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Brief paper

New FIR filter-based adaptive algorithms incorporating with commutation error to improve active noise control performance☆

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Abstract

This study considers a commutation error (CE) that results from a difference associated with the altered sequence in real active noise control (ANC) applications as compared with that at the derivation stage. New adaptive algorithms are developed as FxLMS/CE, FxNLMS/CE and FxRLS/CE in an aim to eliminate the CE-associated disturbance and to liberate the restriction of slow adaptation imposed on the existing adaptive algorithms in the ANC applications. Computer simulations show that the rate of convergence is greatly improved for the new adaptive algorithms as compared with that of the conventional algorithms. In parallel with the improved rate of convergence, simulations exhibit efficient ANC performance for all CE-based algorithms. The best ANC performance is seen for FxRLS/CE algorithm that can acquire ~ 2 s of convergence rate and ~ 34 dB reduction of sound pressure level for band-limited white noise. All experimental results indeed demonstrate enhanced ANC performance; the FxNLMS/CE algorithm can acquire ~ 2 s of convergence rate and ~ 20 dB reduction of sound pressure level for band-limited white noise. Our data together support the effectiveness to include CE into the FIR filter-based adaptive algorithms for superior ANC performance with respect to the convergence speed and noise reduction level.

Keywords: Active noise control; Commutation error; Residual error; Finite impulse response filters; Adaptive algorithms; Convergence speed

1. Introduction

Active noise control (ANC) technology can effectively reduce undesired low-frequency noise as compared with the passive techniques such as use of absorbent materials for high-frequency noise (Kuo & Morgan, 1996; Lin & Liao, 2001). Adaptive digital filter acts as an ANC controller to generate control signal to the secondary source (Burgess, 1981; Nelson & Elliott, 1992). An adaptive digital filter consists of two distinct parts: a digital filter to perform the desired signal processing, and an adaptive algorithm using a reference signal and a residual error to adjust the coefficients (weights) of that filter. Based on a finite-impulse-response (FIR) structure, adaptive digital filter with a filtered-x least mean square (FxLMS) algorithm is most widely used for ANC applications due to the relative simplicity in design and implementation (Morgan, 1980; Snyder & Hansen, 1994). The FxLMS algorithm is derived based on an assumption of slow adaptation. The FxLMS has a convergence factor (or step size) to control stability (Douglas & Meng, 1994). A small value of step size is commonly used in real ANC applications to guarantee satisfaction of the assumption of slow adaptation to ensure convergence of the algorithm. In practices, very high order of FIR filter must be used with the FxLMS adaptive algorithm to achieve effective noise attenuation. As a result, adaptive FIR filter with FxLMS algorithm generally has a slow convergence performance.

To improve convergence speed of FIR-based adaptive filters, a filtered-x recursive least squares (FxRLS) algorithm is further proposed for updating weights. Again, the assumption of slow adaptation is utilized so that transfer function of the FIR filter and transfer function of the secondary path can be

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commuted in the derivation of the FxRLS algorithm. In the absence of convergence factor, a low-order FIR filter is applied with this algorithm to achieve effective noise attenuation. Unlike FxLMS algorithm, a fast adaptation rate nonetheless can appear intermittently in real ANC applications, which leads to a violation of the assumption of slow adaptation and hence results in a convergence failure. Other adaptive algorithms such as IIR-based filtered-u recursive LMS (FuLMS) algorithm for ANC applications (Wang & Ren, 1999) are also restricted by the slow-adaptation assumption.

In this study, we propose a novel approach to include a commutation error in addition to the conventional residual error for design of adaptive filters for ANC, allowing the system to exclude the restrain of slow adaptation. We first define a commutation error from commutation of FIR-filter transfer function and secondary-path transfer function on a reference signal. A new residual error that combines this commutation error with the conventional residual error is then utilized to develop new LMS- and RLS-based adaptive algorithms for FIR filters. Computer simulations and experiments are then conducted to evaluate the performance of the developed algorithms in ANC applications.

2. Commutation error and new residual error

Consider a block diagram of ANC system described in Fig. 1 where $H_{P1}(z)$ and $H_{P2}(z)$ denote transfer functions of primary path and secondary path, respectively.

An adaptive filter $W(z)$ is connected in series to $H_{P2}(z)$. Let $W(z)$ be an FIR filter of order L, i.e.

$$W(z) = w_0 + w_1 z^{-1} + \cdots + w_{(L-1)} z^{-(L-1)}. \tag{1}$$

Define weight vector $\boldsymbol{w}^{\mathrm{T}}(n)$ and reference signal vector $\boldsymbol{x}^{\mathrm{T}}(n)$, respectively, as

$$\boldsymbol{w}^{\mathrm{T}}(n) = [w_0(n)\ \ w_1(n) \cdots w_{(L-1)}(n)], \tag{2}$$

$$\boldsymbol{x}^{\mathrm{T}}(n) = [x(n)\ \ x(n-1) \cdots x(n-L+1)]. \tag{3}$$

Output of the FIR filter can then be represented as

$$y(n) = \boldsymbol{w}^{\mathrm{T}}(n)\boldsymbol{x}(n). \tag{4}$$

Measured output of the system can also be obtained as

$$e(n) = d(n) + y'(n), \tag{5}$$

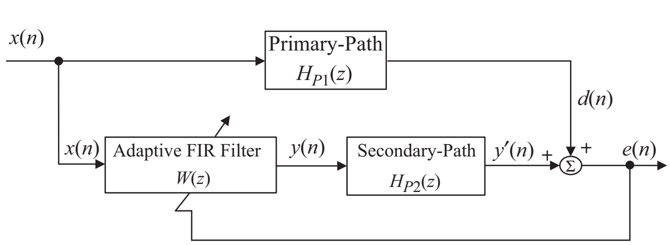

Fig. 1. Block diagram of ANC system.

where $d(n)$ denotes noise generated via the primary path and

$$y'(n) = h_{P2}(n) * y(n), \tag{6}$$

where $h_{P2}(n)$ is the impulse response of $H_{P2}(z)$, and "$*$" denotes linear convolution. Let a desired performance output be given as $e_{\mathrm{desired}}(n) = 0$. Then a conventional residual error is defined as

$$\varepsilon(n) \equiv e_{\mathrm{desired}}(n) - e(n) = -e(n). \tag{7}$$

Notably, there is altered sequence between the derivation stage and the ANC applications: the sequence is (signal $\boldsymbol{x}(n) \rightarrow$ secondary path $(H_{P2}(z)) \rightarrow$ adaptive FIR filter $(W(z)) \rightarrow$ output) at derivation, while that is (signal $\rightarrow$ adaptive FIR filter $\rightarrow$ secondary path $\rightarrow$ output) in the ANC applications. A commutation error is thus considered to represent a potential difference associated with the altered sequence as below. Define a commutation error (CE) as

$$\varepsilon_{\mathrm{COM}}(n) \equiv \boldsymbol{w}^{\mathrm{T}}(n)\boldsymbol{x}'(n) - y'(n), \tag{8}$$

where

$$\boldsymbol{x}'(n) = h_{P2}(n) * \boldsymbol{x}(n). \tag{9}$$

Utilizing (5) and (8) for (7), we rewrite the conventional residual error as

$$\varepsilon(n) = -d(n) - \boldsymbol{w}^{\mathrm{T}}(n)\boldsymbol{x}'(n) + \varepsilon_{\mathrm{COM}}(n). \tag{10}$$

$\boldsymbol{w}(n)$ is usually assumed to vary slowly in the derivation stage, i.e.

$$\varepsilon(n) \approx -d(n) - \boldsymbol{w}^{\mathrm{T}}(n)\boldsymbol{x}'(n). \tag{11}$$

Such an approximation nonetheless imposes a restriction on the adaptation speed of $\boldsymbol{w}(n)$.

Here, we take account of commutation error and define a new residual error as

$$\varepsilon_N(n) \equiv \varepsilon(n) - \varepsilon_{\mathrm{COM}}(n), \tag{12}$$

where the commutation error present in the conventional residual error is eliminated to obtain the new residual error. Note that when $\boldsymbol{w}(n)$ becomes a constant vector, $\varepsilon_{\mathrm{COM}}(n)$ equals zero and $\varepsilon_N(n)$ equals $\varepsilon(n)$. To derive adaptive algorithm, we utilize (10) to rewrite the new residual error as

$$\varepsilon_N(n) = -d(n) - \boldsymbol{w}^{\mathrm{T}}(n)\boldsymbol{x}'(n). \tag{13}$$

3. Adaptive algorithms with new residual error

3.1. LMS-based adaptive algorithm

3.1.1. Derivation of adaptive algorithms

Define a cost function as $[-d(n) - \boldsymbol{w}^{\mathrm{T}}(n)\boldsymbol{x}'(n)]^2$. A LMS-based adaptive algorithm for weight vector update to minimize the cost function can be derived as

$$\boldsymbol{w}(n+1) = \boldsymbol{w}(n) + \mu\boldsymbol{x}'(n)[-d(n) - \boldsymbol{w}^{\mathrm{T}}(n)\boldsymbol{x}'(n)], \tag{14}$$

where μ is a step size. Results of convergence analysis of (14) have been reported in the literature. To ensure stability, μ is restricted to $0 < \mu < 2/\lambda_{\max}$ where $\lambda_{\max}$ is the largest eigenvalue