Comparison of Virtual Sensing Techniques for Broadband Feedforward Active Noise Control

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***Abstract*—Active noise control (ANC) is one of noise reduction techniques based on the acoustic wave superposition. When an anti-noise wave with the same amplitude and opposite phase of the noise wave is generated from the secondary source, the sound pressure level of the unwanted acoustic noise can be reduced at the desired location, where an error microphone is placed to monitor the error signal and make the whole system a closed-loop control problem. The virtual sensing (VS) techniques are developed for the situation when the error microphone cannot be placed at the desired location due to the application constraint or physical limitation. In this paper, we compare two virtual sensing techniques for reducing the broadband noise. They are the remote microphone (RM) method and the auxiliary filter based virtual sensing (AF-VS) method. The former estimates the transfer function from an error microphone location to the desired location, which has been validated to reduce the narrowband noise effectively. The latter preserves the information about the optimal noise control filter that can achieve the maximum noise reduction at the desired location. The experiment results demonstrate that the AF-VS method has more superior advantages for broadband noise reduction at the desired location than the RM method and has no limitations on the geometrical relationship between the error microphone location and the desired location.**

I. Introduction

Active noise control (ANC) utilizes the superposition property of acoustic waves to abate noise [1]–[3]. An anti-noise wave is transmitted purposely from the secondary source. When the anti-noise wave has the same amplitude and opposite phase as the unwanted acoustic noise wave, the acoustic noise level can be reduced at the desired location. An error microphone is necessarily placed there to monitor the error signal and form a closed-loop control in the overall system. ANC is classified into two control structures, i.e. feedforward and feedback control structures. In this paper, we focus on the feedforward control structure since it is more efficient for reducing the broadband noise.

Adaptive controllers are preferable in order for the ANC systems to adjust correspondingly to the environmental changes. The adaptive feedforward ANC usually requires reference microphones to obtain the reference signal that is correlated with the unwanted acoustic noise. The error microphones are used to measure the noise reduction performance and get the error signal used for the update of noise control filter. The filtered reference least mean squares (FxLMS) is the standard adaptive algorithm for updating. The secondary loudspeakers transmit anti-noise signals, which are the output of the noise control filter. The noise reduction area over 10 dB is called the zone of quiet (ZoQ). The ZoQ is readily formed around the error microphone.

When the error microphone and the desired location are not collocated, in order to create the ZoQ around the desired location not the error microphone location, the virtual sensing technique is generally utilized. The virtual sensing technique is roughly classified into three classes [4]. One of them is called the forward difference prediction technique, which fits a polynomial to the signals from a number of physical microphones in an array [5], [6]. However, this technique requires much space due to creating an array, so the applications are limited.

Another technique is based on estimates of the primary disturbances at the desired locations from the primary disturbances at the physical microphones [7]–[9]. This technique is called the remote microphone (RM) method and is effective for narrowband noise control. However, when the RM method is applied to reducing the broadband noise, the noise reduction performance may be degraded due to inaccurate estimate of the transfer function between the error microphone location and the desired location, because the dip occurs at specific frequencies even if the unwanted acoustic noise has flat frequency spectrum. In other words, when the signal picked up by the error microphone has some dips on the frequency spectrum, it is unlikely to get accurate estimate of the transfer function from the error microphone location to the desired location in that frequency band. The noise reduction performance of the RM method is therefore deteriorated for broadband noise. In addition, the RM method also has the geometrical arrangement constraint that the error (physical) microphone location must be closer to the noise source than the desired (virtual microphone) location. If the unwanted acoustic noise arrived at the desired location ahead of the error microphone location, the transfer function has non-causality and the noise reduction performance is consequently degraded.

The last technique is called the auxiliary filter based virtual sensing (AF-VS) method, which preserves the information related to the optimal noise control for the desired location [10]–[13]. This technique has greater advantages that the geometrical arrangement constraint is not occurred and the noise reduction performance is not affected by the dips involved in the signal picked up by the error microphone. Differing from the RM method, the AF-VS method does not require the transfer function from the error microphone location and the desired location. We have already applied the AF-VS method to several ANC applications (e.g. ANC headrest, ANC window, ANC pillow and so forth) for reducing both narrowband and broadband noises [14]–[18]. In this paper, we compare the noise reduction performance between the RM method and the AF-VS method experimentally. The experiment results demonstrate that the AF-VS method can realize higher noise reduction for broadband noise at the desired location than the RM method and has no limitations on the geometrical relationship between the error microphone location and the desired location.

This paper is organized as follows. Firstly, the restriction of the ZoQ in the ANC system is described. Next, the RM and the AF-VS methods are explained. After that, the basic noise reduction performance for broadband noise is examined for both methods. Moreover, the RM and the AF-VS methods are compared in the case of the non-causal geometrical arrangement. Finally, we conclude this paper and discuss on the future works.

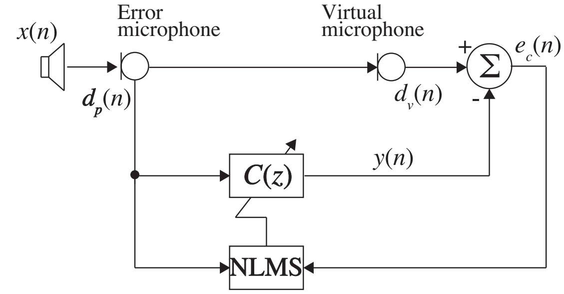
II. ZoQ Created by ANC

The ZoQ is achieved in the vicinity of the error microphone in the ANC system. The size of the ZoQ is known to be approximated by 1/10 of the wavelength of the noise wave around the error microphone in the single-channel ANC system and relatively larger in the multi-channel ANC system. Therefore, in the broadband feedforward ANC, the size of ZoQ strongly depends on the maximum frequency components and the number of channels of the ANC system. The shape of ZoQ strongly depends on the geometrical relationship among the noise source, the secondary source, and the error microphone [19]–[22]. The noise reduction cannot be sufficiently achieved if the desired location is apart from the error microphone location.

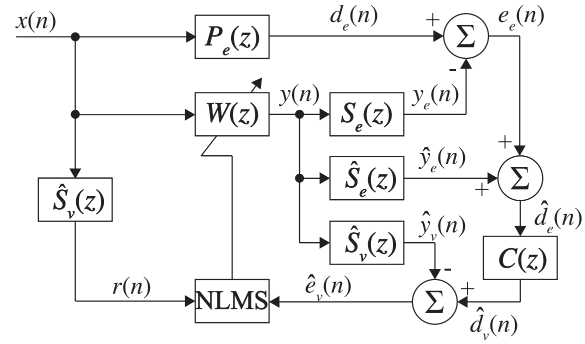
In some practical applications such as headrest ANC, pillow ANC, window ANC and so on, the error microphone has to be placed far from the desired location due to physical limitations. Hence, minimizing the output of the error microphone cannot guarantee an adequate noise reduction at the desired location. Consumer ANC systems such as the noise canceling headphone and ANC headrest aim to reduce the noise level around the ears of the listener. When the wavelength of the noise wave is of a sufficient length, placing the error microphone inside the headrest or pillow is acceptable, but when the noise contains noticeable power in the frequency range above 500 Hz, it is necessary to work out an ANC system that can realize the noise reduction at the desired location without placing the error microphone there.

III. Remote Microphone (RM) Method

Figure 1 shows the block diagram of the broadband feedforward ANC system using the RM method. $P_e(z)$ is the impulse response of the primary path from the reference microphone to the error microphone. $S_e(z)$ and $S_v(z)$ are the impulse responses of the secondary paths from the secondary source to the error microphone and the desired (virtual microphone) location, respectively. This system firstly estimates the path $C(z)$ from the error microphone to the virtual microphone placed at the desired location as shown in Fig. 1(a). Subsequently, as shown in Fig. 1(b), this system estimates the desired noise signal at the desired location by utilizing the path model $C(z)$. However, the noise reduction performance may be deteriorated by the dips occurring at the specific frequencies in the signals picked up by the error microphone and the virtual microphone for broadband noise. Moreover, when the virtual microphone is located closer to the noise source than the error microphone, the path $C(z)$ has non-causality. In this case, the path $C(z)$ is more difficult to be accurately modeled, and the noise reduction performance is dramatically degraded.



(a) Tuning stage

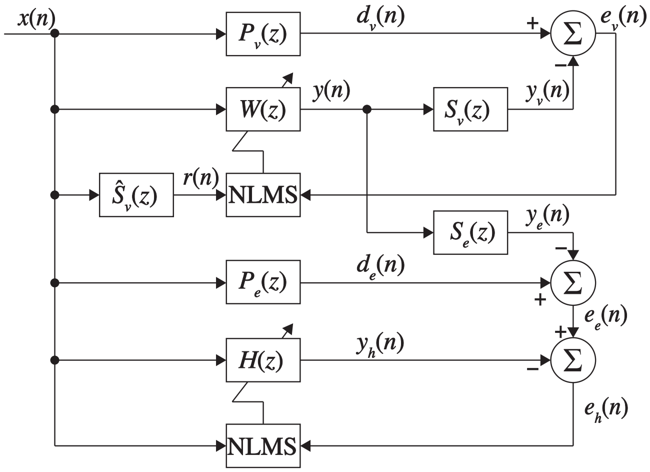


(b) Control stage

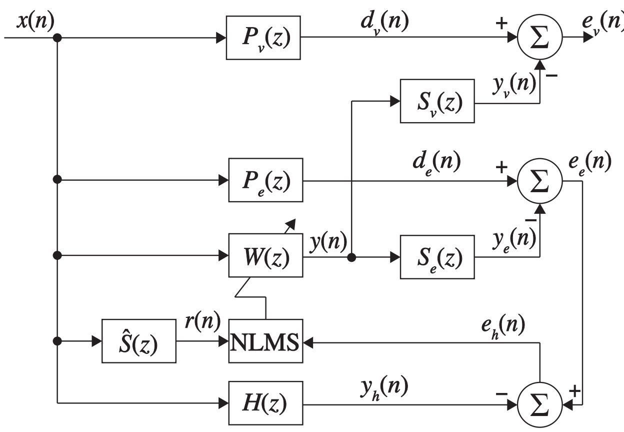
Fig. 1. Block diagram of broadband feedfoward ANC system with the remote microphone method. (a) Tuning stage. (b) Control stage.

IV. Auxiliary Filter based Virtual Sensing (AF-VS) Method

Figure 2 shows the block diagram of the broadband feedforward ANC system with the auxiliary filter based virtual sensing (AF) method, where $P_e(z)$ is the transfer function of the primary path from the reference microphone to the error microphone; $P_v(z)$ is the transfer function of the primary path from the reference microphone to the desired location; $S_e(z)$ is the transfer function of the secondary path from the secondary source to the error microphone; and $S_v(z)$ is the transfer function of the secondary path from the secondary source to



(a) Tuning stage

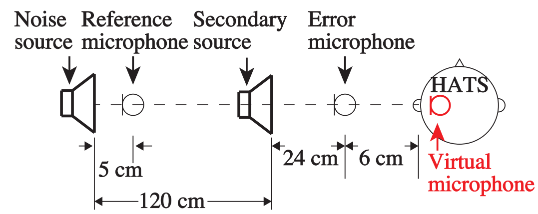


(b) Control stage

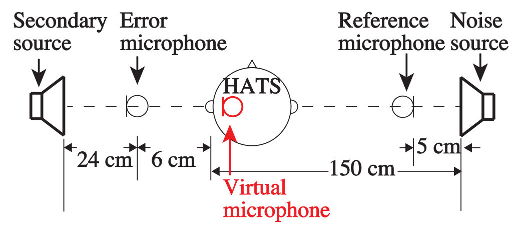
Fig. 2. Block diagram of broadband feedfoward ANC system with the auxiliary filter based virtual sensing method. (a) Tuning stage. (b) Control stage.

TABLE I
MEASUREMENT CONDITIONS.

Tap length of noise control filter W	400
Tap length of auxiliary filter H	400
Tap length of path model C	500
Tap length of secondary path model	100
Update algorithm	NLMS
Step size parameter	0.01
Regularization parameter	1.0×10^{-6}
Sampling frequency	12000 Hz
Cut-off frequency of analog low-pass filter	2500 Hz



(a) Causal arrangement



(b) Non-Causal arrangement

Fig. 3. Experimental arrangement. (a) Causal arrangement. (b) Non-Causal arrangement.

the desired location. This system achieves the optimum noise reduction at the desired (virtual microphone) location through tuning and control stages.

In the tuning stage, the auxiliary filter $H(z)$ converges to

$$H(z) = P_e(z) - \frac{S_e(z)P_v(z)}{S_v(z)} = P_e(z) - S_e(z)W_o(z), \quad (1)$$

where $W_o(z)$ represents the optimal noise control filter that can realize the maximum noise reduction at the desired location. Hence, the auxiliary filter $H(z)$ can preserve the information of the optimal noise control filter.

In the control stage, the error signal $e_e(n)$ picked up by the error microphone is modified by the output of the auxiliary filter $H(z)$. The z-transform of the modified error signal $e_h(n)$ is given by

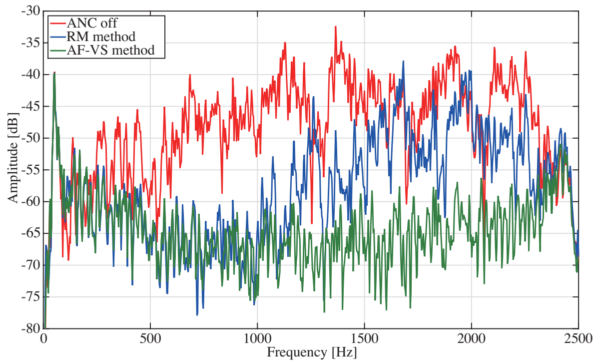
$$\begin{aligned} E_h(z) =& E_e(z) - H(z)X(z) \\ =& \left[\frac{P_v(z)}{S_v(z)} - W(z)\right] S_e(z)X(z). \end{aligned} \quad (2)$$

Hence, the noise control filter $W(z)$ converges to the optimal solution $P_v(z)/S_v(z)$. The maximum noise reduction can hence be realized at the desired location without placing the physical microphone there.

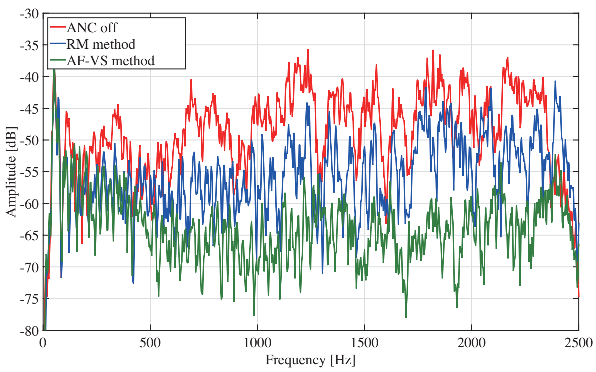
V. EXPERIMENTAL RESULTS

In this section, we examine the noise reduction performance of the broadband feedforward ANC with the RM and the AF-VS methods by experiments. The experimental parameters are listed in Table I and the experimental arrangements are illustrated in Fig. 3. There are two arrangements: (1) the causal arrangement and (2) the non-causal arrangement. The secondary paths are offline identified by a white noise excitation. The primary source plays back another white noise at a sound pressure level of 80 dB calibrated at the desired location (microphone inside the HATS). The noise reductions are measured at the desired location.

As a comparison of the noise reduction performance, the frequency spectra of the residual noise at the desired location are shown in Fig. 4. It can be seen from Fig. 4 that the AF-VS method can realize higher noise reduction than the RM method in the both (causal and non-causal) arrangements. Moreover, it can be seen that the noise reduction performance of the RM method is largely deteriorated in the frequency band from 1200 to 2000 Hz in the causal arrangement. Based on this fact, we focus on the deterioration of the noise reduction performance in the frequency band from 600 to 1200 Hz



(a) Causal arrangement



(b) Non-causal arrangement

Fig. 4. Comparison of the noise reduction performance between the RM and the AF-VS methods. (a) Causal arrangement. (b) Non-Causal arrangement.

for the non-causal arrangement. The average deterioration of the noise reduction level of the RM method is 7.32 dB. On the other hand, the noise reduction performance of the AF-VS method rarely changes, and the average deterioration of the noise reduction performance is only 2.24 dB. Therefore, we confirm that the AF-VS method can achieve better noise reduction performance than the RM method, regardless of the geometrical arrangements.

VI. Conclusion

In this paper, two virtual sensing techniques for the broadband feedforward ANC system with the virtual sensing technique were compared by experiments. The RM method estimated the transfer function from the error microphone location to the desired location and the AF-VS method utilized the auxiliary filter to preserve the optimal noise control filter information. In the experiment, two geometrical arrangements, i.e. causal and non-causal arrangements were examined. Experimental results demonstrated that the AF-VS method obtained higher noise reduction over the whole testing frequency band than the RM method. Moreover, the AF-VS method was not affected by the geometrical arrangements. In the future, we will examine the performance of the AF-VS method when head movements occur.

Acknowledgment

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