Journal of Information Hiding and Multimedia Signal Processing ©2015 ISSN 2073-4212
Ubiquitous International Volume **6**, Number **2**, March **2015**

A Hybrid Narrowband Active Noise Control System for Uncorrelated Narrowband Disturbance

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Received July, 2014; revised Octobe, 2014

Abstract. *Performance of the conventional narrowband active noise control (NANC) system may degrade severely when the uncorrelated narrowband disturbance noise is present in the system. In this paper, we propose a new hybrid NANC system capable of reducing the primary noise and the uncorrelated disturbance simultaneously. First, some simple analysis is used to show why the NANC system may indicate poor performance in the presence of the uncorrelated disturbance. Next, a new hybrid NANC is proposed to tackle this problem. The new system consists of three subsystems: 1) a conventional NANC subsystem to cancel the primary noise; 2) a feedback ANC (FANC) subsystem to cancel the uncorrelated narrowband disturbance; 3) an sinusoidal noise canceler (SNC) subsystem using adaptive notch filter of linear combination which is designed to remedy the problem of common error. Extensive simulations are conducted to demonstrate the proposed system can effectively mitigate such noise, and improves considerable the overall performance of the system.*
Keywords: FXLMS, Narrowband active noise control (NANC), Feedback ANC, Hybrid ANC, Convergence speed

1. **Introduction.** Active noise control (ANC) is a more effective technique for attenuating low-frequency noises where the passive noise control (PNC) techniques [1, 2] are either ineffective or increase the size, weight, volume and cost of the overall systems. Research of ANC has received considerable attention, and many system structures and adaptive algorithms and successful applications are developed during the past two decades [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. The theory of ANC is based on the principle of destructive interference of acoustic waves, where an antinoise of equal amplitude and opposite phase is generated and combined with the primary noise by an ANC system, resulting in the cancellation of both noises. In many practical ANC applications, the primary noise is periodic or nearly periodic generated by rotating machines, such as fans, compressors, and engines. These types of noises include multiple narrowband components and may be modelled as sinusoidal signals in the additive noise. The narrowband active noise control (NANC) [3, 4] system can effectively cancel such noise.

The block diagram of typical conventional NANC system in a duct is illustrated in Figure 1, where acoustic and signal processing regions are clearly distinguished. In acoustic region, an acoustic data acquisition system, including the nonacoustic sensor, microphone and loudspeaker, is used to obtain the measurement data from acoustic environment for the signal processing region. The nonacoustic sensor, such as a tachometer [4], could detect the fundamental frequency of the primary noise and generate synchronization signal which could trigger signal generator to produce the reference signal $x(n)$. The error

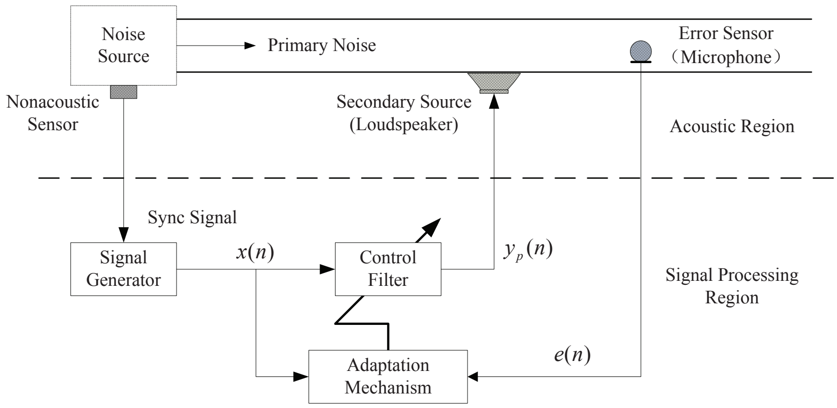

Figure 1. Block diagram of the conventional narrowband ANC (NANC) system in a duct (single-channel) that includes acoustic and signal processing regions.

sensor(microphone) is used to gather the residual signal $e(n)$. The loudspeaker is driven by $y_p(n)$ to produce anti-noise for mitigating primary noise. In signal processing region, a NANC controller, containing control filter and adaptive mechanism, is used to generate secondary source $y_p(n)$ and monitor the performance of the overall NANC system by adapting the filter coefficients automatically using the adaptive algorithm. A equivalent sampled-time block diagram of the conventional narrowband ANC (NANC) system with FXLMS algorithm is shown in Figure 2. The controller is linear combiner(LC) [9], and a adaptive notch filter is used as control filter. The cosine wave $x_{a_i}(n)$ and sine wave $x_{b_i}(n)$ are the reference signal $x(n)$. $p(n)$ is the primary noise which contains multiple narrowband components at the error sensor. $S(z)$ is the true secondary path modeled by an MA system and its estimated $\hat{S}(z)$. Secondary signal $y_p(n)$ generated by LC. The filter-x least mean square(FXLMS) algorithm [3] is used as the adaptive mechanism. The FXLMS algorithm is the most popular adaptive algorithm for its simplicity. It is a modified version of the well-known LMS algorithm. It works quite well if the uncorrelated norrowband disturbance $d(n)$ is not present in the system. However, the reference signal generator may not produce all of frequency components in real-life NANC applications. Such disturbance noise may degrade the performance of the NANC system severely. To tackle this problem, introducing the hybrid structure into the NANC system may be worth attempting.

There have been several contributions made in researching the Hybrid structure ANC system by many researchers and practitioners. In [13], Akhtar proposed a new hybrid ANC system based on the conventional hybrid ANC system, and improves noise reduction and at a fast convergence speed. In [14], a self-tuning hybrid ANC method is proposed by Mokhtarpour. By this performance optimized strategy, the system continuously estimates the parameters during its operation to obtain better the robustness of the system. In [15, 16], Xiao propose a new hybrid ANC system to remedy the problem of "firework" noise which are caused by the mixture of wideband and narrowband components in the conventional broadband ANC (BANC). In addition, the practical application of the hybrid structure ANC system has attracted a great deal of attention, and many successful applications are achieved such as [17, 18]. It should be noted that the above-mentioned efforts have all been made for the BANC.

In this paper, we focus on the NANC and present a new hybrid NANC method capable of canceling the primary noise and uncorrelated narrowband disturbance noise simultaneously. The new system consists of three subsystems: 1) a conventional NANC subsystem

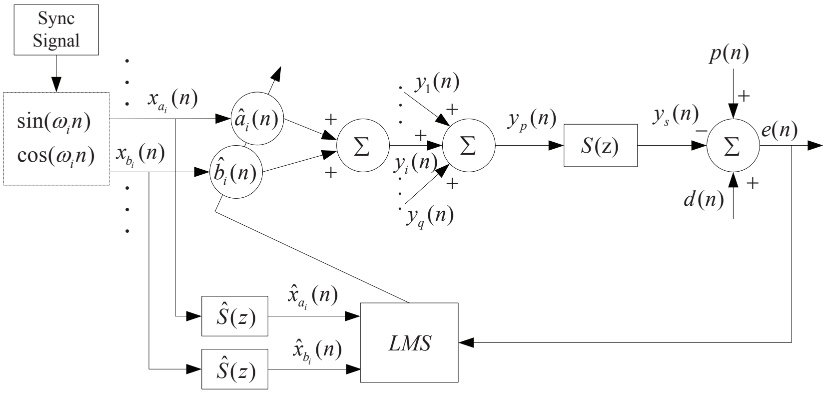

FIGURE 2. Equivalent sampled-time block diagram of the conventional narrowband ANC (NANC) system with FXLMS algorithm (ith channel) shown in Fig.1.

to cancel the primary noise; 2) a FANC subsystem to cancel the uncorrelated narrowband disturbance; 3) an sinusoidal noise canceler (SNC) subsystem using adaptive notch filter of linear combination which is designed to solve the problem of common error. Extensive simulations are conducted to demonstrate that the proposed system can effectively improves considerable the overall performance of the system.

The rest of the paper is organised as follows. In section II, the conventional NANC system, where the FXLMS algorithm is used, and its performance in the presence of the uncorrelated disturbance is briefly described. Section III presents the proposed method in detail. In section IV, the result of extensive simulations are conducted for various scenarios to demonstrate the superiority of the proposed method. Finally, discussion and conclusion are given in section V.

2. **NANC system and Its Performance for uncorrelated narrowband disturbance.** Consider the conventional NANC system depicted in Figure 2. The primary noise is given by

$$p(n) = \sum_{i=1}^{q} \{a_i \cos \omega_i n + b_i \sin \omega_i n\} + v_p(n) \tag{1}$$

where q is the number of frequency components of the primary noise, ω_i is the frequency of the ith component, $v_p(n)$ is a zero-mean additive white noise with variance σ_p^2. $\{a_i(n), b_i(n)\}$ are the discrete Fourier coefficients (DFC) of ith frequency components. The reference sine and cosine waves are defined as

$$x_{a_i}(n) = \cos(\omega_i n), x_{b_i}(n) = \sin(\omega_i n) \tag{2}$$

where ω_i is identified from the synchronization signal. The output of secondary source is expressed as

$$y_p(n) = \sum_{i=1}^{q} y_i(n) = \sum_{i=1}^{q} \{\hat{a}_i(n) x_{a_i}(n) + \hat{b}_i(n) x_{b_i}(n)\} \tag{3}$$

where $\{\hat{a}_i(n), \hat{b}_i(n)\}_{i=1}^{q}$ are DFC estimations of the secondary source updated by some adaptive algorithms. The true secondary path is modeled by an MA system

$$S(z) = \sum_{j=0}^{M-1} s_j z^{-j} \tag{4}$$

where M is the model order, and $\{s_j\}_{j=0}^{M-1}$ are the model coefficients. The error signal is measured by an error microphone, given by

$$e(n) = p(n) - y_s(n) \tag{5}$$

where $y_s(n)$ is the output signal of secondary source affected by $S(z)$ and is written as follows:

$$y_s(n) = \sum_{j=0}^{M-1} s_j y_p(n-j) \tag{6}$$

The FXLMS algorithm for the DFC estimation of secondary source is given as

$$\hat{a}_i(n+1) = \hat{a}_i(n) + \mu_i e(n)\hat{x}_{a_i}(n) \tag{7}$$

$$\hat{b}_i(n+1) = \hat{b}_i(n) + \mu_i e(n)\hat{x}_{b_i}(n) \tag{8}$$

where μ_i is the step size that directly determines the convergence speed, $\hat{x}_{a_i}(n)$ *and* $\hat{x}_{b_i}(n)$ are the input filtered reference signal which can be calculated by

$$\hat{x}_{a_i}(n) = \sum_{j=0}^{\hat{M}-1} \hat{s}_j x_{a_i}(n-j) = \hat{\alpha}_i x_{a_i}(n) + \hat{\beta}_i x_{b_i}(n) \tag{9}$$

$$\hat{x}_{b_i}(n) = \sum_{j=0}^{\hat{M}-1} \hat{s}_j x_{b_i}(n-j) = -\hat{\beta}_i x_{a_i}(n) + \hat{\alpha}_i x_{b_i}(n) \tag{10}$$

$$\hat{\alpha}_i = \sum_{j=0}^{\hat{M}-1} \hat{s}_j \cos(j\omega_i), \hat{\beta}_i = \sum_{j=0}^{\hat{M}-1} \hat{s}_j \sin(j\omega_i) \tag{11}$$

$$\hat{S}(z) = \sum_{j=0}^{\hat{M}-1} \hat{s}_j z^{-j} \tag{12}$$

In practical ANC application, $S(z)$ is unknown and must be estimated in advance by using offline [3] or online [19, 20] secondary path modeling techniques. Parameter $\hat{M}$ and $\hat{s_j}$ are the order and FIR coefficients of the secondary path estimate $\hat{S}(z)$, respectively.

The conventional NANC system usually works well if reference signal generator could capture all frequency components of the primary noise. However, some uncorrelated low-frequency disturbance sinusoids may exist in the system, and are picked up by error microphone. The residual noise $e(n)$ are modified as follow:

$$e(n) = p(n) - y_s(n) + d(n) \tag{13}$$

where $d(n)$ is the uncorrelated low-frequency disturbance sinusoids. Substituting (13) into (7) and (8), one gets

$$\hat{a}_i(n+1) = \hat{a}_i(n) + \mu_i(p(n) - y_s(n))\hat{x}_{a_i}(n) + \mu_i d(n)\hat{x}_{a_i}(n) \tag{14}$$

$$\hat{b}_i(n+1) = \hat{b}_i(n) + \mu_i(p(n) - y_s(n))\hat{x}_{b_i}(n) + \mu_i d(n)\hat{x}_{a_i}(n) \tag{15}$$

Compared with the (7) and (8), it is obvious that the adaptation process is disturbed by the disturbance sinusoids $d(n)$, and hence the performance of the NANC system is degraded severely, as shown in Figure 6 and Figure 7.

3. **Proposed method.** In this section, a hybrid NANC system is proposed by introducing feedback ANC (FANC) structure into the NANC system. Moreover, in view of low-convergence speed caused by common error of the system, a modified hybrid NANC system is designed for further improvement in the performance of the system.

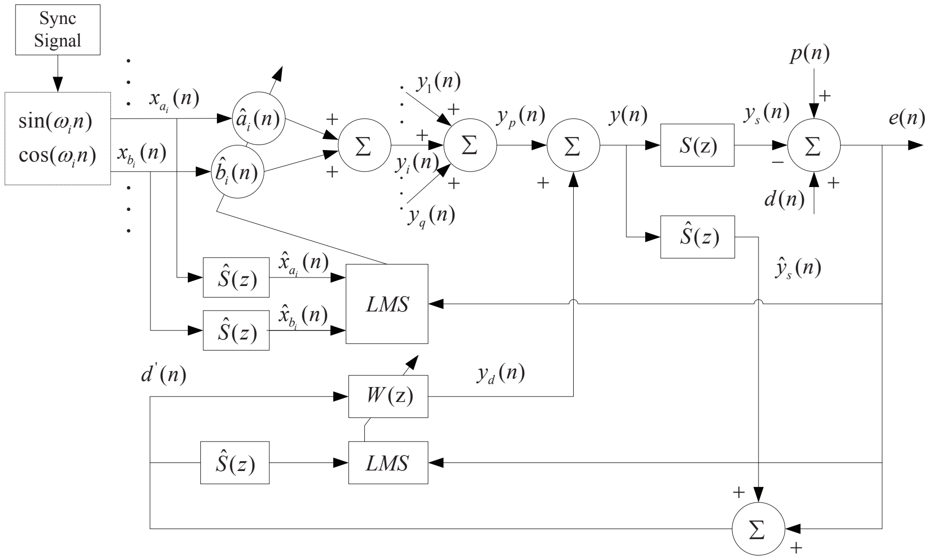

FIGURE 3. The block diagram of the hybrid NANC system (ith channel).

3.1. **Hybrid NANC system.** The block of the hybrid NANC system is depicted in Figure 3, which comprises a conventional NANC and FANC subsystem. The FANC is used to cancel the $d(n)$ for decreasing the residual error. The filter $W(z)$ is selected as FIR filters. The FXLMS algorithm is used in both NANC and FANC subsystem.

The secondary source $y(n)$ is the sum of the output of the NANC and FANC subsystem, given by

$$y(n) = y_p(n) + y_d(n) = y_p(n) + \mathbf{w^T(n)d'(n)} \tag{16}$$

where $y_p(n)$ is output of the NANC subsystem calculated by the Eq.(3). Defining coefficient (weight) vector of the filter $W(z)$ and reference signal vector, respectively, as follow,

$$\mathbf{w(n)} = [w_0(n) \quad w_1(n) \quad \cdots \quad w_{L-1}(n)]^T \tag{17}$$

$$\mathbf{d'(n)} = [d'(n) \quad d'(n-1) \quad \cdots \quad d'(n-L-1)]^T \tag{18}$$

where L is the order of $W(z)$. The $d'(n)$ is the reference signal of the FANC subsystem, given by

$$d'(n) = e(n) + y(n) * \hat{s}(n) \tag{19}$$

where $*$ denotes linear convolution. The error signal $e(n)$ is given by

$$e(n) = p(n) + d(n) - y_s(n) = p(n) + d(n) - y(n) * s(n) \tag{20}$$

Substituting (20) in (19) and assuming $S(z) \approx \hat{S}(z)$ leads to

$$d'(n) = p(n) + d(n) - y(n) * s(n) + y(n) * \hat{s}(n) \approx p(n) + d(n) \tag{21}$$

Putting (16) in (20), one gets

$$e(n) = p(n) - y_p(n) * s(n) + d(n) - y_d(n) * s(n) = p(n) - y'_p(n) + d(n) - y'_d(n) \tag{22}$$

Defining $e_{NANC}(n) = p(n) - y'_p(n), e_{FANC}(n) = d(n) - y'_d(n)$ and putting into the above equation, one has

$$e(n) = e_{NANC}(n) + e_{FANC}(n) \tag{23}$$

The FXLMS algorithm used to update weight vector $\mathbf{w(n)}$ of the FANC subsystem is given as [3]

$$\mathbf{w(n+1)} = \mathbf{w(n)} + \mu_w e(n)\mathbf{\hat{d}'(n)} \tag{24}$$

where μ_w is the step size, $\hat{\mathbf{d}}'(\mathbf{n})$ is the filtered reference vector, and can be expressed by

$$\hat{\mathbf{d}}'(\mathbf{n}) = [\hat{d}'(n) \quad \hat{d}'(n-1) \quad \cdots \quad \hat{d}'(n-L-1)]^T \tag{25}$$

$$\hat{d}'(n) = d'(n) * \hat{s}(n) \tag{26}$$

The updating equation of DFC estimates for NANC subsystem are given as

$$\hat{a}_i(n+1) = \hat{a}_i(n) + \mu_i e(n) \hat{x}_{a_i}(n) \tag{27}$$

$$\hat{b}_i(n+1) = \hat{b}_i(n) + \mu_i e(n) \hat{x}_{b_i}(n) \tag{28}$$

From (24),(27),and (28), we can see that the two subsystems use the same $e(n)$ called common error. For NANC subsystem, the first part $e_{NANC}(n)$ of the common error is appropriate for the adaptation process, and the second part $e_{FANC}(n)$ acts as a disturbance. For FANC subsystem, the signal $d'(n)$ contains $p(n)$, the common error may be appropriate for the adaptation process. Although, the FANC subsystem can cancel the mixture noise of $p(n)$ and $d(n)$, it degrades the the performance of the NANC subsystem, and reduces the convergence speed of the overall system. For the hybrid system, the FANC subsystem plays the major role in reducing the error $e(n)$. In order to remedy the problem of the common error, a modified hybrid NANC system is designed in section 3.2.

3.2. **Modified Hybrid NANC system for improvement.** The block of the modified hybrid NANC system is depicted in Figure 4. Compared with the hybrid NANC, an SNC subsystem is designed to solve the problem of common error. Other subsystems are same as the hybrid NANC. In addition, the well-known LMS algorithm is adopt by SNC subsystem.

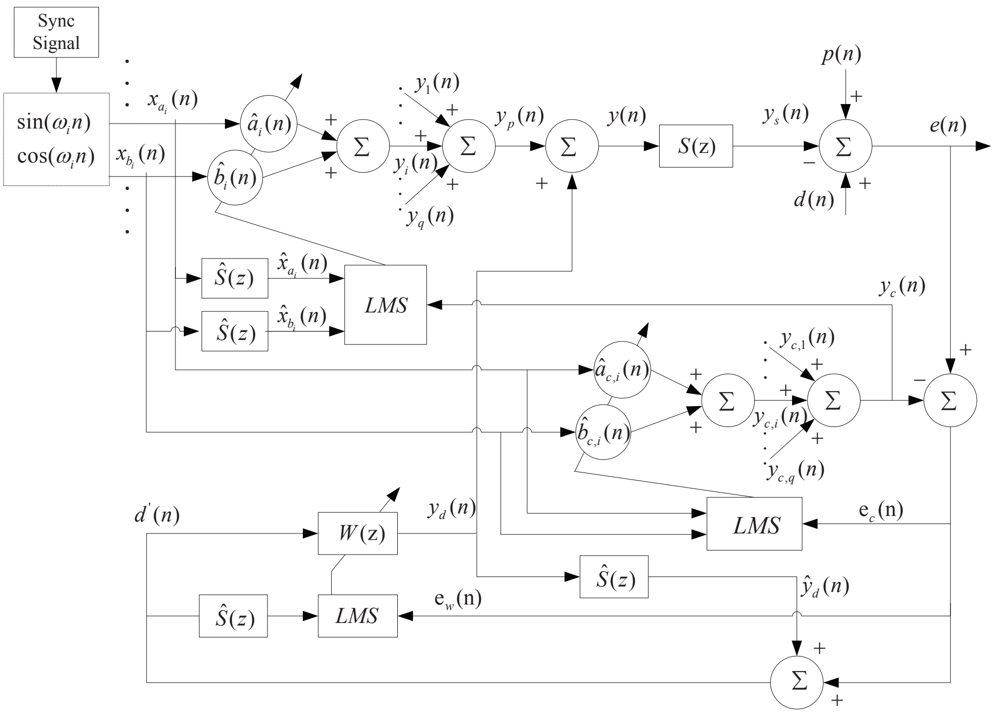

FIGURE 4. The block diagram of modified hybrid NANC system.

The output signal of the SNC subsystem can be calculated by

$$y_c(n) = \sum_{i=1}^{q} y_{c,i}(n) = \sum_{i=1}^{q} \{\hat{a}_{c,i}(n) x_{a_i}(n) + \hat{b}_{c,i}(n) x_{b_i}(n)\} \tag{29}$$

The error signal of the SNC subsystem can be obtained by

$$e_c(n) = e(n) - y_c(n) \tag{30}$$

Putting (22) in the above equation, one gets

$$e_c(n) = p(n) - y'_p(n) + d(n) - y'_d(n) - y_c(n) \tag{31}$$

The updating of DFC estimations for the SNC subsystem are given as

$$\hat{a}_{c,i}(n+1) = \hat{a}_{c,i}(n) + \mu_{c,i} e_c(n) x_{a_{c,i}}(n) \tag{32}$$

$$\hat{b}_{c,i}(n+1) = \hat{b}_{c,i}(n) + \mu_{c,i} e_c(n) x_{b_{c,i}}(n) \tag{33}$$

where $\mu_{c,i}$ is the step size, $x_{a_{c,i}}(n)$ and $x_{b_{c,i}}(n)$ are reference signal, which are correlated with $y'_p(n)$ and $p(n)$ contained in $e_c(n)$. Thus, when the filter of SNC subsystem converges,one has

$$y_c(n) \approx [p(n) - y'_p(n)] = e_{NANC}(n) \tag{34}$$

Comparing with $e(n)$, the $e_{NANC}(n)$ is more suits to be used to update of DFC estimates for the NANC subsystem, one obtains,

$$\hat{a}_i(n+1) = \hat{a}_i(n) + \mu_i e_{NANC}(n) \hat{x}_{a_i}(n) \tag{35}$$

$$\hat{b}_i(n+1) = \hat{b}_i(n) + \mu_i e_{NANC}(n) \hat{x}_{b_i}(n) \tag{36}$$

Putting (34) in (31),one gets

$$e_w(n) = e_c(n) \approx [d(n) - y'_d(n)] = e_{FANC}(n) \tag{37}$$

The input signal of the FANC subsystem, $d'(n)$, is given by

$$d'(n) = e_c(n) + \hat{y}_d(n) = e_c(n) + y_d(n) * \hat{s}(n) \tag{38}$$

Substituting (37) in (38), one has

$$d'(n) \approx d(n) - y'_d(n) + \hat{y}_d(n) = d(n) - y_d(n) * s(n) + y_d(n) * \hat{s}(n) \tag{39}$$

Assuming $S(z) = \hat{S}(z)$, the above equation simplifies to $d'(n) \approx d(n)$. Comparing with (24), the more appropriate signals $e_{FANC}(n)$ and $d'(n)$ are used to update the filter $W(z)$ of the FANC subsystem, one obtains

$$\mathbf{w(n+1)} = \mathbf{w(n)} + \mu_w e_{FANC}(n) \hat{\mathbf{d}}'(\mathbf{n}) \tag{40}$$

From the descriptions given above and Figure 4, we can see that the SNC subsystem of the modified hybrid NANC system could separate appropriate error signal form the common error for the NANC and FANC subsystem. As result of designing this subsystem, the mutual disturbances between the adaptive process of NANC and FANC subsystem can be reduced greatly, and hence improves convergence speed compared with the hybrid NANC system.

4. **Simulations and performance results.** In this section, extensive simulations are conducted to evaluate the effectiveness of the proposed method in difference scenarios. The true secondary path $S(z)$ adopt an experimental data provided in [3]. Its order is $M = 24$, and assumes the estimation of secondary path $\hat{S}(z) = S(z)$ in simulations. The frequency response of acoustic path is shown in Figure 5. A zero-mean white Gaussian noise of variance 0.1 is added to primary noise as measurement noise. In each simulation scenario, results are averaged over 100 Monte Carlo runs. Some typical simulation results are given below.

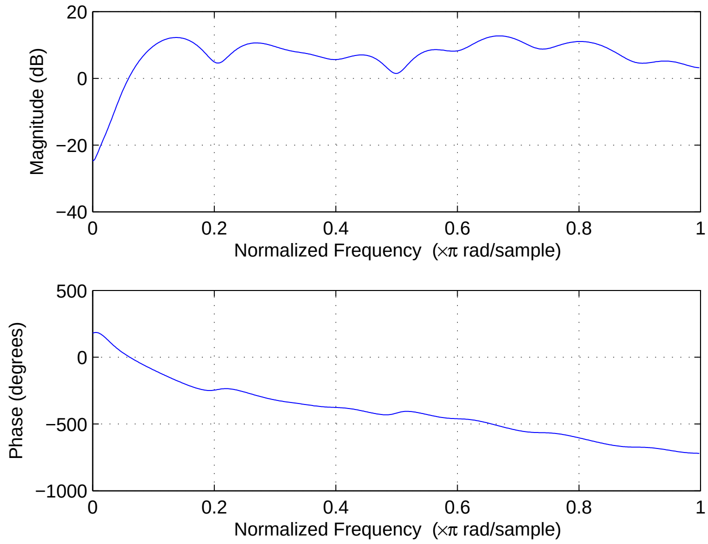

FIGURE 5. Frequency response of the secondary path $S(z)$.

4.1. **Case 1.** In this case, the primary noise includes three frequencies ($q = 3$), i.e. $w_1 = 0.1\pi$, $w_2 = 0.2\pi$, and $w_3 = 0.3\pi$. There corresponding DFCs are set to $a_1 = 2.0$, $b_1 = -1.0$, $a_2 = 1.0$, $b_2 = -0.5$, $a_3 = 0.5$, $b_3 = 0.1$. The uncorrelated narrowband disturbance $d(n)$ contains a single frequency signal $w_d = 0.15\pi$, and its corresponding DFCs are set to $a_d = 0.5$, $b_d = 0.1$.

Firstly, the effect of the uncorrelated narrowband disturbance $d(n)$ on the performance of the convention NANC is provided in Figure 6 and Figure 7. Here, the step size of FXLMS algorithm are set to be $\mu_i = 0.01$ for all i. Figure 6(a)-(c) show the DFCs estimation MSEs of primary noise $p(n)$, which can be expressed by $E[\varepsilon^2_{\hat{a}_i}(n)] = E[(\hat{a}_{i,opt} - \hat{a}_i)^2]$ and $E[\varepsilon^2_{\hat{b}_i}(n)] = E[(\hat{b}_{i,opt} - \hat{b}_i)^2]$. Constants $\hat{a}_{i,opt}$ and $\hat{b}_{i,opt}$ are the optimum values for a perfect cancellation of all the targeted sinusoids of the primary noise, which can be computed by [21, Eq.(24)]. To identify the effect of $d(n)$ on the performance of NANC more clearly, the mean error $E[e(n)]$ and MSE $E[e^2(n)]$ are given in Figure 7.

Secondly, comparison among three systems including NANC, Hybrid NANC and the modified hybrid NANC system is studied in Figure 8 and Figure 9. The parameters of three methods are set as follow. In NANC system, $\mu_i = 0.001$ for all i . For the hybrid NANC system, $\mu_i = 0.001$ for all i. The feedback subsystem $W(z)$ is selected as FIR filters of length 20, $\mu_w = 0.00003$. For modified NANC system, $\mu_i = 0.001$ for all i, $\mu_w = 0.00015$, and use the same $W(z)$ as the hybrid NANC system; $\mu_{c,i} = 0.08$ for all i. Figure 8(a)-(f) show the comparisons of the DFCs estimation MSEs of primary noise $p(n)$ among the three systems. The mean square estimation errors $E[e^2(n)]$ is given in Figure 9.

As indicated in these figures, the following remarks may be obtained. 1)The performance of the NANC system degrades severely in presence of uncorrelated narrowband disturbance $d(n)$. See Figure 6 and Figure 7 for details. At first, $d(n)$ reduces the system ability for canceling the primary noise $p(n)$, and causes greater DFC estimation MSEs, as shown in Figure 6(a)-(f). Moreover, the NANC system could not mitigate $d(n)$, and remains in the residual noise, which further degrades performance of steady-state, as shown in Figure 7. 2)From Figure 8(a)-(f), we see that the NANC subsystem of the hybrid

NANC has poor performance to cancel $p(n)$ because of using the common error. However, the modified method use the SNC subsystem to obtain appropriate error signal for the NANC subsystem, which could better cancel the primary noise. 3)As compared with the NANC, the hybrid NANC and the modified method could more effectively mitigate the primary noise and the uncorrelated disturbance simultaneously. However, the modified method has faster convergence speed than the hybrid NANC system, as shown in Figure 9.

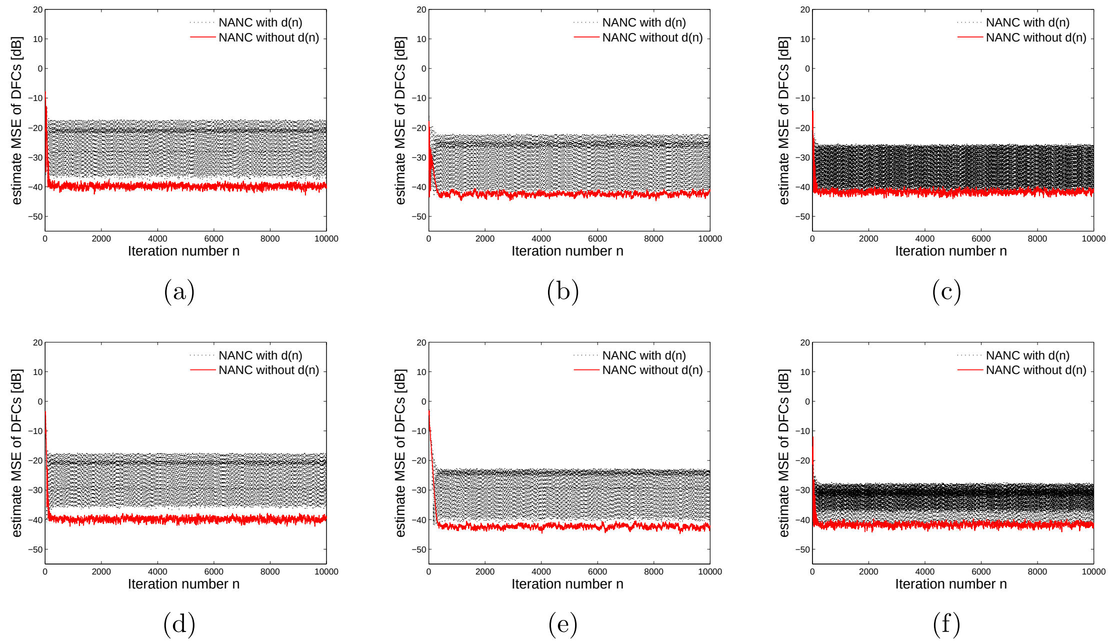

FIGURE 6. The effect of $d(n)$ on the performance of the convention NANC system. (a) $E[\varepsilon^2_{a_1}(n)]$. (b) $E[\varepsilon^2_{a_2}(n)]$. (c) $E[\varepsilon^2_{a_3}(n)]$. (d) $E[\varepsilon^2_{b_1}(n)]$. (e)$E[\varepsilon^2_{b_2}(n)]$. (f) $E[\varepsilon^2_{b_3}(n)]$.

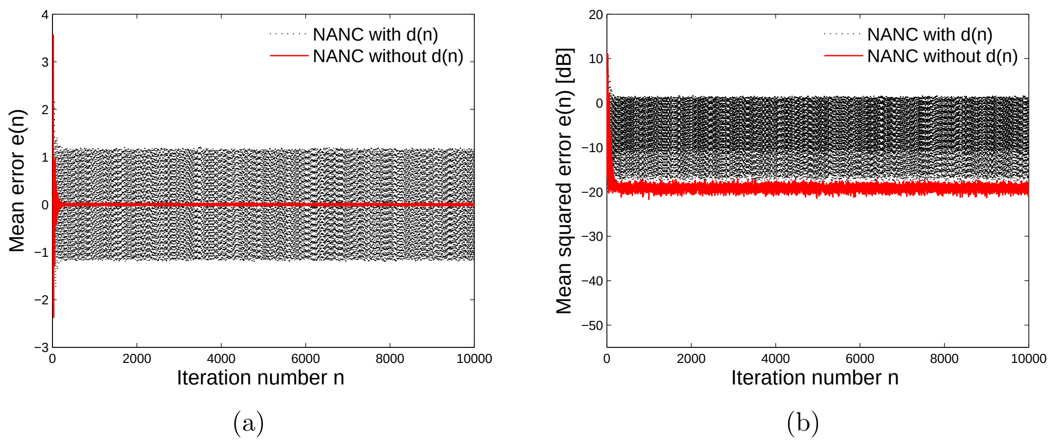

FIGURE 7. The effect of $d(n)$ on the performance of the convention NANC. (a) Mean error $E[e(n)]$. (b)Mean square error $E[e^2(n)]$.

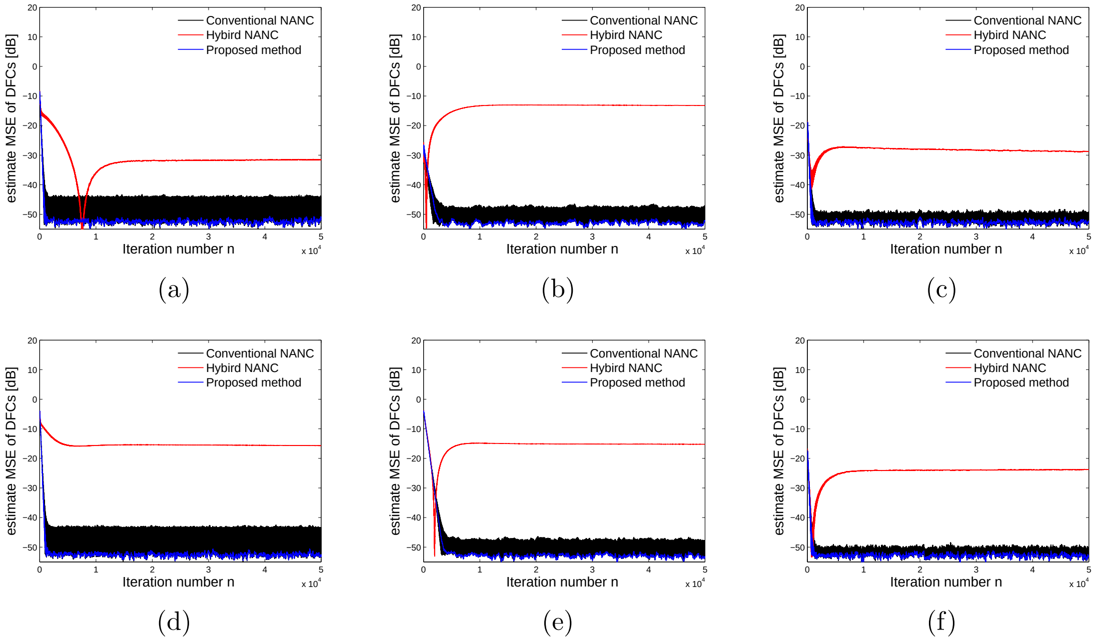

FIGURE 8. Comparisons of the performance of among the conventional NANC, Hybrid NANC, and Modified Hybrid NANC system. (a) $E[\varepsilon_{a_1}^2(n)]$. (b) $E[\varepsilon_{a_2}^2(n)]$. (c) $E[\varepsilon_{a_3}^2(n)]$. (d) $E[\varepsilon_{b_1}^2(n)]$. (e) $E[\varepsilon_{b_2}^2(n)]$. (f) $E[\varepsilon_{b_3}^2(n)]$.

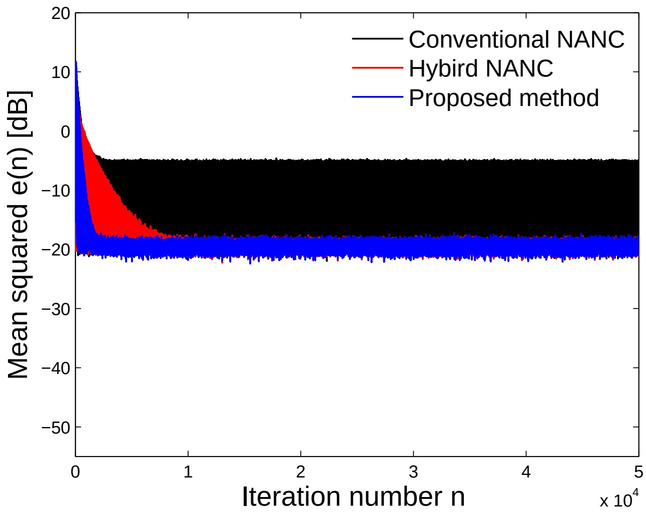

FIGURE 9. Comparison of $E[e^2(n)]$ the conventional NANC, Hybrid NANC, and Modified Hybrid NANC system.

4.2. **Case 2.** In this case, the primary noise contains four frequencies ($q = 4$), i.e. $w_1 = 0.1\pi$, $w_2 = 0.2\pi$, $w_3 = 0.3\pi$, and $w_4 = 0.4\pi$. Their corresponding DFCs are set to $a_1 = 2.0$, $b_1 = -1.0$, $a_2 = 1.0$, $b_2 = -0.5$, $a_3 = 0.5$, $b_3 = 0.1$, and $a_4 = 1.5$, $b_4 = 0.5$. The uncorrelated narrowband disturbance $d(n)$ include two frequency signals, i.e. $w_{d1} = 0.15\pi$, $w_{d2} = 0.26\pi$, and its corresponding DFCS are set to $a_{c,1} = 2.0$, $b_{c,1} = -1.0$, and $a_{c,2} = 0.5$, $b_{c,2} = 0.1$. The parameters of three methods are set as follow. For NANC method, $\mu_i = 0.001$ for all i. For the hybrid NANC method, $\mu_i = 0.001$ for all i, and $\mu_w = 0.00003$. For modified hybrid NANC, $\mu_i = 0.001$ for all i, $\mu_{c,i} = 0.05$ for all i, and $\mu_w = 0.00005$.

Similar comparisons results as case 1 are shown in Figure 10 and Figure 11. From these figures, we can see that the proposed method also exhibits excellent performance.

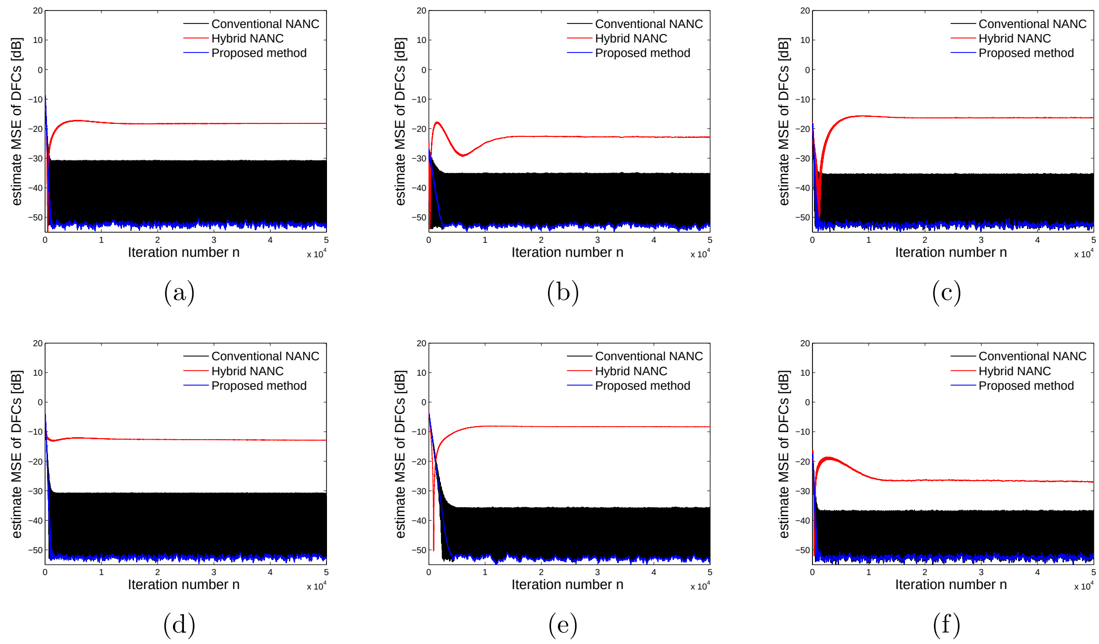

FIGURE 10. Comparisons of the performance of among the conventional NANC, Hybrid NANC, and Modified Hybrid NANC system. (a) $E[\varepsilon_{a_1}^2(n)]$. (b) $E[\varepsilon_{a_2}^2(n)]$. (c) $E[\varepsilon_{a_3}^2(n)]$. (d) $E[\varepsilon_{b_1}^2(n)]$. (e) $E[\varepsilon_{b_2}^2(n)]$. (f) $E[\varepsilon_{b_3}^2(n)]$.

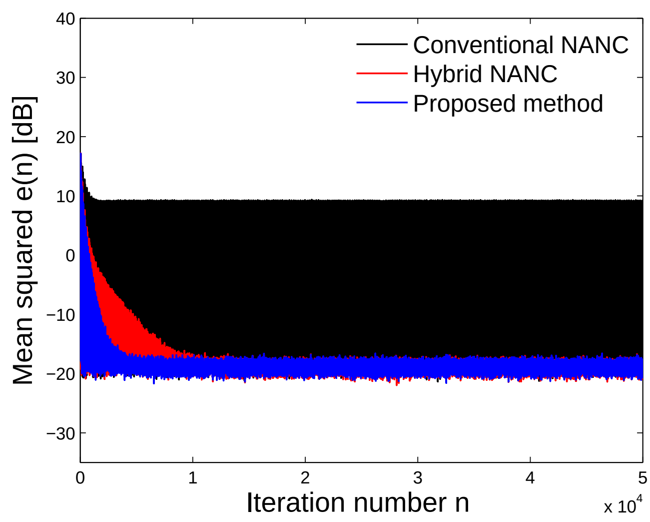

FIGURE 11. Comparison of $E[e^2(n)]$ among the conventional NANC, Hybrid NANC, and Modified Hybrid NANC system.

5. **Conclusions.** In this paper, simple analysis are investigated in detail to reveal the poor performance of the conventional NANC in presence of the uncorrelated narrowband disturbance noise. Then, a new hybrid NANC system is proposed to effectively cancel both the primary noise and the uncorrelated narrowband disturbance noise simultaneously. Firstly, the proposed method introduces FANC subsystem into the NANC

system to suppress the disturbance noise, and hence improves noise reduction; Next, a SNC subsystem is designed to extract suitable error signal from common error for NANC and FANC subsystem and improves the convergence speed. Extensive simulations are conducted to prove the effectiveness of the new system.

Acknowledgment. This work was supported in part by the National Science and Technology Support Program of China (NO: 2012BAI34B03-3).

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