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Secondary path modeling for narrowband active noise control systems

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ABSTRACT

This work examines the performance of both offline and online secondary path modeling algorithms that are used in narrowband active noise control (NANC) systems. Theoretical analysis reveals that disturbances that are sensed by error sensors reduce the convergence rate and accuracy of adaptive system identification. In a parallel-structure narrowband active noise control system, a filterbank is applied to partition the full-band excitation and error signals to utilize an independent and lower-order secondary-path modeling filter for every channel. This method increases convergence speed and modeling accuracy. The results of an analysis and improved performance are confirmed by simulations in which measured transfer functions are used.

1. Introduction

Most practical active noise control (ANC) systems use the filtered-X least mean square (FXLMS) algorithm, which requires an estimate of the secondary path to update adaptive noise control filters. The secondary path includes both electrical and acoustic components from the output of the ANC filter to the output of the error microphone. Generally, a secondary path includes a DAC (digital-to-analog converter), reconstruction (low pass) filter, power amplifier, loudspeaker, acoustic path information, error sensor and preamplifier, anti-aliasing (low pass) filter, and an ADC (analog-to-digital converter) [1].

Rotating machines, such as engines, generate narrowband noise that comprises numerous tonal components at the fundamental frequency and its harmonics. Fig. 1(a) displays the direct-structure NANC system. The narrowband primary noise $d(n)$ is assumed to comprise k harmonics, and is expressed as

$$d(n) \triangleq = \sum_{i=1}^{k} d_i(n) + u(n) \tag{1}$$

where $d_i(n)$ is the narrowband noise and $u(n)$ is the disturbance at frequency ω_i for $i = 1,\cdots,k$. The internally generated reference signal $x(n)$ is the sum of k sinusoids

$$x(n) = \sum_{i=1}^{k} x_i(n) = \sum_{i=1}^{k} \cos(\omega_i n) \tag{2}$$

where $x_i(n)$ is the ith reference sinusoidal signal which has the same frequency as the respective $d_i(n)$. Besides, the $P(z)$ and $S(z)$ denote the primary and secondary paths transfer functions, and $W(z)$ is the adaptive filter updated by the FXLMS algorithm based on the measured error signal $e(n)$. Notably, the FXLMS algorithm utilizes the secondary path model $\hat{S}(z)$ to compensate for the characteristics of secondary path $S(z)$.

Based on the assumption that the effects of $S(z)$ are time-invariant but unknown, a NANC system may utilize an offline modeling method to model $S(z)$ in the initialization stage before activating the ANC, and then the estimated model $\hat{S}(z)$ is applied to realize the FXLMS algorithm during online ANC operation [2,3]. Because white noise has a uniformly distributed spectral density across all frequencies, it is commonly used as the excitation signal for the adaptive identification of $S(z)$ in most practical applications [1]. Fig. 1(b) displays the offline secondary path estimation method, where $v(n)$ is the internally-generated white noise; the model $\hat{S}(z)$ is an adaptive filter that is updated by the LMS algorithm, and $u(n)$ represents the disturbance.

There are some research discussing about active noise control systems with additive disturbances [4–7]. When the secondary path is time varying, it may be required to continuously estimate $S(z)$ online while ANC is in operation. Several online secondary path modeling techniques using extra random noise were developed [8–13]. A block diagram of the FXLMS-based ANC system with the online secondary path modeling is illustrated in Fig. 1(c), which adds the auxiliary white noise $v(n)$ as the excitation signal to the anti-noise $y(n)$ for the modeling purpose [8]. The estimated secondary path model $\hat{S}(z)$ is copied to filter the reference signal $x(n)$. In the figure, the measured disturbance $u(n)$ corrupts the residual noise $e(n)$ that is picked up by the error sensor. Numerous researchers have analyzed this method and developed improved online secondary path modeling methods. Kuo and

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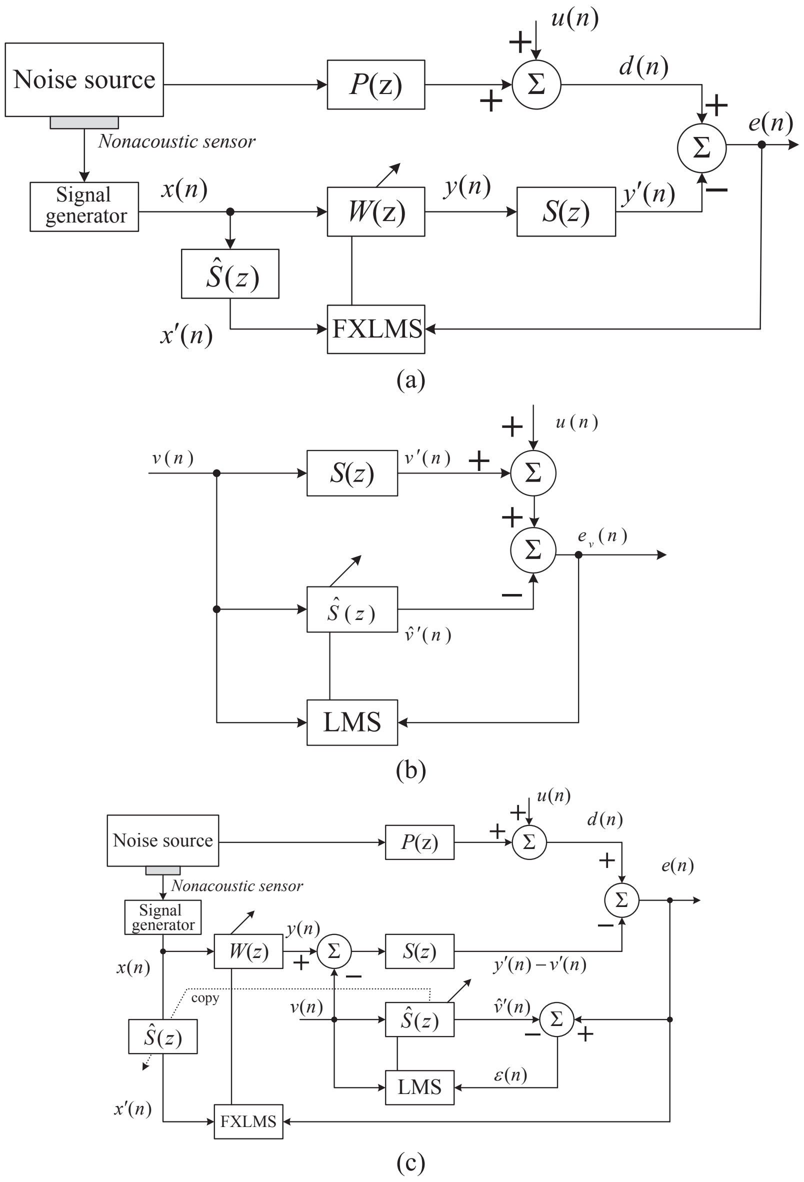

Fig. 1. Narrowband active noise control system (a) direct form, (b) offline secondary path estimation method, (c) online secondary path estimation method.

Vijayan eliminated the disturbance using an adaptive predictor to track error signal for adaptation [9]. Gaiotto proposed a tuning-less method that was based on the given modeling mean square error (MSE) [10]. A convergence analysis of the online secondary path modeling method was carried out in terms of weight estimation error [11]. Ahmed, Akhtar, and Zhang presented a two-stage gain scheduling strategy to control the power of injected auxiliary random noise, improving the noise reduction of the ANC system [12]. Chan and Chu developed a method for decoupling the noise cancellation from the secondary path estimation to analyze the performance of the overall ANC system [13]. They also derived the steady-state excess MSE of the secondary path estimator. Some online secondary path modeling methods that do not use extra random noise have also been proposed [14,15]. Some researchers have also examined the ANC system without or with an imperfect secondary path model [16–20]. Their works are based on broadband ANC systems. In contrast, this work analyzes narrowband ANC systems and proposes an effective algorithm for improving both offline and online secondary-path modeling.

In this work, the convergence rate and accuracy of both offline and online secondary path modeling for broadband and narrowband ANC systems are analyzed, and then a filterbank is utilized to partition both the excitation signal and the error signal for a parallel-structure NANC system. In this enhanced algorithm, each channel estimates only the secondary path at the respective sub-band with a small bandwidth. Therefore, the filter length of the secondary path estimate in every channel can be significantly decreased. The bandpass filter also eliminates the out-of-band disturbance and residual noise that is picked up by the error signal. Theoretical analysis and computer simulations demonstrate that the new algorithm can improve the convergence rate and the accuracy of both online and offline secondary path modeling for NANC systems. Notably, the proposed secondary path modeling method can be used for narrowband active noise equalization [21] to improve the subjective performance.

The remainder of the paper is organized as follows. Section II reviews some conventional secondary path modeling techniques. Both offline and online methods are discussed and the performance degradation due to the disturbance is analyzed. Section III introduces an enhanced algorithm that uses a bandpass filterbank to partitioning both the excitation and error signals for the secondary path modeling at each sub-band with a lower-order filter, and analyzes its performance enhancement. Section IV uses computer simulations with the measured transfer functions to verify theoretical analysis and demonstrate improved performance of the proposed technique.