A NEW ROBUST NARROWBAND ACTIVE NOISE CONTROL SYSTEM STRUCTURE WITH ONLY ONE CHANNEL FOR REFERERNCE SIGNAL FILTERING

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ABSTRACT

In a conventional narrowband active noise control system, each reference cosine wave has to be filtered by an estimate of the secondary-path. We call this part *x-filtering* block. The number of x-filtering blocks is equal to the number of targeted frequencies. The computational cost of the system due to the x-filtering operations may form a bottleneck in real system implementation. In this paper, we propose a new narrowband ANC system structure which requires only one x-filtering block regardless of q. All the cosine waves are combined as an input to a x-filtering block whose output is decomposed by an efficient bandpass filter bank into filtered cosine waves for the FXLMS that follows. As a result, the computaional cost of the system is considerably reduced. The new structure is further implanted in a recently developed ANC system that is capable of mitigating the frequency mismatch (FM). Simulations demonstrate that the new systems present robust performance very similar to that of their counterparts, but enjoy considerable advantages in system implementation.

1. INTRODUCTION

Noisy sinusoidal signals generated by rotating machines, such as diesel engines, motors, fans, factory cutting machines, etc. may be effectively reduced by narrowband active noise control (ANC) systems, especially the lower frequency portion. For example, high-power cutting machines used in factories generate such noise signals which are harmful to their operators. Narrowband active noise control (ANC) systems have been utilized in reducing these annoying noise signals.

As is well-known, research and development in the ANC area has been carried out since the early 1970s, and many promising system structures and adaptive algorithms have been developed, see [1]-[8] and the references therein. The finite-impulse-response (FIR) filters adapted by a filtered-x least mean square (FXLMS) algorithm are usually used in the ANC systems [3]. Other techniques using recursive least squares (RLS) and Kalman filtering based algorithms have also been developed for the FIR-type ANC systems [3],[6], which generally provide better noise reduction performance at the expense of more computational cost.

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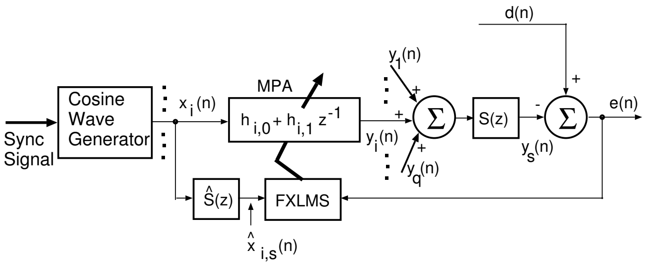

Fig. 1 The conventional narrowband ANC system (i-th channel).

Several conventional narrowband ANC systems have been found effective in suppressing sinusoidal noise signals in different scenarios for many real-life applications [3]. Fig.1 depicts a block diagram of such a typical parallel form ANC system that uses a two-weight FIR-type magnitude/phase adjuster (MPA) as controller in each frequency channel. The FXLMS algorithm has been used to adapt all the parallel channels simultaneously. In each frequency channel, one (1) x-filtering block ($\hat{S}(z)$) is required. If q becomes large, the number of x-filtering blocks will increase. Because the order $\hat{M}$ of the estimated FIR-type secondary path ($\hat{S}(z)$) can be as large as 128 or even higher in practice, the complexity due to the x-filtering blocks may become a real burden and bottleneck in system implementation. This has motivated us to explore new system structure that has less computational requirements but enjoys performance similar to that of the original system in Fig.1.

A new narrowband ANC system structure is proposed that requires only a single x-filtering block regardless of q. The computaional cost of the new system is significantly reduced particularly for large q and/or $\hat{M}$. In the new system, all the reference cosine waves are added together as an input to a x-filtering block whose output is decomposed into separated filtered cosine waves for the FXLMS by a bandpass filter bank. The cells of the bandpass filter bank are bandpass filters derived from IIR notch filters with constrained poles and zeros [9].

The new structure is also transplanted to a recently developed ANC system capable of mitigating the frequency mismatch (FM) that might exist in real-life applications due to sensor aging and fatigue [8, 10].

Extensive simulations are provided to demonstrate that the new systems present performance that is extremely similar or almost identical to that of the conventional system, but enjoy great cost merit in system implementation.

2. NEW NARROWBAND ANC SYSTEMS

2.1. Conventional system

The primary noise signal in Fig.1 is given by

$$d(n) = \sum_{i=1}^{q} \{a_{p,i}\cos(\omega_{p,i}n) + b_{p,i}\sin(\omega_{p,i}n)\} + v(n) \quad (1)$$

where q is the number of frequency components of $d(n)$, $\omega_{p,i}$ is the frequency of the i-th component, $v(n)$ is a zero-mean additive white Gaussian noise with variance σ_v^2. The i-th reference cosine wave is given by

$$x_i(n) = a_{r,i}\cos(\omega_i n), \;\; a_{r,i} \neq 0 \quad (2)$$

where frequency ω_i is derived from the synchronization signal in a regression fashion [3]. Speed sensor such as tachometer is usually used as the reference sensor. If the sensor works perfectly, $\omega_{p,i}$ will be exactly the same as ω_i, and no FM exists. The output of the i-th channel is expressed by

$$y_i(n) \; = \; h_{i,0}(n)x_i(n) + h_{i,1}(n)x_i(n-1) \quad (3)$$

The block $S(z)$ is the secondary-path or error-path and is modelled as an FIR filter with coefficients $\{s_j\}_{j=0}^{M-1}$, while its estimate $\hat{S}(z)$ (:$\{\hat{s}_j\}_{j=0}^{\hat{M}-1}$) is assumed to be known *a priori* or estimated in some way in advance. The FXLMS algorithm is utilized to update the two FIR weights in each channel as follows [3].

$$h_{i,0}(n+1) \;=\; h_{i,0}(n) + \mu_i e(n)\hat{x}_{i,s}(n), \quad (4)$$
$$h_{i,1}(n+1) \;=\; h_{i,1}(n) + \mu_i e(n)\hat{x}_{i,s}(n-1) \quad (5)$$

where μ_i is a positive step size parameter, and

$$\hat{x}_{i,s}(n) = \sum_{j=0}^{\hat{M}-1} \hat{s}_j x_i(n-j), \;\; i = 1, 2, \cdots, q \quad (6)$$

$$e(n) = d(n) - \sum_{j=0}^{M-1} s_j \left\{ \sum_{i=1}^{q} y_i(n-j) \right\} \quad (7)$$

Here, one x-filtering block ($\hat{S}(z)$) must be placed in each channel. As the number of frequencies targeted increases, the number of x-filtering blocks will go up and the computational cost involved may become a serious cost issue in system implementation.

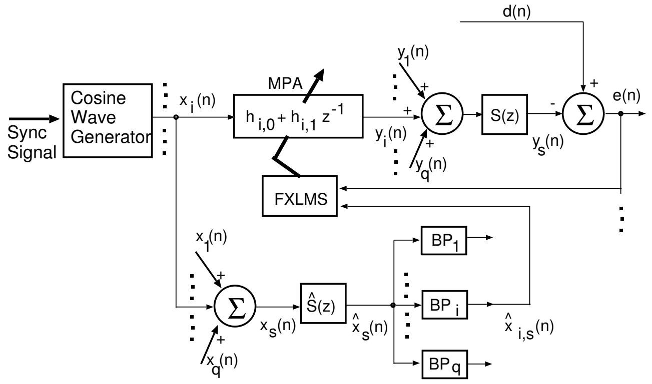

Fig. 2 A new narrowband ANC system structure (i-th channel).

2.2. A new system structure

To reduce the number of x-filtering blocks, we resort to an idea of first filtering all the cosine waves by a single x-filtering block and then decomposing the block output into separated elements by a proper bandpass filter bank. Such a new system structure is given in Fig.2, where

$$x_s(n) = \sum_{i=1}^{q} x_i(n), \;\; \hat{x}_s(n) = \sum_{j=0}^{\hat{M}-1} \hat{s}_j x_s(n-j) \quad (8)$$

and the transfer function of i-th filter of the bandpass filter bank is given by

$$H_{bp_i}(z) \;=\; \frac{(\rho-1)c_i z^{-1} + (\rho^2-1)z^{-2}}{1 + \rho c_i z^{-1} + \rho^2 z^{-2}}, \quad (9)$$
$$c_i \;=\; -2\cos(\omega_i), \quad (10)$$

and ρ is a pole attraction factor (or pole radius) over $(0, 1)$. This bandpass filter is derived from an IIR notch filter with constrained poles and zeros [9]. The filtered signals $\hat{x}_{i,s}(n)$ for FXLMS that follows is the output of the above bandpass filter.

$$\hat{x}_{i,s}(n) = -\rho c_i \hat{x}_{i,s}(n-1) - \rho^2 \hat{x}_{i,s}(n-1) + (\rho-1)c_i\hat{x}_s(n-1) + (\rho^2-1)\hat{x}_s(n-2), \quad (11)$$

where four (4) multiplications are involved. It is not difficult to prove that $H_{bp_i}(e^{\nu\omega_i}) = 1$ ($\nu = \sqrt{-1}$) for any ρ, which implies that the proposed system will have properties very similar to those of the conventional system. ρ may be chosen according to the spacing of the signal frequencies considered. If they are closely spaced, some ρ very close to unit may be selected to allow the bandpass filters to produce clean reference waves for the FXLMS. However, this may bring some delay to the system's dynamics, because the bandpass filter with larger ρ has a longer time constant. Note that this delay

Table 1 Comparison of complexity between the conventional and proposed systems shown in Figs. 1 and 2 (blk: number of x-filtering blocks, mult: number of multiplications).

	Conventional		Proposed	
	blk	mult	blk	mult
$q, \ \hat{M}$	q	$q\hat{M}$	1	$\hat{M}+4q$
$q=3, \hat{M}=41$	3	123	1	53
$q=3, \hat{M}=64$	3	192	1	76
$q=3, \hat{M}=128$	3	384	1	140
$q=10, \hat{M}=41$	10	410	1	81
$q=10, \hat{M}=64$	10	640	1	104
$q=10, \hat{M}=128$	10	1280	1	168

does not directly contribute to the dynamics of the system and thus will not be so severe. See simulation results in next Section for the resultant delay that is actually quite small even for a ρ very close to unit.

The number of x-filtering blocks and the corresponding multiplications is compared in Table 1 for the new and the conventional systems. The computational merit of the new system is obvious and significant.

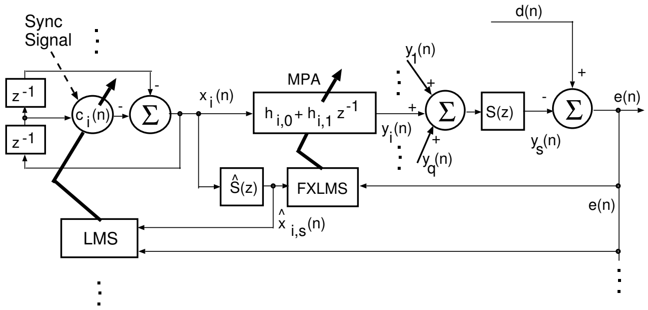

Fig. 3 A robust narrowband ANC system in the presence of FM, recently developed in [8] (i-th channel).

2.3. A modified system structure in the presence of FM

When there is a frequency mismatch (FM) between the reference waves and the primary noise due to the sensor aging and fatigue, the performance of conventional system will degrade severely [8, 10]. To make the system robust to the existence of FM, we have recently proposed an ANC system shown in Fig.3, where the frequency-related coefficient $c_i(n)$ is updated by an LMS-like algorithm as follows [8].

$$c_i(n+1) \quad = \quad c_i(n) - \mu_{c_i} e(n) h_{i,0}(n) \hat{x}_{i,s}(n-1) \quad (12)$$

where μ_{c_i} is a positive step size parameter, and the update implements the minimization of the remaining error signal power ($e^2(n)$). The idea used in the new system of Fig.2 is simplely introduced to the system in Fig.3 to obtain a modified system given in Fig.4 which is not only computationally efficient but also robust to the FM. The computational advantage of the modified system over that shown in Fig.3 is still preserved to the same extent. Only two (2) additional mutiplications for each bandpass filter are required as c_i is now adaptively updated (see (11) for the number of multiplications involved in a bandpass filter).

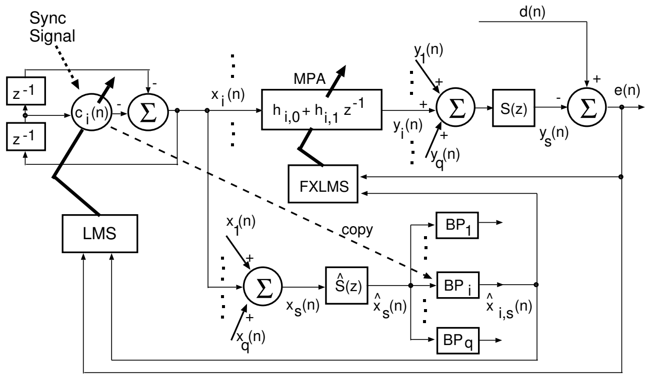

Fig. 4 A modified robust narrowband ANC system in the presence of FM (i-th channel).

3. SIMULATIONS

It has been made clear that the two proposed systems have significant computational advantages over the conventional system [3] and a recently developed system [8], and are expected to possess very similar performance as their counterparts. Extensive simulations have been performed. Here, we provide some representative simulation results.

Fig.5 presents a comparison between the conventional system of Fig.1 and the new system in Fig.2. Obviously both systems indicate very similar dynamics and almost identical steady-state remaining noise power. The convergence of the new system is delayed a little bit, and this is the only sacrifice we have to make.

Comparisons between the systems shown in Figs.1-4 are provided in Fig.6, with Fig.6(a) and (b) being the remaining noise signals produced by systems of Figs.1 and 2, respectively, and Fig.6(c) and (d) being the same signals generated by systems of Figs.3 and 4, all in the presence of an FM. From these simulation results, the proposed and modified systems work almost the same as their counterparts do. Systems in Figs.1 and 2 failed completely due to an FM of 1%. The modified systems of Figs. 3 and 4 have the capabilities of mitigating the influence of the FM very effectively.

4. CONCLUSIONS

In this paper, two narrowband ANC systems with new structures have been proposed, which provide performance very similar to that of the conventional and a recently established systems, while requiring considerably less computational cost. Extensive simulations have been conducted to demonstrate that the proposed systems are very promising even in the presence of FM. DSP-based implementation of the proposed systems and their detailed performance analysis are remaining research topics.

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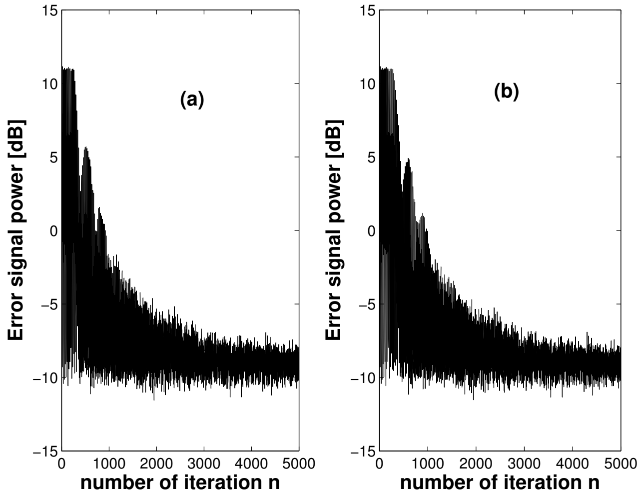

Fig. 5 Comparisons between systems in Figs.1 ((a)) and 2 ((b)) (signal frequencies: $0.10\pi,\ 0.20\pi,\ 0.30\pi$; $a_1 = 2.0$, $b_1 = -1.0$, $a_2 = 1.0$, $b_2 = -0.5$,$a_3 = 0.5$, $b_3 = 0.1$; $\mu_1 = \mu_2 = \mu_3 = 0.015$; $\sigma_p = 0.33$, $M = 256$, $\hat{M} = 128$, $\rho = 0.985$, 100 runs).

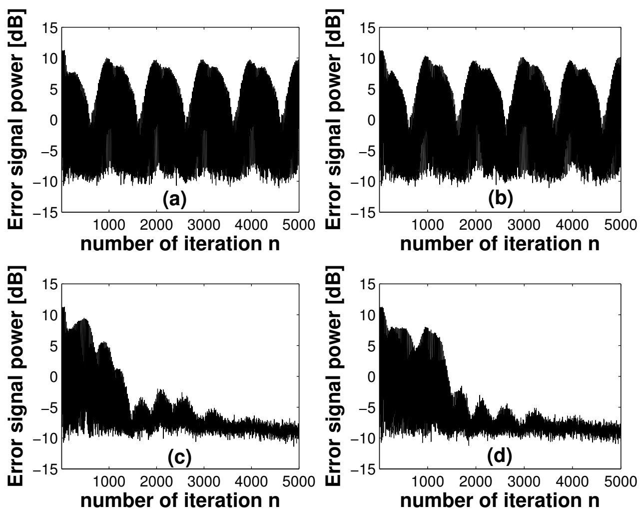

Fig. 6 Performance comparisons among systems in Figs.1 ((a)), 2 ((b)), 3 ((c)) and 4 ((d)) that were all simulated in the presence of FM (frequency mismatch ($\Delta\omega_i = \frac{\omega_{p,i}-\omega_i}{\omega_i} \times 100\%$) is 1% for all the frequencies targeted; $\mu_{c_1} = 0.00005$, $\mu_{c_2} = 0.0001$, $\mu_{c_3} = 0.00015$; $M = 64$, $\hat{M} = 41$, $\rho = 0.985$, other simulation conditions the same as in Fig.5).