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Technical Note

A simplified adaptive feedback active noise control system

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ABSTRACT

In the adaptive feedback active noise control system based on the internal model control (IMC) structure, the reference signal is regenerated by synthesizing the error signal and the secondary signal filtered with the estimation of the secondary path, hence more computation load and extra programming are required. Motivated by the engineering truth that the primary noise cannot be completely cancelled in most practical active noise control applications and the error signal still contains some portions of the primary noise, a simplified adaptive feedback active noise control system is proposed in this paper, which adopts the error signal directly as the reference signal in an adaptive feedforward control system and utilizes the leaky filtered-x LMS algorithm to update the controller. The convergence properties of the proposed system are investigated and its advantages are discussed by comparing with other feedback control systems as well as the weakness. Finally, simulations and experiments are carried out to demonstrate the effectiveness of the proposed system.

1. Introduction

Active noise control (ANC) employs an electro-acoustic system to cancel the primary noise based on the principle of superposition, where an anti-noise (secondary signal) of equal amplitude and opposite phase is generated and combined with the primary noise to obtain the cancellation of both noises [1,2]. Feedback ANC system differs from the feedforward system in that it has no reference sensor to give time-advanced reference signal about the primary noise and is used in applications where the primary noise cannot be directly observed or there are too many primary noise sources to economically obtain reference signal [3–13]. Headset [5–7], headrest [8], headphones [9], double glazed window [10] and duct [11] are typical applications of feedback ANC because of its small scale.

Feedback ANC system can be classified into two types: non-adaptive system and adaptive system. The former achieves noise reduction by designing the fixed controller to have a high gain over the frequency band of interest but low gain at other frequencies. However, the stability and robustness problem may arise under changing conditions such as the non-stationary primary noises and the uncertain secondary path. Several techniques [3–11] have been proposed to design the non-adaptive feedback controller in an attempt to have both good noise reduction performance and sufficient stability. These techniques design the controller by formulating the performance specifications from practice into the optimization problem with various design criteria and constraints. It is known that most numerical algorithms to solve the optimization problem cannot be guaranteed to find a global optimal solution, abundant experience and repeated attempts are often required to obtain a satisfactory controller. Therefore, there is a need for the adaptive feedback system.

A single-channel adaptive feedback ANC system was proposed in [14] and then extended to the multiple channel case [15]. By regenerating the reference signal based on the internal model control (IMC) structure, i.e., using the secondary signal filtered by the estimation of secondary path and the error signal to synthesize it, the adaptive feedback system can be viewed as an adaptive feedforward system. Thus, an immediate advantage of IMC based adaptive feedback system is that the control filter can be adapted to minimize the mean square error and the widely used filtered-x least mean square (FxLMS) algorithm may be directly applied for the adaptation of the control filter [1,2]. Comparing with non-adaptive ANC system, the stability and robustness problem with the IMC based system becomes relatively simple since it depends on the complementary sensitivity function [2,16]. Under certain conditions, the IMC based adaptive ANC system can be interpreted as an adaptive predictor and its performance depends on the predictability of the primary noise.

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When using the IMC based adaptive feedback system, secondary path is usually modeled by a FIR filter that has hundreds of or even thousands of coefficients. Filtering the secondary signal through the estimated secondary path is a heavy burden for real time controllers, especially for the multiple channel ANC system, and such a computational burden is directly related to the increment of hardware cost. In this paper, a simplified adaptive feedback (SimpAFB) ANC system is proposed which adopts the error signal directly as the reference signal. In comparison with the IMC based system, the proposed system has twofold advantages. First, its computational load is lower because of elimination of the convolution operation required for generating the reference signal. Second, current commercial available active controllers usually employ the FxLMS algorithm, so the proposed system can be easily implemented by feeding the error signal directly to the reference input of the commercial available controller. However, the feasibility and properties of the proposed system are not clear, which will be the objectives of this paper.

2. The simplified adaptive feedback ANC system

2.1. Feedback ANC systems

For the sake of consistency, all signals in this paper are assumed to be represented in the discrete time domain with time index k. A model for a typical non-adaptive feedback ANC system is shown in Fig. 1. The electrical and acoustical path between the error sensor and the output of the controller is described by the secondary path $S(z)$, which contributes for the properties of the digital-to-analog converter (DAC), the power amplifier, the loudspeaker, the acoustic path and the analog-to-digital converter (ADC). The control filter $W_{na}(z)$ transforms the error signal $e(k)$ into the secondary signal $y(k)$ for the noise cancellation.

Assuming the existence of the z-transforms of $d(k)$ and $e(k)$, the closed-loop transfer function of the ANC system shown in Fig. 1 is given by

$$H_{na}(z) = \frac{E(z)}{D(z)} = \frac{1}{1 - S(z)W_{na}(z)} \tag{1}$$

Eq. (1) shows that significant noise reduction can be achieved by designing the controller $W_{na}(z)$ to have a large gain over the frequency of interest. Unfortunately, the frequency response of practical $S(z)$ can never be perfectly flat and free of shift, and the physical path from the secondary source to the error sensor introduce some delay due to the sound propagation time, resulting in the increased phase shift in $S(z)$ with frequency. The phase modification introduced by $S(z)$ may cause the system to be unstable if the phase shift approaches 180° and the negative feedback becomes positive feedback. Therefore, in practical non-adaptive feedback ANC systems, trade-off between the noise reduction and the stability under changing conditions due to non-stationary $d(k)$ and uncertain $S(z)$ must be considered. For example, the gain of $W_{na}(z)$ is limited to be not large enough to make the net loop gain greater than unity when the total phase shift becomes 180° [2]. As a result, it may be impossible to obtain the perfect cancellation of primary noise and the error signal still contains potions of primary noise in practical non-adaptive ANC systems.

It is known that the optimal $W_{na}(z)$ in Eq. (1) depends on the spectral properties of $d(k)$, as well as on the frequency response of $S(z)$. If the characteristics of $d(k)$ or/and $S(z)$ changes, the pre-designed $W_{na}(z)$ will not be optimal and $H_{na}(z)$ may be unstable, so an adaptive system is necessary to deal with these changes. The adaptive controller can make the feedback system stable over a larger range of changes and the IMC based adaptive feedback ANC system using the FxLMS algorithm is illustrated in Fig. 2. The basic idea is to estimate the primary noise and use it as a reference signal $x(k)$ for the control filter $W_a(z)$.

If the secondary path $S(z)$ is measurable and approximated by $\hat{S}(z)$, the reference signal can be synthesized as:

$$X(z) = E(z) - \hat{S}(z)Y(z) \tag{2}$$

The corresponding closed-loop transfer function of the IMC based system is

$$H_a(z) = \frac{E(z)}{D(z)} = \frac{1 + \hat{S}(z)W_a(z)}{1 - [S(z) - \hat{S}(z)]W_a(z)} \tag{3}$$

Even $S(z) = \hat{S}(z)$ is satisfied, the physical path from the secondary source to the error sensor introduces some delay due to the sound propagation time, so the synthesized reference signal is a delayed version of the primary noise, i.e., $x(k) = d(k-\Delta)$ and Δ is the approximated delay in $S(z)$. Thus the IMC based system in Fig. 2 acts as an adaptive predictor of $d(k)$ to minimize the residual noise $e(k)$ and its performance depends on the predictability of the primary noise $d(k)$. It is known that $d(k)$ may not be completely predictable in real noise conditions and consequently the perfect cancellation of primary noise is usually unpractical and the error signal often contains some potions of primary noise. In addition, Eq. (3) shows that the ideal solution is $W_a(z) = 1/S(z)$ for perfect noise control, i.e. $W_a(z)$ should be the inverse of $S(z)$, but $S(z)$ might be non-minimum phase and noninvertible because of the delay in it. This also limits the achievable performance, and perfect control cannot be obtained. On the other hand, perfect estimation of the secondary path response may also be difficult in practice because the secondary path response may be time-variable, the mismatch between the true secondary path response and its estimation always exists, and this may also influence the IMC based system performance. Therefore, the error signal contains potions of primary noise in practical IMC based ANC systems too.

2.2. The simplified adaptive feedback ANC system

A simplified adaptive feedback system (SimpAFB) is proposed in this paper, as depicted in Fig. 3, where the reference signal comes from the error signal directly, i.e.

$$X_{sa}(z) = E(z) \tag{4}$$

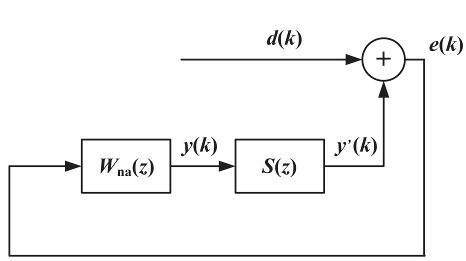

Fig. 1. Block diagram of the non-adaptive single-channel feedback ANC system.

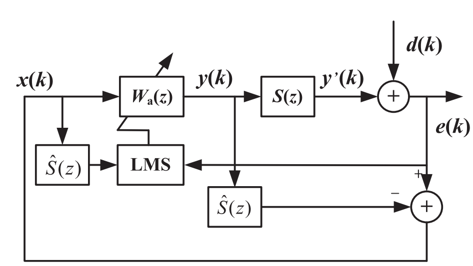

Fig. 2. Block diagram of the IMC based adaptive single-channel feedback ANC system using the FxLMS algorithm.