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CROSSTALK-RESISTANT THREE-CHANNEL NOISE CANCELLER

Akihiro Hirano, Kenji Nakayama, Shin'ya Arai

Faculty of Engineering, Kanazawa University
40-20, Kodatsuno 2-Chome, Kanazawa, 920-8667, JAPAN
e-mail:{hirano,nakayama}@t.kanazawa-u.ac.jp

ABSTRACT

This paper proposes two crosstalk-resistant three-channel adaptive noise cancellers (ANC's) for two independent noise sources. Signal distortion by a signal-to-reference crosstalk is reduced by the first ANC, while the second ANC cope with a long impulse response caused by a noise-to-reference crosstalk. Computer simulations show smaller signal distortion by almost 20dB for a signal-to-reference crosstalk. Eight times faster convergence and 30% reduction of computational cost are achieved for a noise-to-reference crosstalk case.

1. INTRODUCTION

Extracting desired signals from noise-corrupted signals is important in communication systems and sound recording. Adaptive noise cancellers (ANC's)[1] are widely used to reduce such noise. Most ANC's use two microphones: the primary microphone for the noise-corrupted signals, and the reference microphone for the noise. For multiple noise sources, multi-channel ANS's with three or more microphones are necessary.

In two-channel ANC's, the desired signal components captured by the reference microphone, known as a "crosstalk[2]," is an important problem. For two-channel ANC's, crosstalk-resistant ANC's has been proposed [2, 3]. Such crosstalk also appears in multi-channel ANC's, however, in tow different ways. The first case is a signal-to-reference crosstalk, which is the same as the two-channel case. The second case is a noise-to-reference crosstalk, in which a reference microphone captures noises from two or more sources.

Blind source separation (BSS)[4] is a possible candidate for multi-channel noise cancellation. However, the learning of a multi-channel BSS becomes difficult even for instantaneous mixture[5]. The permutation problem caused by the signal power imbalance[5], the implementation of non-linear functions, and the slower convergence speed than ANC's are also difficult problems.

This paper proposes two crosstalk-resistant three-channel ANC's for two independent noise sources. Section 2 proposes an ANC which reduces the signal distortion caused by a signal-to-reference crosstalk. Section 3 investigates the influence of a noise-to-reference crosstalk and show that the impulse response becomes very long when the crosstalk becomes strong. A novel ANC with fast convergence and less computational complexity is also described. Computer simulations have been carried out to show the performance of the proposed ANC's.

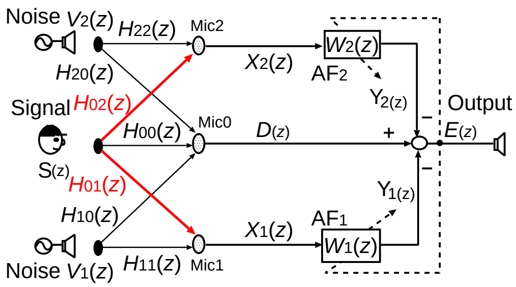


Fig. 1. 3-channel noise canceller in presence of signal-to-reference crosstalk.

2. SIGNAL TO REFERENCE CROSSTALK

2.1. Primitive Noise Canceller

Figure 1 depicts a simple extension of an ANC, "primitive ANC" in this paper, for two independent noise sources $V_1(z)$ and $V_2(z)$. The ANC output $E(z)$ is calculated by

$$\begin{aligned} E(z) &= (H_{00}(z) - H_{01}(z)W_1(z) - H_{02}(z)W_2(z))S(z) \\ &\quad +(H_{10}(z) - H_{11}(z)W_1(z))V_1(z) \\ &\quad +(H_{20}(z) - H_{22}(z)W_2(z))V_2(z) \end{aligned} \tag{1}$$

where $S(z)$ is a signal source, $H_{i,j}(z)$ is a transfer function from i-th source to j-th microphone Mic$i$, and $W_i(z)$ is a transfer function of an adaptive filter AFi. From (1), the optimum value for adaptive filters which cancel the noise are

$$W_1^{opt}(z) = \frac{H_{10}(z)}{H_{11}(z)}, \quad W_2^{opt}(z) = \frac{H_{20}(z)}{H_{22}(z)}. \tag{2}$$

Also, for distortion-free output, i.e., $E(z) = H_{00}(z)S(z)$, the adaptive filters should satisfy

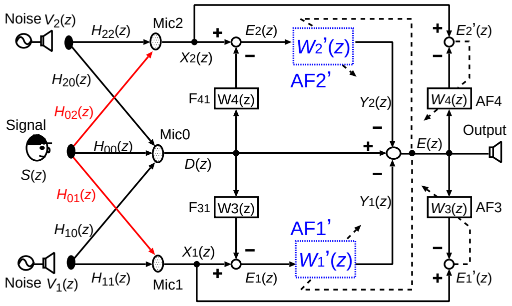
$$H_{01}(z)W_1(z) + H_{02}(z)W_2(z) = 0. \tag{3}$$

It is obvious that there are no solution which provide both noise-free and distortion-free output.

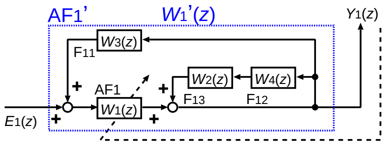
2.2. Proposed Noise Canceller

Figure 2 (a) demonstrates the proposed ANC which reduces the influence of the signal-to-reference crosstalk. Four filters F31, F41, AF3, AF4 are introduced. Filters F31 and F41 cancel crosstalk components from Mic0 output $D(z)$. The condition for crosstalk cancellation is

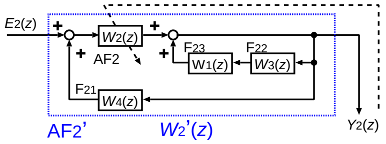
$$W_3^{opt}(z) = \frac{H_{01}(z)}{H_{00}(z)}, \quad W_4^{opt}(z) = \frac{H_{02}(z)}{H_{00}(z)} \tag{4}$$



(a) Structure



(b) Implementation of AF1'



(c) Implementation of AF2'

Fig. 2. Proposed noise canceller in presence of signal-to-reference crosstalk.

where $W_3^{opt}(z)$ and $W_4^{opt}(z)$ are the optimum transfer functions for F31 and F41, respectively.

Though it seems possible to estimate $W_3(z)$ and $W_4(z)$ by F31 and F41, the noise components $H_{10}(z)V_1(z)$ and $H_{20}(z)V_2(z)$ in $D(z)$ disturbs correct adaptation[3]. Using a noise-free output $E(z)$, the adaptive filters AF3 and AF4 can estimate the transfer functions $W_3(z)$ and $W_4(z)$, which are also used by F31 and F41.

Using the crosstalk-free noise signals $E_1(z)$ and $E_2(z)$, adaptive filters AF1' and AF2' successfully cancel noises. Their optimum transfer functions are

$$W_1'^{opt}(z) = \frac{\frac{H_{10}(z)}{H_{11}(z)}}{1-\frac{H_{10}(z)}{H_{11}(z)}W_3(z)-\frac{H_{20}(z)}{H_{22}(z)}W_4(z)} \quad (5)$$

$$W_2'^{opt}(z) = \frac{\frac{H_{20}(z)}{H_{22}(z)}}{1-\frac{H_{10}(z)}{H_{11}(z)}W_3(z)-\frac{H_{20}(z)}{H_{22}(z)}W_4(z)}. \quad (6)$$

Since these optimum value is too complicated, recursive structure shown in Fig. 2 (b) and (c) are used as AF1' and AF2'. The transfer functions of AF1' and AF2',

$$W_1'(z) = \frac{W_1(z)}{1-W_1(z)W_3(z)-W_2(z)W_4(z)} \quad (7)$$

$$W_2'(z) = \frac{W_2(z)}{1-W_1(z)W_3(z)-W_2(z)W_4(z)}, \quad (8)$$

have the same structure as (5) and (6). Only $W_1(z)$ and $W_2(z)$ should be estimated in AF1' and AF2' because $W_3(z)$ and $W_4(z)$ are already estimated by AF3 and AF4. Therefore, a simple adaptation algorithm for an FIR adaptive filter can be used. The optimum transfer functions for AF1 and AF2 are

$$W_1^{opt}(z) = \frac{H_{10}(z)}{H_{11}(z)}, \quad W_2^{opt}(z) = \frac{H_{20}(z)}{H_{22}(z)}, \quad (9)$$

which are simple and the same as the crosstalk-free case.

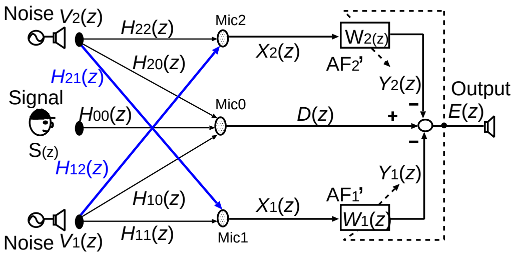


Fig. 3. 3-channel noise canceller in presence of noise-to-reference crosstalk.

3. NOISE TO REFERENCE CROSSTALK

3.1. Primitive Noise Canceller

This section concentrates on a noise-to-reference crosstalk case. As shown in Fig. 3, both Mic1 and Mic2 capture both $V_1(z)$ and $V_2(z)$. This is true if both Mic1 and Mic2 are located close each other.

In this case, the ANC output $E(z)$ is calculated by

$$\begin{aligned} E(z) &= H_{00}(z)S(z) \\ &+ (H_{10}(z)-H_{11}(z)W_1(z)-H_{12}(z)W_2(z))V_1(z) \\ &+ (H_{20}(z)-H_{21}(z)W_1(z)-H_{22}(z)W_2(z))V_2(z). \end{aligned} \quad (10)$$

As opposed to a signal-to-reference crosstalk case, we have an optimum solution which provides both noise-free and distortion-free output. The optimum transfer functions for AF1 and AF2 are derived as

$$W_1^{opt}(z) = \frac{H_{10}(z)H_{22}(z)-H_{12}(z)H_{20}(z)}{H_{11}(z)H_{22}(z)-H_{12}(z)H_{21}(z)} \quad (11)$$

$$W_2^{opt}(z) = \frac{H_{11}(z)H_{20}(z)-H_{10}(z)H_{21}(z)}{H_{11}(z)H_{22}(z)-H_{12}(z)H_{21}(z)}, \quad (12)$$

which look very complicated.

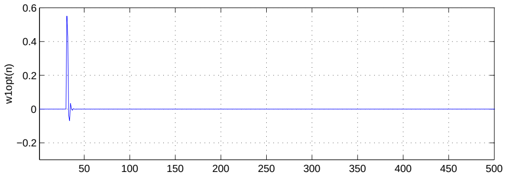
A numerical example demonstrates the influence of a noise-to-reference crosstalk. As unknown systems $H_{ij}(z)$, Butterworth low-pass filters $L_{ij}(z)$ with gain factors g_{ij} and flat delays k_{ij}

$$H_{ij}(z) = g_{ij}z^{-K_{ij}}L_{ij}(z) \quad (13)$$

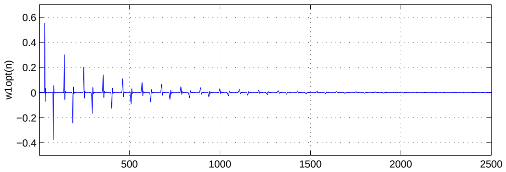
are used. The parameters are shown in Tab. 1. $H_{00}(z)$ is assumed to be 1. Figure 4 shows the impulse responses of AF1 with and without the noise-to-reference crosstalk. The differences are only the gain factors g_{12} and g_{21}, which are zero for crosstalk-free case and 0.9 for crosstalk case. The noise-to-reference crosstalk causes too long impulse response more than 1500 taps, while only 50 taps are sufficient for crosstalk-free case. Such a long impulse response degrades the convergence speed and increases the hardware size.

Table 1. Unknown systems for noise-to-reference crosstalk.

Unknown System	Order	Cutoff	Delay	Gain
$H_{10}(z)$	2	0.6	30	0.9
$H_{11}(z)$	2	0.8	0	1
$H_{12}(z)$	2	0.4	53	g_{12}
$H_{20}(z)$	2	0.65	23	0.9
$H_{22}(z)$	2	0.85	0	1
$H_{21}(z)$	2	0.45	53	g_{21}



(a) Without crosstalk



(b) With crosstalk

Fig. 4. Optimum filter coefficients.

3.2. Proposed Noise Canceller

In order to reduce the computational cost for a long impulse response, a recursive structure is introduced for adaptive filters. Figure 5 depicts the proposed ANC. Recursive filters AF1' and AF2' shown in Figs. 5 (b) and (c) are used. The transfer functions of AF1' and AF2' shown by

$$W_1(z) = \frac{A_1(z) - B_1(z)A_2(z)}{1 - B_1(z)B_2(z)} \tag{14}$$

$$W_2(z) = \frac{A_2(z) - A_1(z)B_2(z)}{1 - B_1(z)B_2(z)} \tag{15}$$

have the same structure as the modified version of the optimum transfer functions given by

$$W_1^{opt}(z) = \frac{\frac{H_{10}(z)}{H_{11}(z)} - \frac{H_{12}(z)}{H_{11}(z)}\frac{H_{20}(z)}{H_{22}(z)}}{1 - \frac{H_{12}(z)}{H_{11}(z)}\frac{H_{21}(z)}{H_{22}(z)}} \tag{16}$$

$$W_2^{opt}(z) = \frac{\frac{H_{20}(z)}{H_{22}(z)} - \frac{H_{10}(z)}{H_{11}(z)}\frac{H_{21}(z)}{H_{22}(z)}}{1 - \frac{H_{12}(z)}{H_{11}(z)}\frac{H_{21}(z)}{H_{22}(z)}}. \tag{17}$$

The optimum transfer functions for $A_i(z)$ and $B_i(z)$ are given by

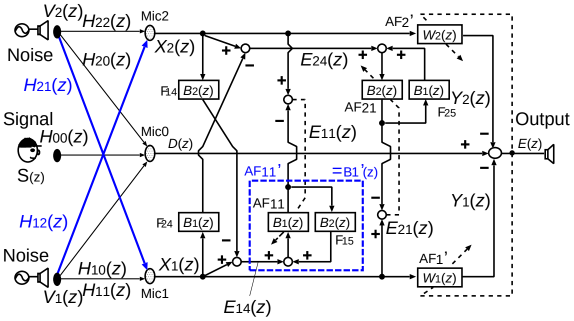
$$A_1^{opt}(z) = \frac{H_{10}(z)}{H_{11}(z)} \tag{18}$$

$$A_2^{opt}(z) = \frac{H_{20}(z)}{H_{22}(z)} \tag{19}$$

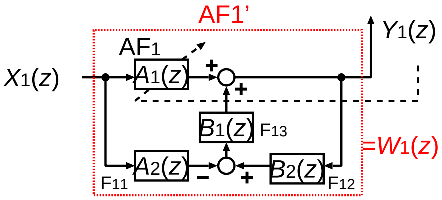
$$B_1^{opt}(z) = \frac{H_{12}(z)}{H_{11}(z)} \tag{20}$$

$$B_2^{opt}(z) = \frac{H_{21}(z)}{H_{22}(z)}, \tag{21}$$

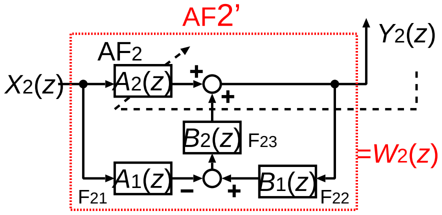
which are much simpler than (11) and (12).



(a) Structure



(b) Implementation of AF1'



(c) Implementation of AF2'

Fig. 5. Proposed noise canceller in presence of noise-to-reference crosstalk.

Table 2. Number of multiplications for ANC.

Type	Total	Exsample
Primitive	$4N$	3,200
Proposed	$6N_1 + 12N_2$	2,160

The filter coefficients of adaptive filters AF1 and AF2 are so updated as to simply reduce the output $E(z)$. Any algorithm for FIR adaptive filters can be used. The transfer functions $B_i(z)$ are estimated by separate filters, adaptive filters AF11 and AF21, filters F14, F15, F24 and F25 in Fig. 5 (a).

An adaptive filter AF11 and two filters F14 and F15 are used to estimate $B_1(z)$. Though F24 seems to estimate $B_1(z)$ using $E_{24}(z)$, $V_2(z)$ component in $X_1(z)$ disturbs the convergence to $B_1^{opt}(z)$[3]. Therefore, a two-stage estimation is introduced. In the first stage, F14 cancels $V_2(z)$ component from $X_1(z)$. The second stage estimates $B_1(z)$ by a recursive filter AF11', which consists of AF11 and F15.

3.3. Computational Cost

Though the computational cost seems to increase for the proposed ANC with a complex structure, the computational cost can be reduced. Table 2 compares the number of multiplications for the primitive and the proposed ANC's. As an adaptation algorithm, the normalized LMS (NLMS) algorithm[6] is assumed. N is the number of taps for the primitive ANC. For the proposed ANC, two

Table 3. Unknown systems for signal-to-reference crosstalk.

Unknown System	Order	Cutoff	Delay	Gain
$H_{01}(z)$	3	0.7	30	0.5
$H_{02}(z)$	3	0.75	23	0.5
$H_{10}(z)$	2	0.6	30	0.9
$H_{11}(z)$	2	0.8	0	1
$H_{20}(z)$	2	0.65	23	0.9
$H_{22}(z)$	2	0.85	0	1

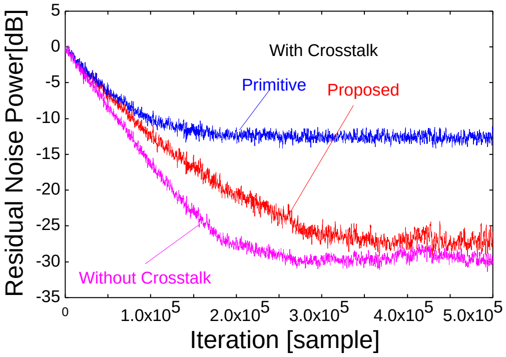


Fig. 6. Residual noise power for signal-to-reference crosstalk.

different length are used. N_1 is the number of taps for AF1, AF2, F11 and F21. N_2 is the number of taps for AF3, AF4, F12, F13, F14, F15, F22, F23, F24 and F25.

The number of multiplications for the primitive and the proposed ANC's are $4N$ and $6N_1+12N_2$, respectively. An numerical example for $N = 800$, $N_1 = 200$ and $N_2 = 80$, which is same as the computer simulations below, demonstrates the cost reduction by the proposed structure. Thanks to the efficient recursive structure, more than 30% reduction is achieved.

4. COMPUTER SIMULATIONS

Simulations have been carried out to show the performance of the proposed ANC's. Unknown systems $H_{ij}(z)$ are same as in (13). The parameters are shown in Tabs. 3 and 1 for a signal-to-reference and a noise-to-reference crosstalk case, respectively. Crosstalk gains g_{12} and g_{21} is 0.8. $H_{00}(z)$ is 1. The desired signal $S(z)$ and the noise sources $N_i(z)$ are independent white Gaussian signals.

As an adaptation algorithm, NLMS is used. For the signal-to-reference crosstalk case, the number of taps $N = 64$ and the step size $\mu = 0.001$ are used. In the noise-to-reference crosstalk case, $N = 800$ and $\mu = 0.01$ are used for the primitive ANC. For the proposed ANC, $N_1 = 200$ and $N_2 = 80$ are used. The step size parameters are chosen as $\mu_1 = 0.01$ for AF1 and AF2, $\mu_2 = 0.001$ for AF3 and AF4.

Figures 6 and 7 demonstrate the residual noise power and the signal distortion for the signal-to-reference crosstalk case, respectively. The proposed ANC improves both the residual noise power and the signal distortion by almost 20dB. The error power for the noise-to-reference crosstalk case is compared by Fig. 8. The proposed ANC converges eight times faster by 30% less computational cost. The signal distortion has not been examined because this crosstalk do not cause it.

5. CONCLUSION

Two crosstalk-resistant three-channel ANC's have been proposed. As crosstalk types, a signal-to-reference crosstalk and a noise-to-reference crosstalk are investigated. For the signal-to-reference crosstalk, an ANC which reduces the signal distortion caused by the crosstalk is proposed. In the noise-to-reference crosstalk case, it is shown that the impulse response becomes very long by the crosstalk. An ANC with fast convergence and less computational complexity is also proposed. Computer simulations show smaller signal distortion by almost 20dB for a signal-to-reference crosstalk. Eight times faster convergence and 30% reduction of computational cost are achieved for a noise-to-reference crosstalk case.

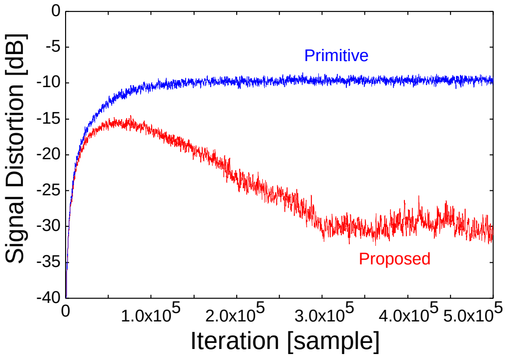


Fig. 7. Signal distortion for signal-to-reference crosstalk.

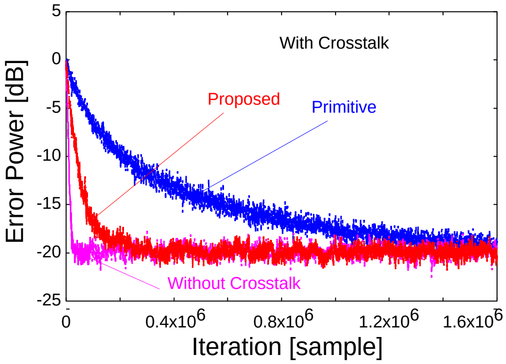


Fig. 8. Error power for noise-to-reference crosstalk.

6. REFERENCES

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