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Active control of vehicle powertrain noise using inverse model LMS algorithm

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ABSTRACT

Current active noise control (ANC) technology cannot yield a balanced performance over broad frequency range when applied to powertrain noise control. It is because most of these ANC systems are configured with the traditional filtered-x least mean squares (FXLMS) algorithm with an inherent limitation in the frequency-dependent convergence behavior. In particular, the phase delay of the secondary path in the FXLMS algorithm will significantly affect the convergence speed and thus lead to a relatively poor tracking ability for the transient event. In this study, a novel inverse model least mean square (IMLMS) algorithm is proposed for active powertrain noise control system with an enhanced convergence speed in order to better track the variation of noise signatures due to unavoidable change in the engine speed. The IMLMS algorithm is realized by utilizing the inverse model of the secondary path to minimize the effect of its dynamics on algorithm's convergence to gain a significant improvement in the convergence speed and tracking ability. Numerical simulation using measured powertrain noise responses is also performed to demonstrate the effectiveness of the proposed algorithm. Results show obvious improvement in the convergence speed and appreciable noise reductions over a broad engine rotational speed range.

Keywords: ANC, FXLMS, Inverse model LMS I-INCE Classification of Subjects Number(s): 38.2

1. INTRODUCTION

Active noise control (ANC) technology has attracted extensive research interests in academia and industry during the last several decades. Recently, this technology has been successfully implemented in automotive industry since it provides an alternative solution to refine the noise, vibration and harshness (NVH) performance in order to further fulfill the demanding requirements from customers. In vehicle interior acoustic responses, powertrain noise is typically dominant when the engine is in idle or changing speeds. The signature of powertrain noise is normally characterized by various harmonics in the lower audible frequency range that is directly related to the engine rotational speed. Because of the tonal nature, it can be very annoying and negatively affect the interior sound quality (1, 2). Hence, major automotive manufacturers have recently released their ANC products to control and tune the engine noise (2-6) inside a vehicle cabin. However, most of these ANC systems are using traditional filtered-x least mean square error (FXLMS) algorithm that has inherent limitations due to the frequency-dependent convergence behavior. This is because the convergence speed of the FXLMS algorithm is determined by the eigenvalue spread of the autocorrelation matrix of the filtered reference signals (7, 8). Hence, there might be an optimal step size for each frequency. It is very desirable to avoid this limitation when designing an adaptive algorithm for powertrain noise control, especially for the large number of harmonics clustered over a broad frequency range as the engine speed changes.

To overcome the frequency-dependent convergence limitation in the traditional FXLMS algorithm, several techniques have been proposed by researchers. Elliott and Cook (9) proposed a preconditioned LMS algorithm that can whiten the reference signal by using the inverse of minimum phase part of secondary path model (representing the transfer function from input of the control speaker to the output of error microphone). Kuo et al. (10) suggested that the amplitudes of the reference signals should be chosen to be inversely proportional to the magnitude response of the secondary path such that the convergence step size is optimal for all frequency components. Based on this similar idea, Li

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et al. (4) proposed a modified narrowband ANC system for tuning the powertrain noise inside a cabin. In this proposed algorithm, an effective step size is derived that can be easily set for all harmonics. However, these manual tunings are relatively cumbersome in practice. Recently, an eigenvalue-equalization FXLMS (EE-FXLMS) algorithm was proposed by Thomas et al. (11, 12) 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. The EE-FXLMS algorithm has shown a significant improvement for multi-harmonic and time-varying frequency control. Enlightened by the eigenvalue equalization algorithm, Duan et al. (5) proposed the channel-equalization FXLMS (CE-FXLMS) algorithm that tends to balance the magnitude differences between various control channels for multi-channel ANC system (multiple control speakers and error microphones). Note the EE process can also be implemented in individual channel to formalize the CE-EE-FXLMS algorithm. The improved performance for multi-channel vehicle powertrain noise control has been demonstrated in Reference (5). Although these recent improvements work well, only the magnitude of the secondary path model and/or amplitude of the reference signal are tuned. The phase delay of the secondary path model still exists in the reference signal path, which also affects the convergence speed (7, 8). Very recently, Li et al. (13, 14) proposed the inverse model LMS (IMLMS) algorithm by adding the inverse model of the secondary path at the output of the control filter to compensate for both the phase delay and amplitude simultaneously. Here, only the LMS algorithm is applied to update the control filter parameters. Hence, the performance is more optimal at each harmonic frequency since the convergence speed is optimal when keeping the power of the reference signals the same for all frequency components. In addition, the computational cost is reduced since there is no convolution operation in the reference signal path. The IMLMS algorithm is not appropriate for broadband disturbance since for most cases the secondary path is a non-minimum phase system. Fortunately, the non-casual filter can be easily found and used for harmonic noise control. The efficacy of IMLMS algorithm demonstrated a promising solution for harmonic noise control occurring in rotatory machineries (13, 14).

The objective of this paper is to design an ANC system for powertrain noise control based on the IMLMS algorithm. The performance of the designed system is validated through numerical simulation by using real measured engine noise data. Here, only the steady-state engine noise control results are shown for engine running at constant rotational speeds. The simulation results demonstrate an enhanced performance of the IMLMS algorithm for control of multi-harmonic engine order noises as compared to the traditional FXLMS and EE-FXLMS algorithms. The description of the control system will be illustrated in the following section.

2. CONTROLLER DESCRIPTION

The traditional ANC system configured with the common FXLMS algorithm for vehicle powertrain noise can be found in References (2, 4, 15). In this section, the IMLMS algorithm proposed by Li et al. (13, 14) is developed for active powertrain noise control. Figure 1 shows the control flowchart of the proposed IMLMS system. 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:

$$x(n) = \cos(2\pi n f_i / F_s) \tag{1}$$

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 inclusion of secondary path model in the reference signal path significantly affects the convergence performance at various frequencies since each frequency has individual optimal step size. The IMLMS algorithm can essentially avoid the frequency-dependent convergence limitation since an inverse model of the secondary path is added in the output path of the control filter $W(z)$. This implementation can not only compensate the phase delay but also equalize the amplitude caused by the secondary path. Hence, the standard LMS algorithm is applied to update the control filter parameters.

One can simply synthesize the reference harmonic signals at various frequencies with unit amplitude without the cumbersome tuning of the step sizes and/or reference signal amplitudes (4). The second implementation of the IMLMS algorithm described in Reference (13) is used in this study.

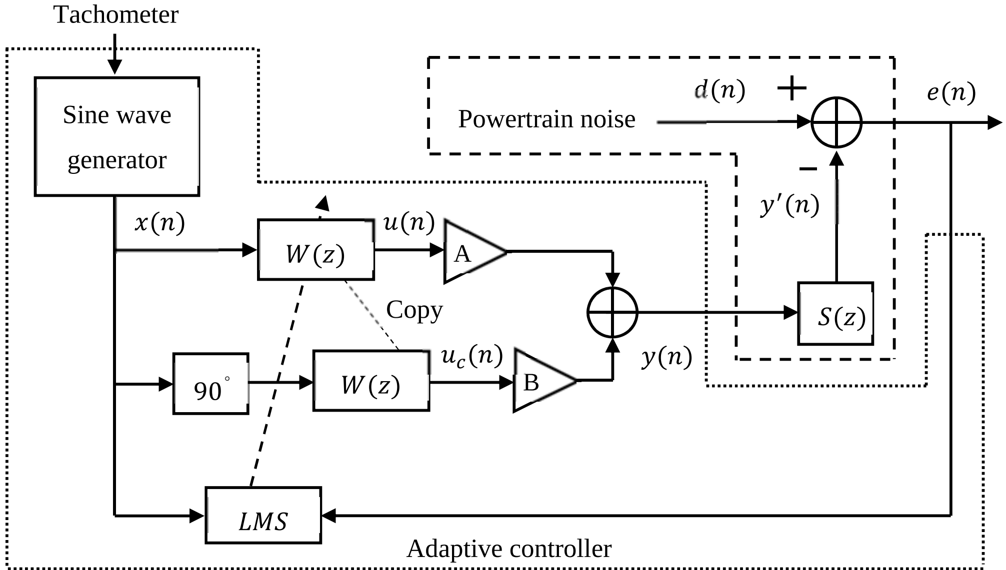

Figure 1 – Control diagram for active powertrain noise control system using IMLMS.

The frequency response of the secondary path at particular sinusoidal frequency can be expressed as $S(j\omega_0) = Re + jIm$, then the inverse model can be expressed as:

$$1/\hat{S}(j\omega_0) = 1/(Re + jIm) \tag{2}$$

where ω_0 is the circular frequency of the reference signal, and Re and Im are the real and imaginary parts of the secondary path response, which can be estimated from the standard system identification approach. The phase and gain of the inverse secondary path model is $\phi = \arctan(-Im/Re)$ and $g = 1/\sqrt{Re^2 + Im^2}$, respectively. It is known that the output of the control filter is also a sinusoidal signal with the same frequency as the reference but with certain phase shifted (ϕ_0) and magnitude modified (multiplied by gain g_0). Similarly, the output of the control filter filtered by the inverse model of the secondary path is also phase shifted by ϕ and amplitude tuned by g. Hence, the control signal $y(n)$ should be $y(n) = gg_0\cos(2\pi n f_i/F_s + \phi_0 + \phi)$. Fortunately, one can easily obtain through:

$$y(n) = gg_0\cos(2\pi n f_i/F_s + \phi_0 + \phi) = Ag_0\cos(2\pi n f_i/F_s + \phi_0) + Bg_0\sin(2\pi n f_i/F_s + \phi_0) \tag{3}$$

where the term $\sin(2\pi n f_i/F_s + \phi_0)$ can be calculated as shown in Figure 1 by performing a 90°conversion of the reference signal and then filtering through the same control filter weights. Here, constants A and B are related to the terms Re and Im as shown in equation (2). Then filter weight update equation of the IMLMS algorithm can be summarized as:

$$u(n) = \boldsymbol{W}(n)^T\boldsymbol{X}(n) \tag{4a}$$

$$u_c(n) = \boldsymbol{W}(n)^T\boldsymbol{X}_c(n) \tag{4b}$$

$$y(n) = Au(n) + Bu_c(n) \tag{4c}$$

$$e(n) = d(n) - y'(n) \tag{4d}$$

$$\boldsymbol{W}(n+1) = \boldsymbol{W}(n) + \mu e(n)\boldsymbol{X}(n) \tag{4e}$$

where $y'(n)$ is the secondary canceling wave, the filter weights of the controller is denoted as: $\boldsymbol{W}(n) = [w_0(n) \quad w_1(n) \quad \cdots \quad w_{L-1}(n)]^T$, L is the order of the control filter, and reference signal vector is $\boldsymbol{X}(n) = [x(n) \quad x(n-1) \quad \cdots \quad x(n-L+1)]^T$. The reference signal vector for the second auxiliary filter is $\boldsymbol{X}_c(n) = [x_c(n) \quad x_c(n-1) \quad \cdots \quad x_c(n-L+1)]^T$, and $x_c(n) = \sin(2\pi n f_i/F_s)$ corresponding to the 90 degree transformation of the original reference $x(n)$ as shown in Figure 1.

3. NUMERICAL SIMULATION

The performance of the proposed control system using the proposed IMLMS algorithm has been simulated in a numerical environment (16). In those simulations, primary powertrain disturbances along with the tachometer signal are recorded on an on-road vehicle with V6 engine at different rotational speeds. Two cases are considered in this study: one is for engine rotating around 4000 rpm and the other is about 2000 rpm. The estimated engine speed according to the tachometer signal is shown in Figure 2(a). The fundamental rotational speed of the engine crankshaft is used to synthesize the cosine wave reference signal. The ANC system is designed to attenuate the dominant engine order noises around the driver and passenger head positions as much as possible. Here, engine orders 1.5, 2.0, 2.5 and 3.0 are used for the analysis. The monitoring error microphones are placed at the ceiling of the vehicle cabin above the heads. The estimated transfer function of the secondary path from loudspeaker to the sound pressure at the error microphone was measured experimentally using an off-line system identification approach. The frequency response function of the secondary path model used in this simulation is as shown in Figure 2(b). The secondary path model is formulated as a finite impulse response (FIR) filter with order 256. Taking the Fourier Transform of the estimated impulse response function, the inverse model constants A and B for the respective reference frequency can be determined. The sampling frequency for data acquisition is 4096 Hz.

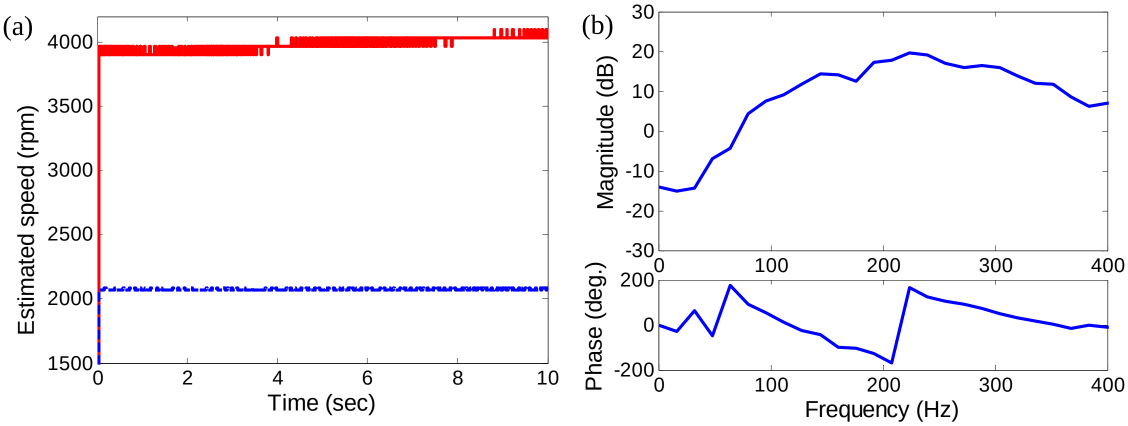

Figure 2 – (a) Estimated engine speed from the tachometer signal and (b) Frequency response function of the secondary path from control speaker to the error microphone
(Keys: blue dashed line – – –, 2000 rpm; red solid line ——, 4000 rpm).

Figure 3 compares the magnitude spectrum for engine speed around 2000 rpm of the baseline primary response to those controlled using the conventional FXLMS and the proposed IMLMS algorithms. Note the amplitudes of the reference signals at different engine orders are set to unity. As seen from Figures 3(a-b), the FXLMS algorithm shows very poor performance at the 2^{nd} order while it can yield similar noise reductions as the IMLMS algorithm at order 3. This is because the filtered reference signal power is very low at the 2^{nd} order, which requires a large step size to have a fast convergence with significant noise reduction at the same time. In comparison, the newly developed IMLMS algorithm shows more balanced performance at these two frequencies since the secondary path dynamics will not affect the convergence of the algorithm. As clearly seen in Figure 3(c) containing the spectrum of the time-domain controlled results from 5.5–6.5s, reductions of about 25 and 15 dBA at the 2^{nd} and 3^{rd} order for the IMLMS algorithm are attained. Here, the reference signal amplitude tuning based on the secondary path response magnitude at individual frequencies as done in Reference (4) can be adopted in the FXLMS algorithm to balance the step size discrepancy at orders 2 and 3 to yield more noise reduction at the 2^{nd} order. However, this modification is quite cumbersome.

Figures 4(a)-(d) show the controlled results for the second case when the engine speed is constant around 4000 rpm. The solid black line is the baseline response, the blue dashed curve is for the control result using the FXLMS algorithm, green dash-dotted line for the EE-FXLMS algorithm, and red dotted curve for the IMLMS algorithm. Note the EE-FXLMS algorithm is simply realized by equalizing the magnitude response of the secondary path, but keeping the phase unchanged. Hence, the frequency-dependent convergence behavior of the traditional FXLMS algorithm can be lessened. As seen from Figure 4, the IMLMS algorithm yields a much more balanced performance at various orders as compared to the FXLMS and EE-FXLMS algorithms. The IMLMS algorithm shows relatively faster convergence rate than the EE-FXLMS algorithm since not only the magnitude of the secondary path is equalized but also the phase is compensated at the controller output. The EE-FXLMS algorithm still

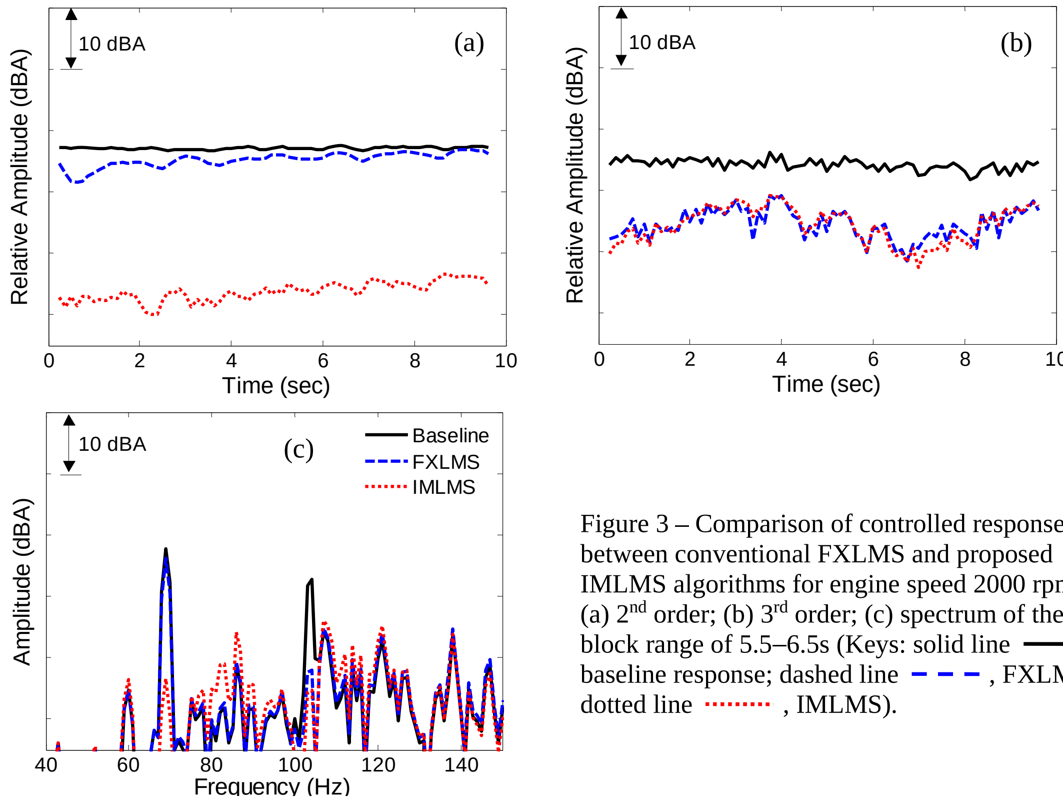

Figure 3 – Comparison of controlled response between conventional FXLMS and proposed IMLMS algorithms for engine speed 2000 rpm: (a) 2nd order; (b) 3rd order; (c) spectrum of the time block range of 5.5–6.5s (Keys: solid line ——— , baseline response; dashed line – – – , FXLMS; dotted line ········ , IMLMS).

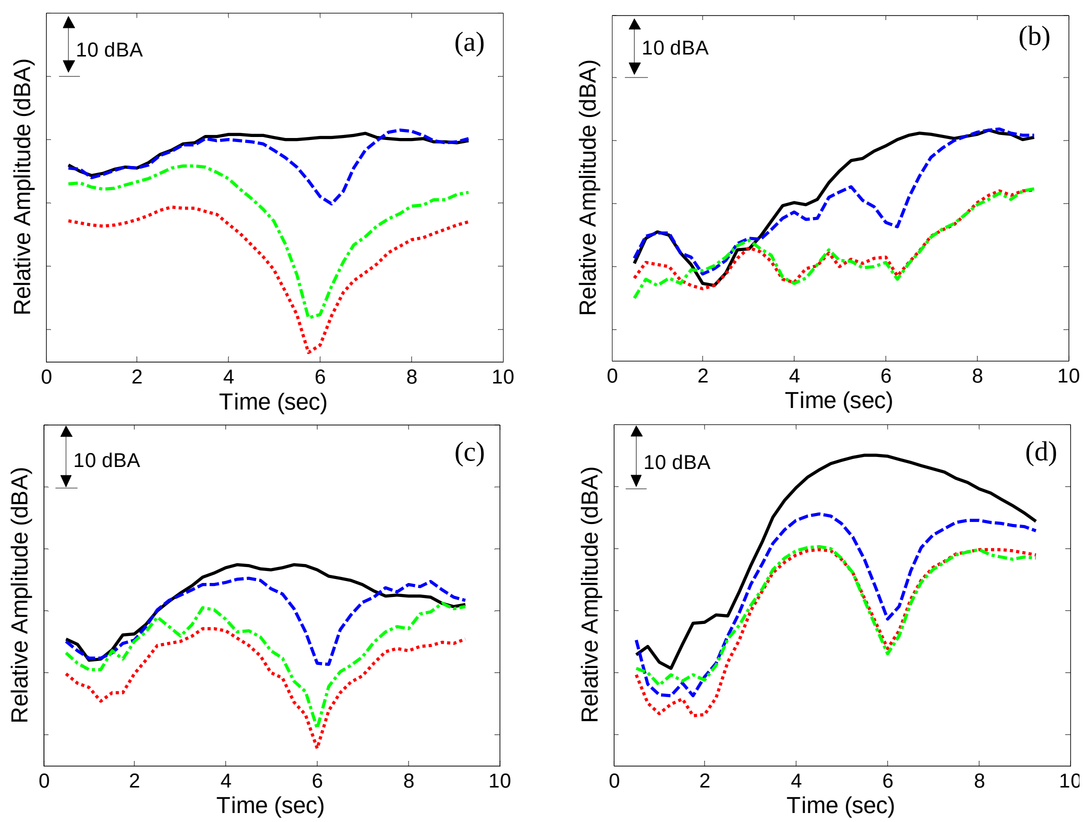

Figure 4 – Comparison of controlled response of FXLMS and IMLMS algorithms for engine speed running around 4000 rpm: (a) 1.5th; (b) 2nd; (c) 2.5th; (d) 3rd orders (Keys: solid line ——— , baseline response; dashed line – – – , FXLMS; dash-dotted line – · – , EE-FXLMS; dotted line ········ , IMLMS).

uses the secondary path model in the filtered reference signal path, where the phase delay has certain effects on the convergence speed of the FXLMS algorithm. Figure 5 shows the spectrum comparison of the controlled responses using these three algorithms. One can see that these four dominant peaks are almost reduced to the background for the IMLMS algorithm.

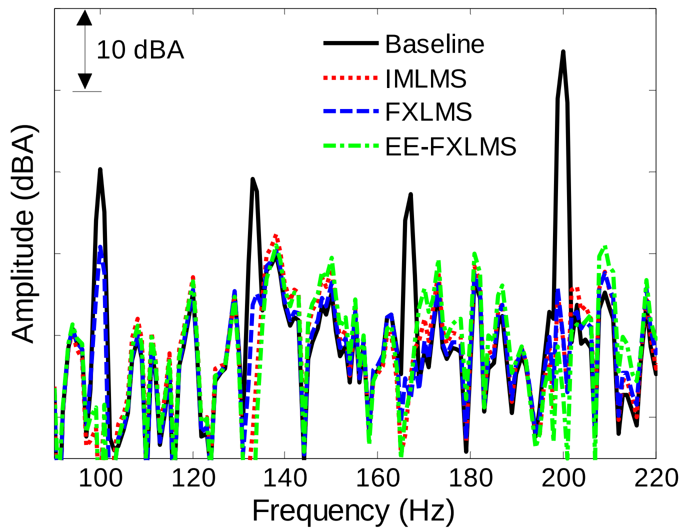

Figure 5– Spectra of the controlled response using time data from the range of 5.5–6.5s for conventional FXLMS, EE-FXLMS and IMLMS algorithms at engine speed 4000 rpm.

4. CONCLUSIONS

This paper proposed an ANC system for vehicle powertrain noise control based on the inverse model LMS (IMLMS) algorithm. The developed algorithm utilizes the inverse model of the secondary path that is added at the output of control filter, which is designed to compensate the phase delay and amplitude responses of system dynamics from control speaker to the error microphone simultaneously. Hence, only the LMS algorithm is required to update the control filter weights. The convergence speed of the LMS algorithm is only dependent on the power of the reference signal, and thus yielding a balanced control performance for various harmonics. Numerical simulations are conducted using real measured powertrain noise data and secondary path from control door speaker to the error microphone attached to the ceiling position. Results show an obvious improvement using the IMLMS algorithm as compared to the traditional FXLMS and EE-FXLMS algorithms. In fact, more than 15 dBA reductions are attained at several engine orders.

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