

Modified FxLMS Algorithm with Equalized Convergence Speed for Active Control of Powertrain Noise

Guohua Sun, Tao Feng, Ji Xu, Mingfeng Li, and Teik Lim
University of Cincinnati

ABSTRACT

Current powertrain active noise control (ANC) systems are not sufficient enough to track the fast engine speed variations, and yield consistent convergence speeds for individual engine order such that a balanced noise reduction performance can be achieved over a broad frequency range. This is because most of these ANC systems are configured with the standard filtered-x least mean squares (FxLMS) algorithm, which has an inherent limitation in the frequency-dependent convergence behavior due to the existence of secondary path model (electro-acoustic path from the input of control loudspeaker to the output of monitoring error microphone) in the reference signal path. In this paper, an overview is given first to compare several recently modified FxLMS algorithms to improve the convergence speed for harmonic responses such as eigenvalue equalization FxLMS (EE-FxLMS) and normalized reference LMS (NX-LMS) algorithms. Then, a novel modified FxLMS algorithm, termed as the inverse model LMS (IMLMS) algorithm, is proposed as the basis for active powertrain noise control. The proposed algorithm is realized by utilizing the inverse model of the secondary path, either cascading at the output of adaptive filter or adding in the reference signal generator, to minimize the effect of its dynamic on the algorithm's convergence. To validate the effectiveness of the proposed algorithm, numerical simulations using measured powertrain noise responses are also performed. Results show comparable convergence speeds at individual engine order and appreciable noise reductions over a broad engine rotational speed range.

CITATION: Sun, G., Feng, T., Xu, J., Li, M. et al., "Modified FxLMS Algorithm with Equalized Convergence Speed for Active Control of Powertrain Noise," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(3):2015, doi:10.4271/2015-01-2217.

INTRODUCTION

Active noise control (ANC) technology has been under extensive research and development over the last two decades. Very recently, the commercialization of this technology has grown and expanded into many industrial noises control applications. In particular, many vehicle models with built-in ANC modules have been released by several major OEMs during the last five years. One of the major situations behind this is that the ANC solution is an effective alternative to the traditional passive noise control (PNC) approaches, especially for mitigating the lower-frequency powertrain and road noises. The basic idea of ANC involves driving a number of actuators (loudspeakers) to create a sound that is out of phase with the noise generated by the vehicle, thus attenuating it by destructive interference. This technique utilizes the acoustic wave propagation characteristic of engine and road noises, which yields a unique advantage in the low-to-middle frequency (long-wave length) noise control. Moreover, it provides an effective way to tune the sound spectrum dynamically rather than simply suppressing the sound pressure levels to achieve a better sound quality. Hence, it has been an attractive topic both in academic and industry [1, 2, 3, 4, 5, 6, 7, 8, 9].

There are a substantial amount of studies reported in the open literature on ANC of vehicle interior noise such as powertrain-related noise [10] and road noise [7, 8, 11]. These applications are mainly for enclosed spaces like vehicle interior cabin. In addition, ANC has been applied to the attenuation of vehicle exterior exhaust noise. The idea

of an active muffler has been proposed in multiple research papers. For instance, an early patent was granted to Ziegler and Gardner [12] for the design of active sound attenuation system for engine exhaust pipes. Their control system used a feedforward control by synchronization with the engine speed in revolution per minute (rpm). Detailed technical papers and recent patents reviews on vehicle ANC applications can be found in the following references [4, 6].

In spite of above reported success of implementing ANC to refine the overall NVH (noise, vibration and harshness) performance, current powertrain ANC systems may not efficient enough to provide consistent convergence speeds for individual engine order, and capable enough to track the fast engine speed variations. This is because most of these ANC systems are realized by adaptive filters with the standard filtered-x least mean squares (FxLMS) algorithm, which exhibits a frequency-dependent convergence behavior due to the eigenvalue spread of the autocorrelation matrix of the filtered reference signal especially with the existing of secondary path model. This paper will give a review on recent advances of ANC system design and algorithm development, and their potential applications for powertrain noise control such that the capability of ANC in vehicle can be further sought out. Moreover, numerical simulations using measured powertrain noise responses are also performed to demonstrate the effectiveness of the proposed algorithm (IMLMS). Results show obvious improvement in the convergence speed and appreciable noise reductions over a broad engine rotational speed range.

CONTROLLER WITH MODIFIED ALGORITHMS

FxLMS Algorithm

The common single-channel feedforward ANC system, as shown in Figure 1, is realized by an adaptive digital filter with the common FxLMS algorithm. Here, $x(n)$ is the reference signal (i.e. sinusoidal signal generated from the tachometer signal), $d(n)$ is the primary noise (i.e. powertrain noise) and $e(n)$ is the error signal after superposition of the primary noise and secondary canceling noise.

The FxLMS algorithm uses the reference signal $x(n)$ to generate the secondary noise adaptively, which is adjusted by the error signal $e(n)$. The reference signal $x(n)$ is internally synthesized based on the engine rotational speed that can be estimated from the tachometer impulse train signal. This can be expressed as:

$$x(n) = \cos(2\pi n f_i / F_s) \quad (1)$$

where n is the time index, i is the engine order index, $f_i = iv/60$ is the frequency of the i -th order, v is the engine speed in rpm (revolution per minute), and F_s is the sampling rate. In the traditional system using the FxLMS algorithm, $x(n)$ needs to be filtered by the secondary path model $\hat{S}(z)$ that relates the dynamic behavior from the control speaker input signal to the error microphone in order to compensate the phase delay and magnitude response incurred by the real secondary path $S(z)$. This secondary path model is normally estimated by using an offline system identification approach before the ANC system is activated. The FxLMS algorithm can be summarized as:

$$e(n) = d(n) - y(n) \quad (2)$$

$$y(n) = \mathbf{S} * [\mathbf{W}^T(n) \mathbf{X}(n)] \quad (3)$$

$$\mathbf{W}(n+1) = \mathbf{W}(n) + \mu e(n) [\hat{\mathbf{S}} * \mathbf{X}(n)] \quad (4)$$

where n is the time index, $\mathbf{S}$ is the impulse response of the secondary path, $*$ denotes the linear convolution of the adaptive filter output with the secondary path, and the filter weights and reference signal vector of the controller are:

$$\mathbf{W}(n) = [w_0(n) \quad w_1(n) \quad \cdots \quad w_{L-1}(n)]^T \quad (5a)$$

$$\mathbf{X}(n) = [x(n) \quad x(n-1) \quad \cdots \quad x(n-L+1)]^T \quad (5b)$$

In Eq. (4), μ is the convergence step size, which determines the convergence speed and stability of the FxLMS algorithm, and L is the order of the adaptive filter. The convergence speed is determined by the eigenvalue spread of the autocorrelation matrix of the filtered

reference signal vector. As noticed that the spectrum of the powertrain noise is typically dominated by harmonics that distribute over a large frequency range for different engine rotation speeds. Also, the frequency response of the secondary path is varying. Hence, applying the standard FxLMS algorithm for powertrain ANC might have inherent performance limitation due to the frequency-dependent convergence behavior. In the following section, several modified FxLMS algorithms will be reviewed and discussed in order to enhance the control performance.

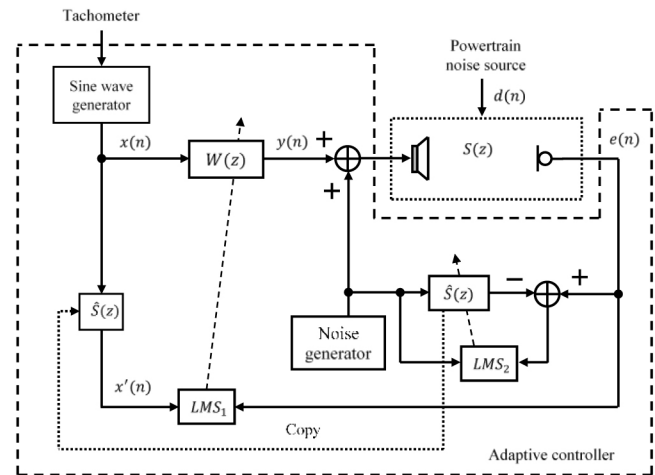


Figure 1. Control diagram of powertrain ANC system using FxLMS.

EE-FxLMS Algorithm

An eigenvalue-equalization FxLMS (EE-FxLMS) algorithm was proposed by Thomas et al. [13] that works by flattening the magnitude response of the secondary path model while keeping the phase unchanged. The amplitude equalization can be simply realized by taking the FFT and normalizing the magnitudes of each frequency bin in the estimated secondary path model. Then, Sun et al. [14] applied this algorithm for vehicle powertrain noise control, the control diagram is as shown in Figure 2. Similar idea was extended by Duan et al. [3] to balance the magnitude differences between various control channels.

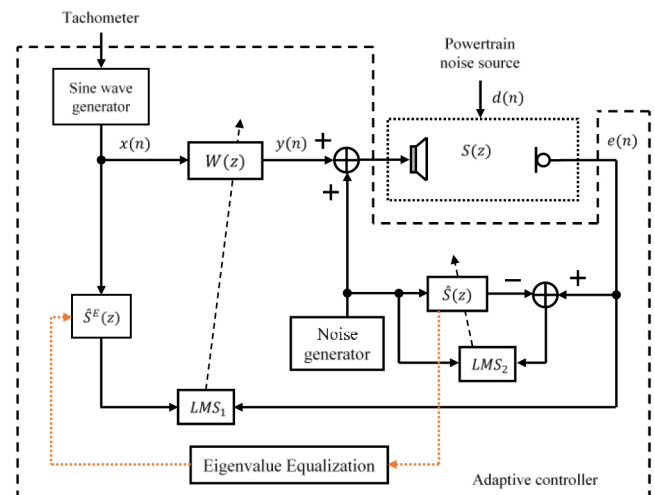


Figure 2. Control diagram of powertrain ANC system using EE-FxLMS.