deployed, often together with one reference microphone and one error microphone at the same time, the ANC system is called a single-channel ANC system. The active noise control headphone is the most successful application of the single-channel ANC system, whereby one ANC system is in charge of each individual ear drum. When the targeted zone of quiet (ZoQ) is relatively large as compared with the noise wavelength, multi-channel ANC systems are necessary, which may include multiple secondary loudspeakers as well as multiple microphones. Thus, this paper will be focusing on the multi-channel feedforward ANC system.

The filtered-x least mean squares (FxLMS) is the most widely used adaptive algorithm in ANC systems (5). The multi-channel version of FxLMS algorithm is also called the multiple error algorithm (6). The goal of FxLMS algorithm is to minimize 2-norm of error signal vector, which includes instant samples from all the error microphones. This is to ensure that ZoQ is formed around error microphones. When error microphones cannot be placed permanently in the targeted ZoQ, *i.e.* the targeted ZoQ is far away from error microphones, remote sensing or virtual sensing technique becomes necessary (7, 8).

The virtual sensing technique was originally proposed for a single-channel feedback ANC system and subsequently developed for a single-channel feedforward ANC system (9, 10). In 2018, it was extended to run with a multi-channel feedforward ANC system (11, 12). However, the validation was carried out with just one reference signal. In this paper, multiple reference microphones are considered to further understand the performance of virtual sensing technique for feedforward ANC systems.

2. VIRTUAL SENSING TECHNIQUE

There are two stages when virtual sensing technique is applied. The first stage is called the training stage. In this stage, temporal microphones, which are also called virtual error microphones, can be placed in the targeted ZoQ in order for adaptive control filters to converge. Meanwhile, auxiliary filters are trained to estimate error signals of microphones that are placed far from the ZoQ. Those error microphones are called physical error microphones.

The second stage of virtual sensing technique is called the control stage. Without any microphones placed in the targeted ZoQ, adaptive control filters converge again by minimizing the difference between error signals and estimates of error signals calculated with reference signals and pre-trained auxiliary filters. Compared with fix-coefficient control filters, the virtual sensing technique is likely to retain some adaptivity to the changes in the operating environment.

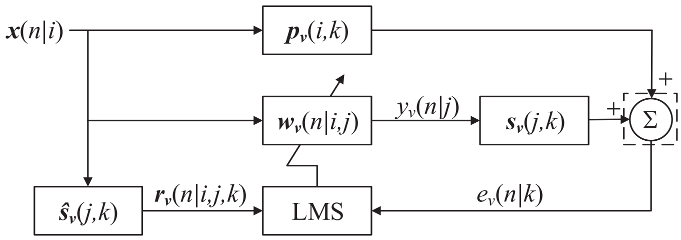

Figure 1 – Block diagram of multi-channel FxLMS algorithm

Figure 1 shows the block diagram of multi-channel FxLMS algorithm. In general, a feedforward multi-channel ANC system consists of I reference microphones, J secondary loudspeakers, and K error microphones. There are $I \times K$ primary paths, $I \times J$ control filters, and $J \times K$ secondary paths and secondary path models. $\boldsymbol{p_v}(i,k)$, $\boldsymbol{s_v}(j,k)$, and $\hat{\boldsymbol{s}}_{\boldsymbol{v}}(j,k)$ denote the primary path, secondary path, and secondary path model, respectively. i, j, and k indicate indices of the reference microphone, secondary loudspeaker, and error microphone, respectively.

At a discrete time n, the control signal is calculated as a dot product between the reference signal vector and the control filter coefficient vector, *i.e.*

$$y_v(n|j) = \sum_{i=1}^{I} \boldsymbol{x}(n|i) \cdot \boldsymbol{w_v}(n|i,j), \tag{1}$$

where $\cdot$ is the dot product operator; $y_v(n|j)$ is the output of the j-th secondary loudspeaker; $\boldsymbol{x}(n|i) = [x(n|i),\ x(n-1|i),\ \dots,\ x(n-L_w+1|i)]$ is the reference signal vector of the i-th reference microphone; and $\boldsymbol{w_v}(n|i,j)$ is the control filter coefficient vector for the j-th secondary loudspeaker and the i-th reference microphone. Moreover, L_w is the tap length of the control filter.

The so-called filtered-x signal is calculated as a dot product between the reference signal vector and the secondary path model, *i.e.*

$$r_v(n|i,j,k) = \sum_{l=1}^{Ls} \hat{s}_v(l|j,k) x(n-l+1|i), \tag{2}$$

where $\hat{s}_v(j,k)$ is the secondary path model for the j-th secondary loudspeaker and the k-th error microphone. L_s is the tap length of the secondary path model. The filtered-x signal vector is therefore given by $\boldsymbol{r_v}(n|i,j,k) = [r_v(n|i,j,k),\ r_v(n-1|i,j,k),\ \dots,\ r_v(n-L_w+1|i,j,k)]$.

According to the FxLMS algorithm, the control filter coefficient vector at the discrete time $n+1$ is updated by

$$\boldsymbol{w_v}(n+1|i,j) = \boldsymbol{w_v}(n|i,j) - \mu \sum_{k=1}^{K} e_v(n|k)\, \boldsymbol{r_v}(n|i,j,k), \tag{3}$$

where μ is the step size and $e_v(n|k)$ is the error signal of the k-th error microphone.

In the training stage of virtual sensing technique, $\boldsymbol{p_v}(i,k)$ $\boldsymbol{s_v}(j,k)$, and $\hat{\boldsymbol{s}}_{\boldsymbol{v}}(j,k)$ are defined with respect to the virtual error microphones. Therefore, they are referred to as the virtual primary path, virtual secondary path, and virtual secondary path model in the latter part of this paper.

Figure 2 highlights the block diagram of the training stage for physical error microphones. $\boldsymbol{p}(i,m)$ and $\boldsymbol{s}(j,k)$ are the primary and secondary paths with respect to physical error microphones. $\hat{\boldsymbol{w}}_{\boldsymbol{v}}(i,j)$ is the fixed-coefficient control filter. The adaptive filter $\boldsymbol{h}(n|i,m)$ is called the auxiliary filter. The tap length of $\boldsymbol{h}(n|i,m)$ is denoted as L_h.

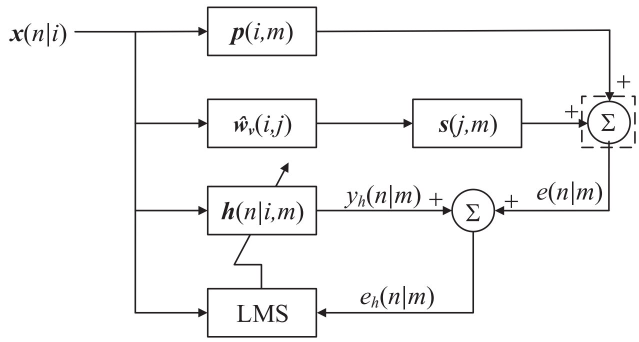

Figure 2 – Training stage of virtual sensing technique for a multi-channel feedforward ANC system

Error signals of physical error microphones are estimated by auxiliary filters based on reference signals. The output of an auxiliary filter is calculated as

$$y_h(n|m) = \sum_{i=1}^{I} \boldsymbol{x}(n|i) \cdot \boldsymbol{h}(n|i,m), \tag{4}$$

where $\boldsymbol{h}(n|i,m)$ is the auxiliary filter coefficient vector for the i-th reference microphone and the m-th physical error microphone.

According to the LMS algorithm, the auxiliary filter coefficient vector at the discrete time $n+1$ is updated by

$$\boldsymbol{h}(n+1|i,m) = \boldsymbol{h}(n|i,m) + \mu e_h(n|m)\boldsymbol{x}(n|i), \tag{5}$$

where $e_h(n|m) = y_h(n|m) + e(n|m)$; and $e(n|m)$ is the error signal of the m-th physical error microphone. When the training stage is complete, the trained auxiliary filter is denoted as $\hat{\boldsymbol{h}}$ and used as fixed-coefficient filters in the control stage (see Figure 3).

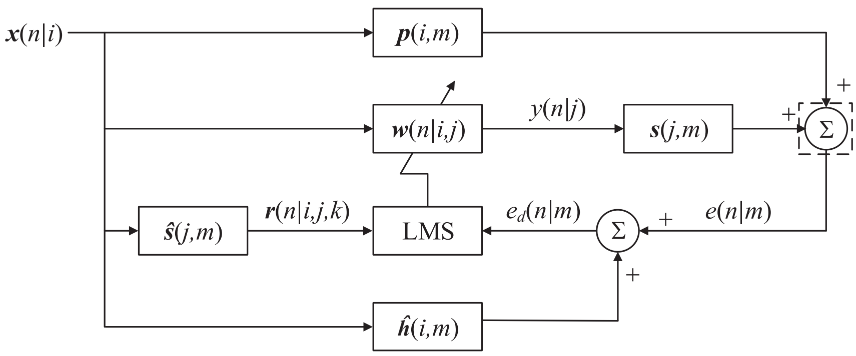

Figure 3 – Control stage of virtual sensing technique for a multi-channel feedforward ANC system

In Figure 3, the desired error signal $e_d(n|m)$ to update the control filter is constructed by

$$e_d(n|m) = e(n|m) + \sum_{i=1}^{I} \boldsymbol{x}(n|i) \cdot \hat{\boldsymbol{h}}(i,m). \tag{6}$$

And the filtered-x signal vector $\boldsymbol{r}(n|i,j,m)$ is calculated by,

$$\boldsymbol{r}(n|i,j,m) = \sum_{l=1}^{LS} \hat{s}(l|j,m)x(n-l+1|i). \tag{7}$$

With the desired error signal, the control filter coefficient vector at the discrete time $n+1$ is updated by

$$\boldsymbol{w}(n+1|i,j) = \boldsymbol{w}(n|i,j) - \mu \sum_{k=1}^{K} e_d(n|m)\, \boldsymbol{r}(n|i,j,m). \tag{8}$$

3. EXPERIMENTAL VALIDATION

The primary and secondary paths are provided by a multiple-channel ANC experiment system shown in Figure 4. Two primary noise loudspeakers are placed in a cube. The two primary broadband noises are uncorrelated and with frequency bands from 300Hz to 1300Hz and from 500Hz to 1100Hz, respectively. The secondary loudspeakers are fixed on the opening of the cube. Distance between two neighboring secondary loudspeakers is 12.5 cm. Three layers of microphones are placed outside the cube. They can be flexibly set up as either physical or virtual error microphones. Each layer consists of four microphones. The distance between two neighboring microphones is 12.5 cm too. The sampling frequency is set to 48kHz. Tap lengths of control filter $\boldsymbol{w}(i,j)$ and auxiliary filter $\boldsymbol{h}(i,m)$ are set to 800 taps. The secondary models have a length of 200 taps. The duration of each adaptation is limited to 30 seconds.

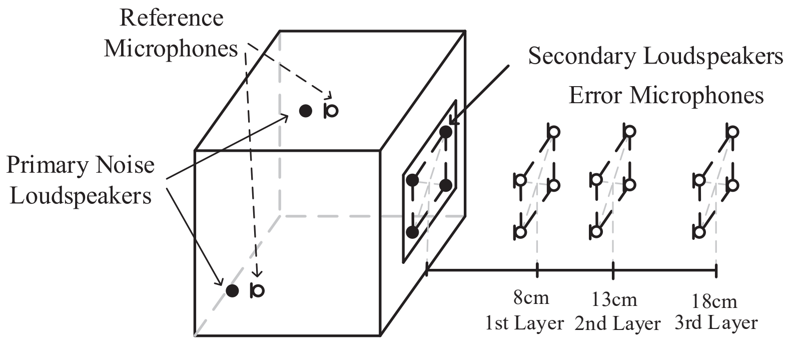

Figure 4 – Multiple-channel ANC experiment system

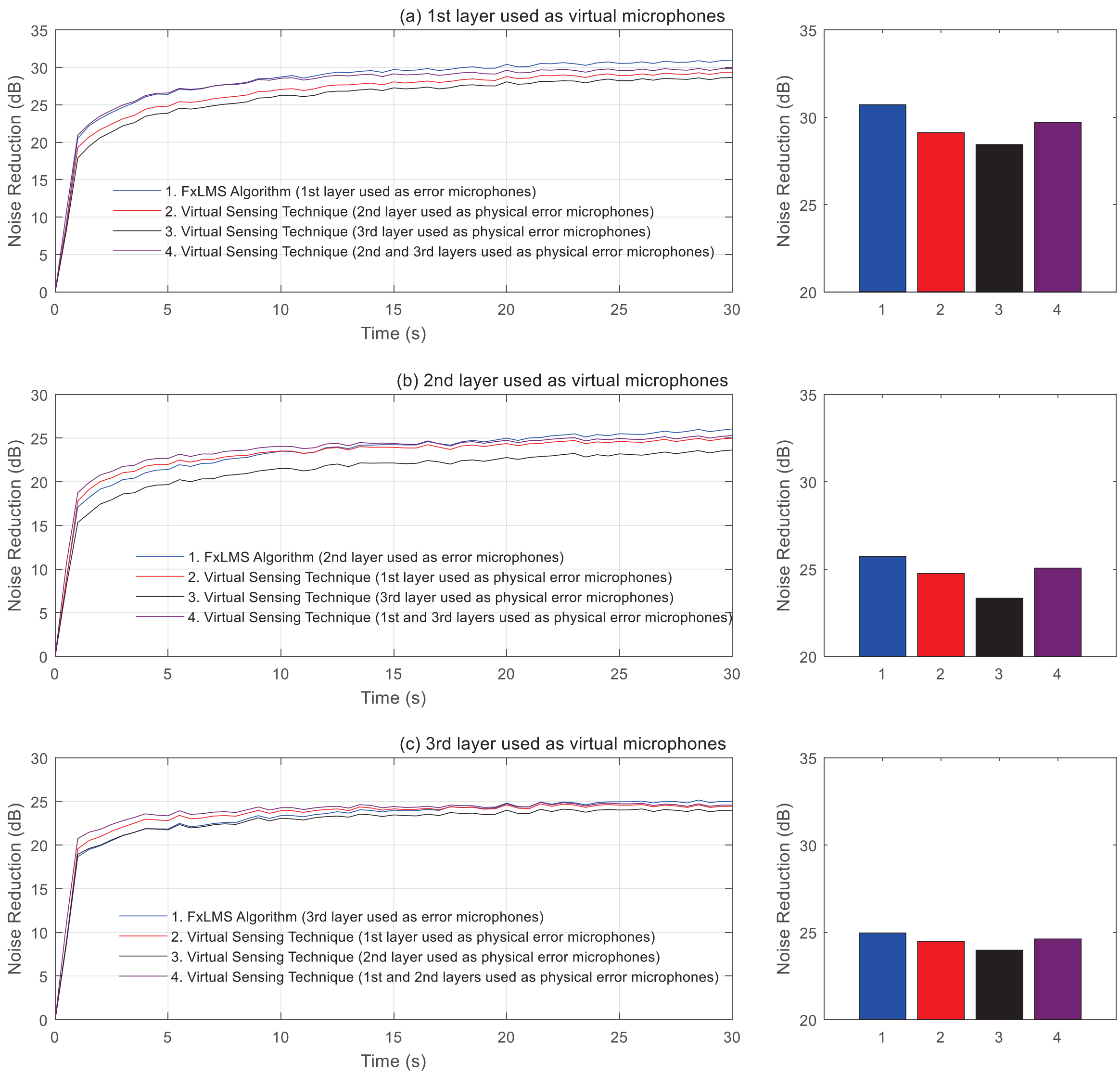

Figure 5 – Comparison of noise reduction performance when there are 4 to 8 physical error microphones and 4 virtual error microphones.

Firstly, microphones in one layer is selected as virtual error microphones. Microphones in the other two layers are wholly or separately used as physical error microphones. The baseline performance is provided by the FxLMS algorithm when error microphones are placed in the targeted ZoQ. The noise reductions of virtual sensing technique are compared among different selections of physical error microphones.

Figure 5(a) demonstrates the case when microphones in the first layer are set up as virtual error microphones. The noise reduction is improved when more physical error microphones are used, *i.e.* microphones in both the second and third layers. The same trend is also observed in Figures 5(b) and 5(c), when microphones in the second and the third layers are configured as virtual error microphones, respectively.

In general, Figure 5 confirms the effectiveness of virtual sensing technique when two reference signals are involved and the positions of physical error microphones have a significant influence on the final noise reduction performance. Using more physical error microphones in the virtual sensing technique can achieve noise reductions closer to the baseline level with the trade-off of increased computational cost. Furthermore, stopping the adaption earlier may result in the observation that virtual sensing technique is more effective in noise reduction than the FxLMS algorithm.

Figure 6 evaluates the cases when there are 8 virtual error microphones. As there are only 4 secondary loudspeakers in the experiment setup, the noise reduction is expectedly lower. The virtual sensing technique is proved to result in similar levels of noise reduction as compared to the standard FxLMS algorithm with error microphones placed in the ZoQ.

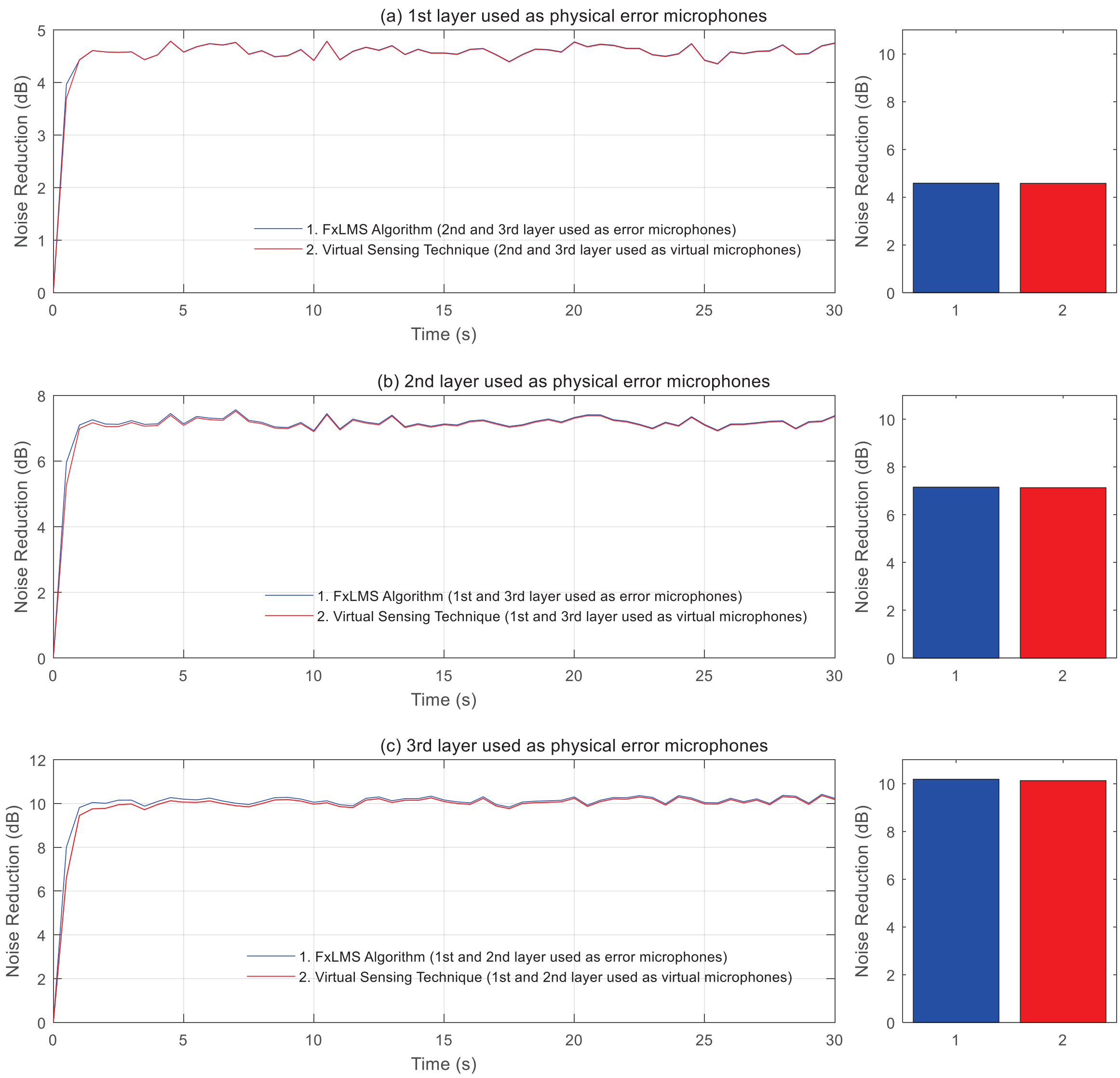

Figure 6 – Comparison of noise reduction performance when there are 4 physical error microphones and 8 virtual error microphones.

Furthermore, Figure 7 shows the comparative results when virtual sensing technique is carried out with different numbers of physical microphones. Figure 7(a) presents the case when microphones in the third layer are considered as virtual error microphones and microphones in the first layer are used wholly or partially as physical error microphones. If one microphone is removed from the first layer, the virtual sensing technique results in a reduced noise reduction level. If more physical microphones are removed, the noise reduction performance worsens. Figure 7(b) exhibits the case when microphones in the first layer are set up as virtual error microphones and microphones in the third layer are used wholly or partially as physical error microphones. In this case, when less than 4 physical error microphones are used, the noise reduction performance of virtual sensing technique is not satisfactory. Lastly, when microphones in both the second and third layers are configured as virtual error microphones, the number of physical error microphones in the first layer barely affects the noise reduction as shown in Figure 7(c). This is due to the fact that the baseline level of noise reduction is relatively low.

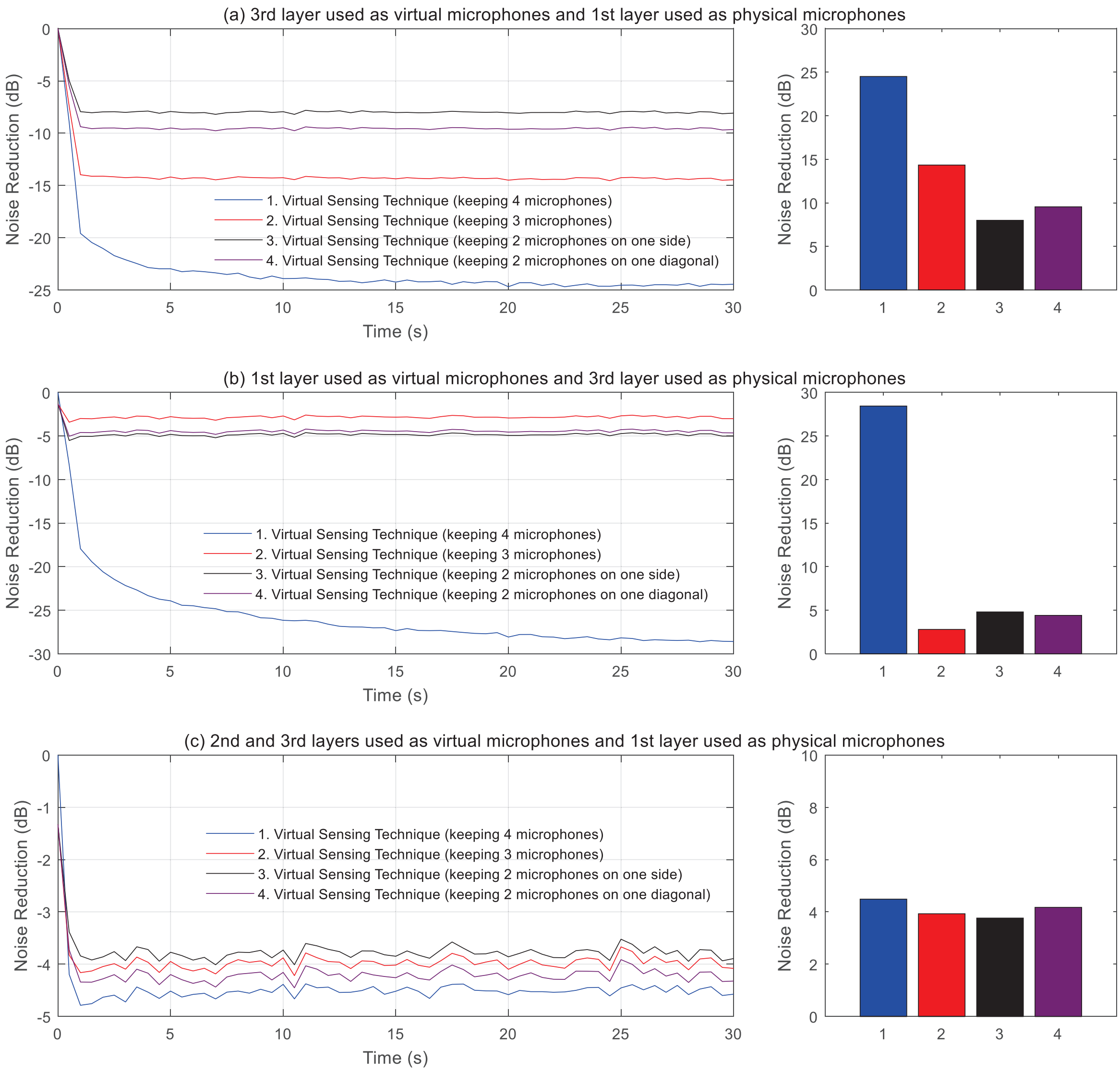

Figure 7 – Comparison of noise reduction performance when there are 2 to 4 physical error microphones and 4 virtual error microphones.

4. CONCLUSIONS

This paper validates the effectiveness of virtual sensing technique for multi-channel feedforward ANC systems. It has been proved that the virtual sensing technique works compatibly with multiple reference signals. Moreover, the increased number of virtual error microphones has no adverse effect on the performance of virtual sensing technique. However, the number of physical error microphones has to be greater than the number of secondary loudspeakers. When there are more secondary loudspeakers than physical error microphones, the multi-channel ANC becomes an underdetermined optimization problem with arbitrary solutions.

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