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Performance evaluation of hybrid active noise control system with online secondary path modeling

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ABSTRACT

A Hybrid Active Noise Control (HANC) system is used to attenuate disturbances in a scenario where a portion of noise is captured by reference sensors. In such scenarios, the secondary path continuously changes due to interference by various electrical equipment used in the Active Noise Control (ANC) system. A practical ANC system should be robust to secondary path effects. In existing literature, the secondary path used in a HANC system is estimated offline. In a real time environment, the secondary path is time varying in nature. Hence, Online Secondary Path modeling (OSPM) is a desirable addition to the design of ANC systems because it significantly improves adaptive filter convergence along with better noise reduction performance. In this paper, we propose modified HANC systems with OSPM as continuous modeling of the noise removes the secondary path effects and the HANC system can be used for real time implementation. To achieve this, we extend the OSPM technique from the Eriksson's method to the conventional HANC system, Sun's cascading adaptive filters algorithm and Akhtar's HANC system. Computer simulations prove that the proposed HANC systems with OSPM improves error modeling accuracy and faster convergence against existing HANC systems where the secondary path is modeled offline. The modified HANC framework is also robust to sudden changes in the behaviour of electrical equipment while ANC operation along with providing improved noise cancelling performance.

1. Introduction

Improvement in electrical and electronics technology with the passage of time has drawn widespread interest in the development of ANC systems. With the rise in the use of domestic and industrial machinery, installing an ANC system has become a necessity for the users to avoid the irritation caused by the noise generated by operating machines. The underlying principle to develop an ANC system is the theory of superposition [1,2]. A silence zone is created by destructively interfering an anti-disturbance signal, with the original disturbance signal [2]. The anti-disturbance signal is generated using various signal processing techniques, and the degree of noise cancellation largely depends upon the accuracy in modeling the anti-disturbance signal. ANC approaches are generally of three types – feedforward ANC, feedback ANC and HANC systems [3]. In scenarios where a free reference signal having proper correlation with the primary noise can be determined, a feedforward ANC is employed. But in most practical applications, independent availability of the reference signal is an issue [4]. In such cases, a feedback ANC system is preferred. It has been found that feedforward ANC systems perform well in controlling broadband noises and a feedback ANC gives better noise cancelling in applications with narrowband noise [3]. For a system affected with both broadband noise and uncorrelated narrowband disturbances, a HANC system is preferred [2,3,5–7]. A HANC system is designed with the combination of a feedforward and feedback ANC systems to exploit the advantages of both the methods [8].

The control filters are usually updated by the much popular Filtered-x LMS (FXLMS) algorithm due to robust performance and fast convergence [9,10]. In employing the FXLMS algorithm, proper modeling of the secondary path is of paramount importance because a practical ANC system comprises of components like digital-to-analog converter, reconstruction filter, power amplifier, loud speaker, acoustic path from loudspeaker to error microphone, error microphone, preamplifier, anti-aliasing filter, analog-to-digital converter is required for updating the filter coefficients [2]. The effect of inaccurate secondary path modeling in the filter adaptation process and noise cancelling performance is studied in great depth in [11–14]. A lot of focus has been given to parameter estimation and identification in secondary path modeling. The intermediate acoustic paths get affected due to factors like variable operating temperature, surrounding changes and

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component aging. A lot of attention has also been paid to the online estimation of the secondary path parameters. There have been many developments in the past by using this approach especially in the online transducer modeling in adaptive attenuation system using random noise [15]. This technique was a novel way for online estimation of secondary path and a lot of developments over this technique were proposed in [16–21]. The necessity for online estimation of the secondary path is of primary importance in the design of an ANC system to control correlated and uncorrelated disturbances. All the existing HANC system have considered offline secondary path modeling and none of the methods in existing literature have attempted for OSPM in a HANC system.

In this paper, we design a new HANC framework with online modeling of the secondary path by continuously injecting a random noise into the system. The reason behind this strategy is that the secondary path transfer function from the loudspeaker to the error sensor changes continually in a HANC system due to the unpredictable nature of the electrical equipment used in the design of an HANC system. By modeling the secondary path online, the ANC system becomes independent of the behaviour of the electrical equipment used which often alters the transfer functions that are necessary for signal processing algorithms used for updating the adaptive filters in the ANC system. Hence, OSPM in a HANC system is a desirable feature to incorporate especially in the modern day scenario where most of the industrial machinery are designed using numerous electrical/electronic equipment. Though the injected random noise initially increases the noise in the HANC system, this issue is taken care by the feedback subsystem during ANC operation as the injected random noise is also an uncorrelated disturbance. We carry out a thorough performance analysis of the most popular HANC systems for simultaneous control of correlated and uncorrelated disturbances in the proposed framework. Here, we have modified the HANC structures proposed in [2,6,11] with OSPM. The simulation results give considerable noise cancelling performance along with fast adaptive filter convergence, thereby establishing the proposed HANC framework as most desirable for practical implementation for real time ANC applications.

For the sake of consistency, the following notation is adopted throughout the paper, k for discrete time index, bold-faced lower case letters for column vectors, and bold-faced upper case letters for matrices. The notation $a(n)\rightarrow b(n)$ implies $a(n)$ converges to $b(n)$ and $a(n)*b(n)$ denotes the linear convolution of $a(n)$ with $b(n)$. The symbol $tr\{.\}$ denotes the trace of a matrix, $\|.\|$ denotes the Euclidean norm of a vector and $(.)^T$ for the transpose of a vector or matrix. A discrete-time filter of length L is represented as a polynomial $F(q)$ in terms of q^{-1} as $F(q)=f_0+f_1q^{-1}+...+f_{L-1}q^{-L+1}$ or by its coefficient vector $\mathbf{f}=[f_0,f_1,...,f_{L-1}]^T$. The signal $p(n)$ is filtered by $F(q)$ as $F(q)p(n)=\mathbf{f}^T(n)\mathbf{p}(n)$, with $\mathbf{p}(n)=[p(n),p(n-1),...,p(n-L+1)]^T$. The random noise used for OSPM is a zero mean white Gaussian noise with variance 0.05. The abbreviations adopted for the proposed methods and its counterparts are given in Table 1.

The article is further organized as follows. A brief introduction to HANC system design is given in Section 2. The modified HANC systems with OSPM and mathematical equations describing the proposed methods is presented in Section 3. In Section 4, we report the simulation results of the HANC systems in the proposed framework and finally, Section 5 gives the concluding remarks.

Table 1
Abbreviations used for various methods.

	Abbreviations	Expansion
1.	HANC	Hybrid ANC system
2.	CHANC	Conventional Hybrid ANC system
3.	SCANC	Sun's Cascading ANC system
4.	AHANC	Akhtar's Hybrid ANC system
5.	M-CHANC	Modified Conventional Hybrid ANC system
6.	M-SCANC	Modified Sun's Cascading ANC system
7.	M-AHANC	Modified Akhtar's Hybrid ANC system

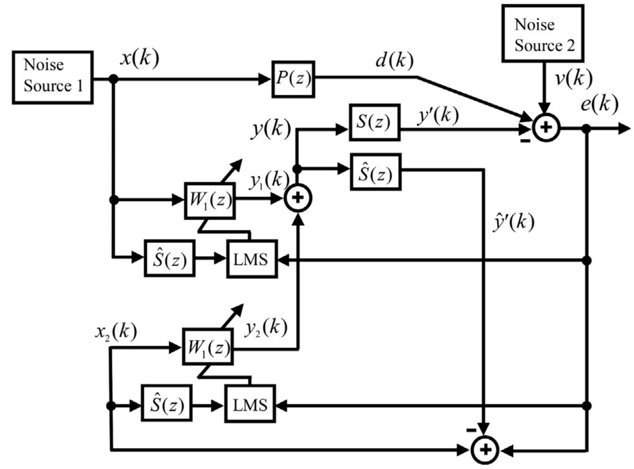

Fig. 1. A conventional HANC system.

2. HANC framework

A Conventional HANC (CHANC) system is built by combining both feedforward and feedback ANC systems as shown in Fig. 1 [2]. In the feedforward structure, the reference noise $x(k)$ is picked up by the reference sensor and another error sensor measures the $e(k)$, which is the error signal for the CHANC system. The cancelling loudspeaker generates the cancelling signal $y_1(k)$ to attenuate the primary noise and an uncorrelated narrowband disturbance given by $v(k)$. The input signal $x(k)$ is filtered by $\hat{S}(z)$ which is the approximation of the secondary path $S(z)$. The adaptive filter in the feedforward part, $W_1(z)$ is represented as the tap weight vector of length L_1, i:e $\mathbf{w}_1(k)=[w_1^0(k),w_1^1(k),...,w_1^{L_1-1}(k)]^T$. The reference signal for the feedforward part is given by $\mathbf{x}(k)=[x(k),x(k-1),...,x(k-L_1+1)]^T$, containing L_1 samples. Similarly, the feedback part consists of the control filter $W_2(z)$ and the reference signal $x_2(k)$. The noise cancelling adaptive filter is represented as the tap weight vector of length L_2, i:e $\mathbf{w}_2(k)=[w_2^0(k),w_2^1(k),...,w_2^{L_2-1}(k)]^T$, the L_2-sample reference signal for the feedback part is given by $\mathbf{x}_2(k)=[x_2(k),x_2(k-1),...,x_2(k-L_2+1)]^T$. The reference signal for the feedback part is synthesized by $e(k)$ and the secondary signal $y(k)$ which is filtered by the estimated secondary path $\hat{S}(z)$. The error signal for the CHANC system from Fig. 1 is

$$e(k)=d(k)+v(k)-s(k)*y(k), \tag{1}$$

where, the output is given as

$$y(k)=y_1(k)+y_2(k). \tag{2}$$

Here, $y_1(k)$ is the feedforward part cancelling adaptive filter $W_1(z)$ output given as,

$$y_1(k)=\mathbf{w}_1^T(k)\mathbf{x}(k), \tag{3}$$

where $\mathbf{w}_1(k)$ is the tap weight vector for the feedforward part cancelling filter $W_1(z)$ and $\mathbf{x}(k)$ is the reference signal vector. Similarly,

$$y_2(k)=\mathbf{w}_2^T(k)\mathbf{x}_2(k). \tag{4}$$

In the above equation, $\mathbf{w}_2(k)$ is the L_2 sample tap weight vector for and $\mathbf{x}_2(k)$ is the L_2-sample reference signal vector for the feedback part cancelling adaptive filter $W_2(z)$. Now, the error signal of the CHANC system from Fig. 1 is given as

$$e(k)=[d(k)-y_1'(k)]+[v(k)-y_2'(k)]. \tag{5}$$

The above equation is the error signal for the FXLMS algorithm for the adaptive filters $W_1(z)$ and $W_2(z)$ in a CHANC system. It can be observed