Effect of Cross-Channel Control Filters in Multi-Channel Feedback Active Noise Control

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***Abstract*—This paper investigates the effect of the cross-channel control filters in the multi-channel feedback active noise control (MCFBANC) system. The simulation is carried out with 2 control sources, 2 error microphones and 4 noise sources distributed near the error microphones. All the acoustic paths are measured in a real environment. The noise reduction performance of the MCFBANC system is examined with the tonal, narrow-band and broad-band noises. The simulation results indicated that when there is no cross-channel control filter, the individual reference signal estimate and the mixed reference signal estimate lead to similar noise reduction levels, which decrease when the frequency band of the primary noise broadens. By contrast, the MCFBANC system with the cross-channel control filters implemented can get much higher noise reduction level, when dealing with the broad-band noise.**

I. Introduction

Active noise control (ANC) is a complemental technique to the passive noise control (PNC) [1]. Together, they can make a quiet living environment. The PNC system targets at isolating the noise source, blocking the propagation path, and protecting the listener, by applying structures and materials that diffract and absorb the noise wave. The ANC system utilizes electro-acoustic devices to transmit an anti-noise wave that has the same amplitude and opposite phase as those of the noise wave, in order for the wave superposition to result in a trivial residual sound pressure level [2].

ANC systems are categorized by their control structures into the feedforward, feedback and hybrid ANC systems [3], [4]. The feedforward ANC system requires reference microphones to provide the input of the control filter. When the coherence between the reference signal and the error signal is high, the feedforward ANC system is likely to have good noise reduction performance. The feedforward ANC system is therefore adopted in the situation when the noise source is clearly recognized. The feedback ANC system consists of control sources and error microphones. The reference signal is estimated from the error signal by certain means, e.g. the internal model method. When the auto-correlation of the error signal is high at a sufficiently large delay, the feedback ANC system is efficient to reduce the noise level even though the noise sources are complicated. Therefore, the feedback ANC system is always believed to work with the narrowband noise.

The noise canceling headphone is the most successful ANC application nowadays. On each side of the headphone, a single-channel ANC system is implemented. The single-channel ANC system consists of just one control source and results in a relatively small zone of quiet. When the target zone of quiet is large, multi-channel ANC systems are necessarily carried out [5], [6], [7]. To the best of our knowledge, there is an ambiguity about the MCFBANC system. Taking the 2×2 MCFBANC system as an example, we notice that a simplified structure with only one control filter in each channel has widely been applied [8], [9], [10], [11]. In certain cases, the primary noise is not even tonal [12]. The effect of the cross-channel control filter has not been elaborated [2], [13], [14].

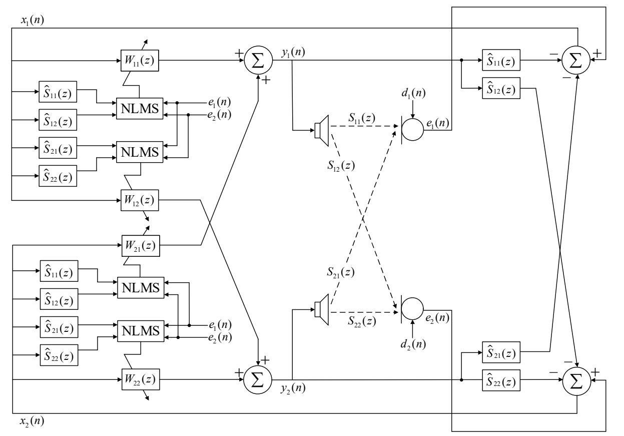

Fig. 1. Block diagram of the 2×2 MCFBANC system with the cross-channel control filters.

Therefore, this paper presents the investigation of two different system structures in the 2×2 MCFBANC system, with and without the cross-channel control filters. The simulation results show that when the bandwidth of the noise increases, the noise reduction performance is degraded in both system structures. However, the MCFBANC system with the cross-channel control filters obviously outperforms that without the cross-channel control filters in reducing the broad-band noise.

II. Theory and Method

The filtered-reference least mean squares (FxLMS) algorithm is well-known as the standard ANC algorithm [15], [16]. The feedforward version of the FxLMS algorithm is quite straightforward. The reference signal processed by the control filter and the secondary path model results in the control signal and the filtered-reference signal, respectively. The control signal is transmitted by the control source, resulting

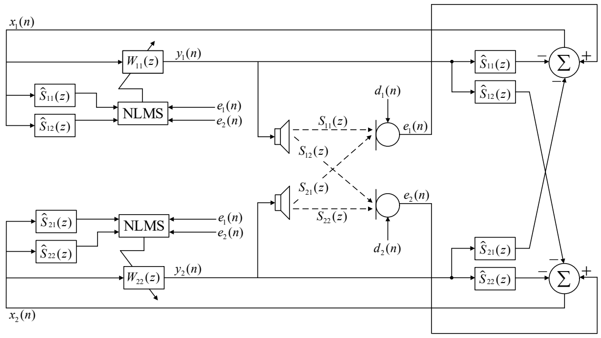

Fig. 2. Block diagram of the 2 × 2 MCFBANC system without the cross-channel control filters.

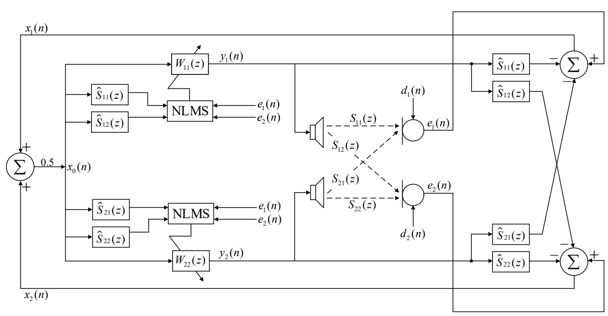

Fig. 3. Block diagram of the 2 × 2 MCFBANC system with the mixed reference signal estimate.

in the acoustic wave that is regarded as the anti-noise wave. The filtered-reference signal is regarded as the input of the least mean squares (LMS) scheme, in order for the control filter coefficients to be updated by iteration. However, in the feedback ANC system, there is no reference microphone to provide the reference signal. Therefore, estimates of reference signals are essentially carried out [17].

Figure 1 shows the block diagram of the 2×2 MCFBANC system with the cross-channel control filters. Individual estimates of the reference signal are generated from two error signals, which are written in a vector form as

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

where i is the index of the reference signal estimate; N is the memory size, depends on the length of the control filter N_w and the length of the secondary path model N_s.

The internal model control is one of the conventional methods to estimate the reference signal as

$$x_i(n) = e_i(n) - \sum_{j=1}^{2} \hat{\mathbf{s}}_{ji} * \mathbf{y}_j(n), \quad (2)$$

where $e_i(n)$ is the error signal of the ith error microphone at the time n; $\hat{\mathbf{s}}_{ji}$ is the secondary path model from the jth control source to the ith error microphone; $*$ denotes the convolution operation; and $\mathbf{y}_j(n)$ is the control signal vector

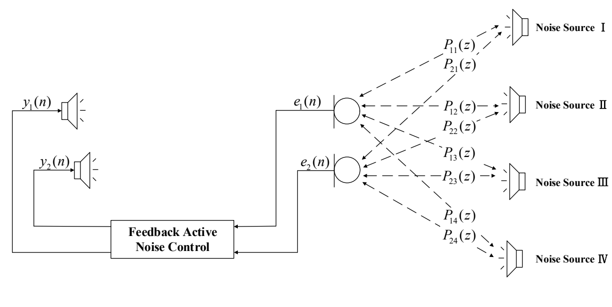

Fig. 4. Simulation configurations.

of the jth control source, of which the current sample is given by

$$y_i(n) = \sum_{j=1}^{2} \mathbf{w}_{ji}^{\mathbf{T}}(n)\, \mathbf{x}_j(n), \quad (3)$$

where the control filter coefficients at the time n are also written in a vector form $\mathbf{w}_{ji}(n)$. In the 2×2 MCFBANC system with the cross-channel control filters, the control filter coefficients are updated by

$$\mathbf{w}_{ji}(n+1) = \mathbf{w}_{ji}(n) - \mu \sum_{k=1}^{2} [\hat{\mathbf{s}}_{ik} * \mathbf{x}_j(n)]\, e_k(n), \quad (4)$$

where $i = 1$ or 2 is the index of the reference signal estimate; $j = 1$ or 2 is the index of the control source; and μ is the step size.

Figure 2 shows the block diagram of the 2×2 MCFBANC system without the cross-channel control filters. In this case, the control signal is given by

$$y_i(n) = \mathbf{w}_{ii}^{\mathbf{T}}(n)\, \mathbf{x}_i(n), \quad (5)$$

which relies only on the reference signal estimate of the same channel. Therefore, the number of control filters in the 2×2 MCFBANC system is reduced from 4 to 2. The control filter coefficients are updated by

$$\mathbf{w}_{ii}(n+1) = \mathbf{w}_{ii}(n) - \mu \sum_{k=1}^{2} [\hat{\mathbf{s}}_{ik} * \mathbf{x}_i(n)]\, e_k(n). \quad (6)$$

Instead of using the individual reference signal estimate, Fig. 3 shows the block diagram of the 2×2 MCFBANC system with the mixed reference signal estimate, which is written as

$$\mathbf{x}_0(n) = \frac{1}{2} \sum_{i=1}^{2} \mathbf{x}_i(n). \quad (7)$$

Therefore, the control signal and control filter coefficients are calculated respectively by

$$y_i(n) = \mathbf{w}_{ii}^{\mathbf{T}}(n)\, \mathbf{x}_0(n) \quad (8)$$

and

$$\mathbf{w}_{ii}(n+1) = \mathbf{w}_{ii}(n) - \mu \left[\sum_{k=1}^{2} e_k(n)\, \hat{\mathbf{s}}_{ik} \right] * \mathbf{x}_0(n). \quad (9)$$

In this case, the number of control filters in the 2×2 MCFBANC system remains to be 2 [19], [20].

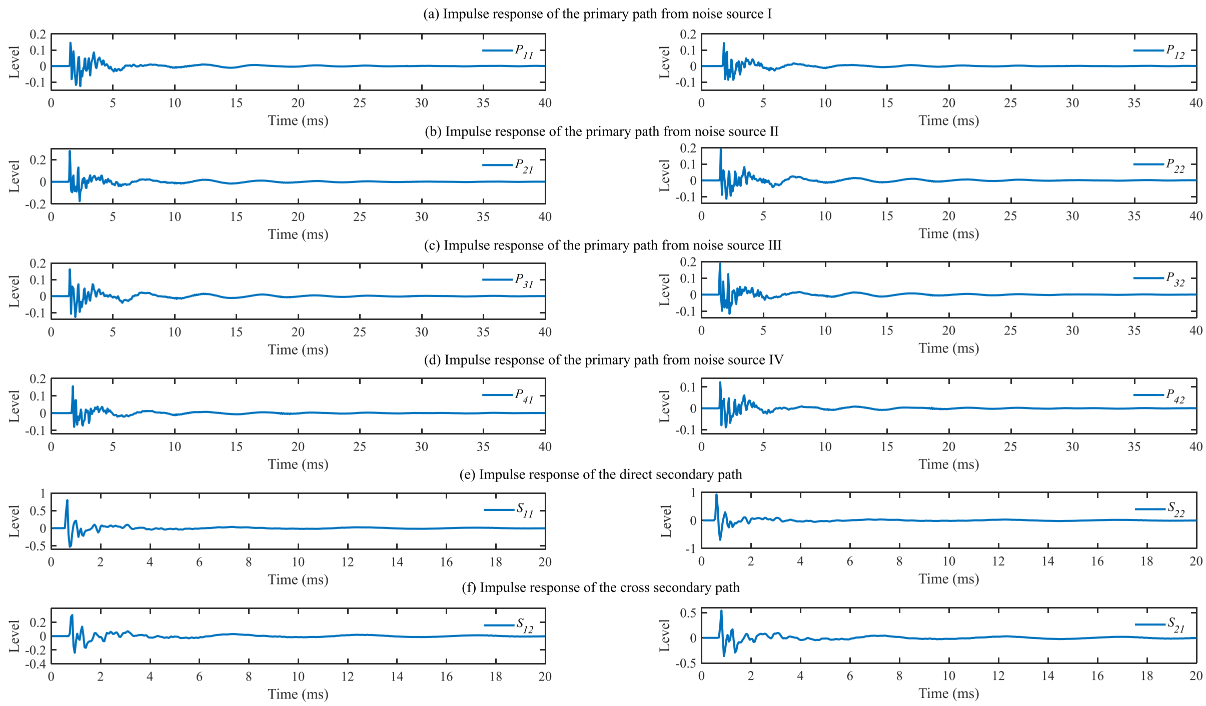

Fig. 5. Acoustic paths in the simulation.

Table 1. Simulation parameters.

Tap length of noise control filter (default setting)	400
Tap length of secondary path model	400
Tap length of primary path model	800
Update algorithm of noise control filter	FxLMS
Step size parameter of tonal noise	1.0E-06
Step size parameter of narrow-band noise	1.0E-05
Step size parameter of broad-band noise	1.0E-05
Sampling frequency	20 kHz

III. Simulation Results

Simulations are carried out with 4 noise sources distributed near the error microphones (see Fig. 4). The acoustic paths are measured in advance, including 8 primary paths and 4 secondary paths. They are shown in Fig. 5. The secondary path model is assumed to be exactly the same as the secondary path. The parameters applied in the simulation are listed in Table 1. The primary noise is set to be tonal, narrow-band and broad-band noise in sequence.

Figure 6 shows the simulation results when each noise source generates a sinusoidal tone at a different frequency, resulting in both error signals consisting of four tones at 500 Hz, 600 Hz, 700 Hz and 800 Hz. The 2×2 MCFBANC system without the cross-channel control filters can achieve the same noise reduction level as that with the cross-channel control filters. When using the individual reference signal estimate, the 2×2 MCFBANC system without the cross-channel control filters converges faster than that using the mixed reference signal estimate. Moreover, halving the length of the noise control filter does not affect the noise reduction level of the 2×2 MCFBANC system with the cross-channel control filters. Figure 7 shows the auto-correlation of the error signal received before the MCFBANC system is turned on. It clearly demonstrates that the primary noise is highly auto-correlated and even periodic. In this case, the cross-channel control filters can be removed to simplify the MCFBANC system. However, depending on the spectrum of the error signal, the individual reference signal estimate can outperform the mixed reference signal estimate.

Figure 8 shows the simulation results when each noise source generates a narrow-band noise at a different frequency band, resulting in both error signals' spectra ranging from 400 Hz to 600 Hz. The 2×2 MCFBANC system with the cross-channel control filters obtains over 6 dB more noise reduction than those without the cross-channel control filters. Halving the length of the noise control filter reduces the noise reduction level of the 2×2 MCFBANC system by less than 1 dB. Moreover, using the mixed reference signal estimate can get slightly better noise reduction performance than using the individual reference signal estimate, when the 2×2 MCFBANC system does not include the cross-channel control filters. Figure 9 shows the auto-correlation of the error signal received before the MCFBANC system is turned on. It

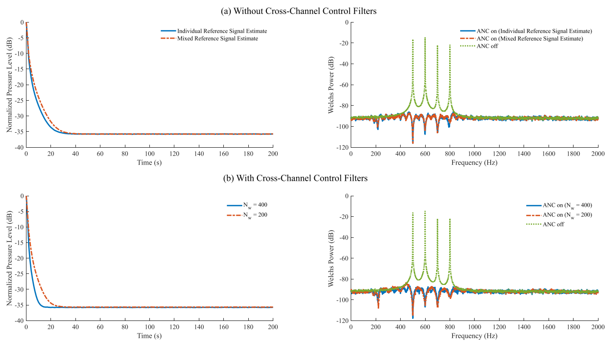

Fig. 6. MCFBANC system performance when the primary noise is tonal.

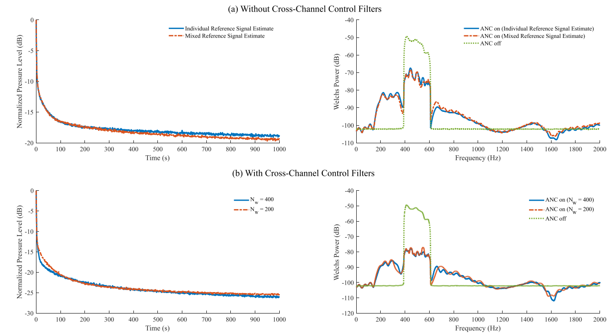

Fig. 8. MCFBANC system performance when the primary noise is a narrow-band noise.

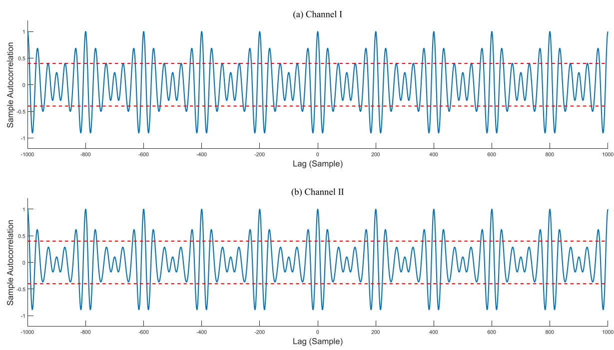

Fig. 7. Auto-correlation of the error signal consisting of four tones at 500, 600, 700 and 800 Hz.

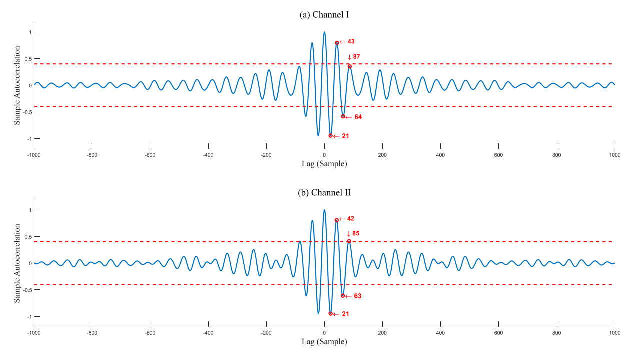

Fig. 9. Auto-correlation of the error signal resulted from a narrow-band noise ranging from 400 Hz to 600 Hz.

demonstrates that the primary noise is considered to be highly auto-correlated when the delay is less than 85 samples. In this case, the cross-channel control filters can improve the noise reduction performance of the MCFBANC system. With the halved length of the control filter, the total number of control filter coefficients in the 2×2 MCFBANC system with the cross-channel control filters remain the same as that without the cross-channel control filters.

Figure 10 shows the simulation results when each noise source generates a narrow-band noise at a different frequency band, resulting in broad-band error signals. Their spectra range from 400 Hz to 1200 Hz. The 2×2 MCFBANC system with the cross-channel control filters obtains about 6 dB more noise reduction than those without the cross-channel control filters. Halving the length of the noise control filter reduces the noise reduction level of the 2×2 MCFBANC system by over 1 dB. Moreover, using the mixed reference signal estimate can get a lower noise reduction level than using the individual reference signal estimate, when there is no cross-channel control filter in the 2×2 MCFBANC system. Figure 11 shows the auto-correlation of the error signal received before the MCFBANC system is turned on. It demonstrates that the primary noise is considered to be highly auto-correlated when the delay is less than 93 samples in one channel, while less than 13 samples in another channel. In this case, the channel with higher auto-correlation leads to better noise reduction performance. The cross-channel control filters can improve the noise reduction performance of the MCFBANC system when the primary noise is a broad-band noise. It is also worth noting that when dealing with the broad-band noise, the feedback ANC system boosts up the frequency components outside the target frequency band due to the existence of the floor noise in the simulation.

IV. Conclusions

The effect of the cross-channel control filters in the MCFBANC system is highlighted in this paper. The MCFBANC systems with and without the cross-channel control filters are compared in the cases of the tonal, narrow-band and broad-band noises. When the auto-correlation of the error signal is high with a sufficiently large delay, the cross-channel control filters can be removed to simplify the implementation of the MCFBANC system. The choice between the individual reference signal estimate and the mixed reference signal estimate should be decided with consideration to the spectrum of the error signal. However, as the frequency band of the primary

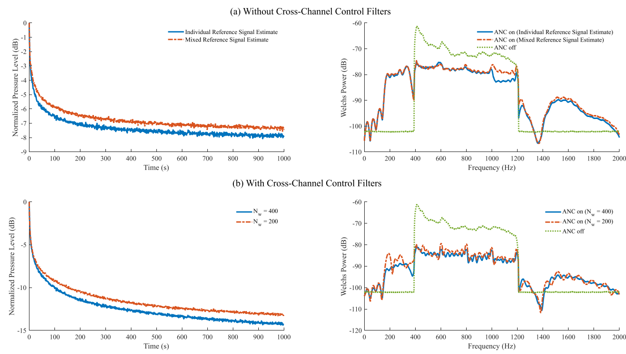

Fig. 10. MCFBANC system performance when the primary noise is a broad-band noise.

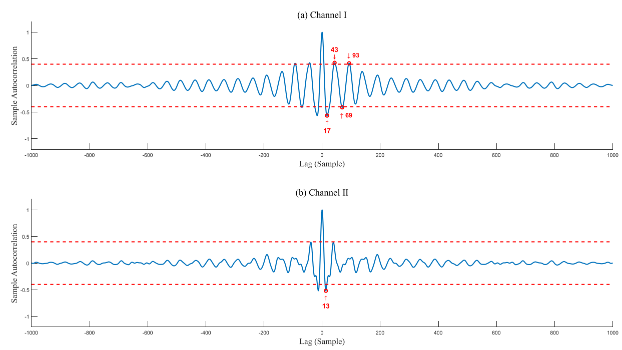

Fig. 11. Auto-correlation of the error signal resulted from a narrow-band noise ranging from 400 Hz to 1200 Hz.

noise broadens, the necessarily of the cross-channel control filters strengthens. Even when the length of the control filter is halved, the MCFBANC system with the cross-channel control filters still outperforms that without the cross-channel control filters.

Acknowledgment

This manuscript is prepared based on the research work supported by Civil Aviation Administration of China (Joint Grant No. U1933127), National Natural Science Foundation of China (Grant No. 61701090 and 61671137), and Sichuan Science and Technology Program (Project No. 2019YJ0182 and 2018JY0218).

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