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Fast Active Sound Tuning System for Vehicle Powertrain Response

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ABSTRACT

This paper describes an active sound tuning (AST) system for vehicle powertrain response. Instead of simply aiming to attenuate cabin interior noise, AST system is capable of reshaping the powertrain response based on predetermined vehicle sound quality criteria. However, conventional AST systems cannot yield a balanced result over the broad frequency range when applied to powertrain noise. It is due to the fact that existing systems are typically configured with the filtered-x least mean square (FXLMS) algorithm or its modified versions, which has inherent frequency dependent convergence behavior due to large dynamic range of secondary path (the electro-acoustic path from the control speaker to the error microphone). Therefore, fast convergence can only be reached at the resonant frequencies. To overcome this inherent limitation, an enhanced adaptive notch filter with inverse model least mean square (ANF-IMLMS) algorithm is proposed as a basis of the AST system for vehicle powertrain response. Compared with the traditional FXLMS algorithm, the proposed algorithm not only increases the convergence speed, but also reduces the computational complexity. Thus, the overall performance of the AST system is improved. Numerical simulation applying measured powertrain data is conducted to validate the performance of the proposed system. Results demonstrate that the proposed system has improved spectral shaping capability with fast convergence.

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INTRODUCTION

Active noise control (ANC) technology is based on the superposition of destructive sound waves [1]. In recent years, ANC technology has gained its popularity in automotive industry. There are two main explanations for this phenomenon: (1) evolution of digital signal processor makes ANC system more affordable; (2) new powertrain technology like cylinder deactivation, hybrid and even electrical vehicle bring new applications for ANC technology [2]. However, new challengers are also presented to vehicle NVH engineers. Simply attenuating the cabin interior noise can no longer satisfy the customers nowadays. Instead, it's highly desirable to improve the interior sound quality, especially for luxury vehicles and sports vehicles. This demand leads to an extension of ANC concept: active sound tuning (AST), which can either attenuate or enhance engine responses selectively based on predetermined sound quality criteria.

Most of current AST systems are configured with the filtered-x least mean square (FXLMS) algorithm or its modified versions [3, 4, 5]. Despite these recent successes, the FXLMS algorithm has inherent frequency dependent convergence behavior due to the existence of secondary path (dynamics of electro-acoustic path from control speaker to error microphone). Thus, fast convergence can only be reached at resonant frequencies. This will adversely affect the AST system performance especially for time-varying cases such as engine speed running up. Therefore, more robust, computational-efficient algorithm is needed for practical applications. In literature, there are many research works aiming to limit the effect of secondary path to improve the convergence behavior [6, 7, 8].Those methods improve the convergence behavior of FXLMS algorithm to some extent. However, only the magnitude response of the secondary path is compensated; the phase delay still exists. Recently, Li [9, 10] proposed the inverse model least mean square (IMLMS) algorithm for general harmonic noise control, which can compensate both the magnitude and phase responses of the secondary path. However, the IMLMS algorithm requires a high-order adaptive filter which puts huge computational burden on the processor. Moreover, it's found that there is still certain discrepancy of the convergence speed at various frequencies.

To overcome the limitation of FXLMS algorithm while still keeping a relatively simple structure, an enhanced adaptive notch filter with inverse model least mean square algorithm (ANF-IMLMS) is proposed as a basis for active tuning of powertrain response. This paper will show the derivation of proposed system. Moreover, to further verify the performance of proposed AST system, numerical simulations are conducted applying measured powertrain response. For demonstration purpose, one order is targeted to be attenuated and one order is targeted to be enhanced. The simulation results demonstrate improved performance of proposed system as compared to the system configured with conventional FXLMS algorithm.

PROPOSED AST SYSTEM

Detailed derivation of AST system with traditional FXLMS algorithm can be found in Reference [1]. The inverse model least mean square (IMLMS) algorithm is originally proposed by Li [9, 10] for harmonic noise control. It's implemented on vehicle powertrain response successfully by Sun *et al* [3].

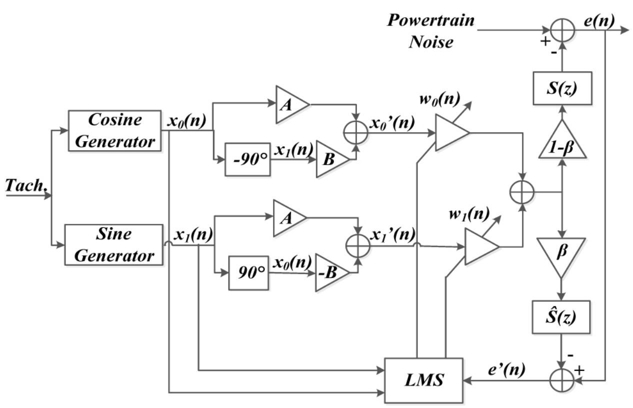

Figure 1. Block diagram of proposed active sound tuning system using ANF-IMLMS algorithm.

In this paper, the proposed AST system employs the idea of IMLMS algorithm to counteract the effect of the secondary path. Moreover, the system performance is further improved by adding the quadrature component of the original output from IMLMS algorithm. Meanwhile, the computational complexity is reduced because only two adaptive weights are needed for each order and the convolution process required for conventional FXLMS algorithm is eliminated.

Figure 1 shows the control diagram of the proposed AST system using ANF-IMLMS algorithm. The reference signal at time n: $x_0(n)$ and $x_1(n)$, as shown in Eqn. (1) and Eqn. (2), are synthesized internally based on tachometer signal:

$$x_0(n) = a_i cos(2\pi n f_i/f_s) = a_i\, cos(f_i{}'n) \tag{1}$$

$$x_1(n) = a_i\, sin(2\pi n f_i/f_s) = a_i\, sin(f_i{}'n) \tag{2}$$

where a_i is the amplitude of the ith order reference, f_i is the ith frequency component, and f_s is the sampling frequency. f_i is user selective and usually is integer order or half order of the engine fundamental rotational speed. $f_i{}'$ is the generalized frequency.

To nullify the effect of secondary path ($S(z)$), the inverse of secondary path model is placed in the reference signal path. Detailed explanation can be found in Reference [9] and Reference [10]. Generally, the inverse model of secondary path doesn't exist for broadband noise. However, for narrowband harmonic like powertrain response, the inverse model can be easily realized by manipulating the input reference signal of the adaptive filter. The response of the secondary path $S(z)$ at a specific frequency (w) can be represented by its gain (g) and phase shift (Θ):

$$S(jw) = g * e^{j*\theta} \tag{3}$$

With the knowledge of gain (g) and phase shift (Θ) of the secondary path, one can construct the constants A and B so that:

$$\begin{aligned} x_0{}'(n) &= x_0(n)/S(z) \\ &= x_0(n) * \mathrm{A} + x_1(n) * B \end{aligned} \tag{4}$$

$$\begin{aligned} x_1{}'(n) &= x_1(n)/S(z) \\ &= x_0(n) * (-\mathrm{B}) + x_1(n) * A \end{aligned} \tag{5}$$

Similar to conventional AST system, the control filter will minimize the mean square value of pseudo-error $e'(n)$. If the secondary path estimate is perfect $S(z)=\hat{S}(z)$, the pseudo-error $e'(n)$ can be expressed as:

$$e'(n) = d(n) - y(n) \tag{6}$$

where $y(n) = w_0(n)\, x_0(n) + w_1(n)\, x_1(n)$, when the system converges ($e'(n) \approx 0$), the actual residual noise $e(n)$ can be expressed as:

$$\begin{aligned} e(n) &\approx d(n) - (1-\beta)y(n) = \beta y(n) \\ &\approx \beta d(n) \end{aligned} \tag{7}$$

As shown in Eqn. (7), one can expect the AST system to perform four different modes of operation by tuning the gain factor β [1]:

a. Cancellation mode: β=0, the AST system is identical to ANC system configured with ANF-IMLMS algorithm
b. Attenuation mode: 0<β<1, the AST system reduces portion of undesired frequency, the amount of reduction depends on β
c. Neutral mode: β=1, the system has no effect at all
d. Enhancement mode: β>1, the system works as an amplifier

NUMERICAL SIMULATION

To demonstrate the performance of proposed system, numerical simulation is conducted using measured powertrain data. The simulation is run in Matlab/Simulink environment [11]. The primary powertrain disturbance and tachometer signal are recorded on a test vehicle with a V6 engine. The sampling frequency is 4096 Hz. The estimated secondary path is modeled as a 256-tap finite impulse response filter. It's measured on the same test vehicle as the transfer function from the control speaker to the error microphone. The control speaker is placed at headrest position of the driver and the error microphone is attached to the ceiling directly above the driver's head position. The frequency response function of estimated secondary path is shown in Figure 2.

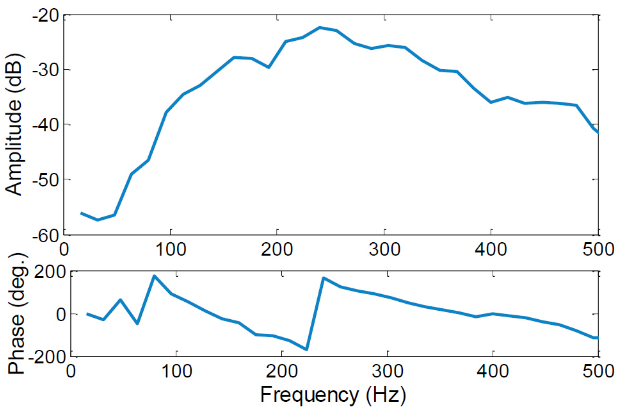

Figure 2. Frequency response function of estimated secondary path.

To verify the tracking ability of the system, a time-varying case is simulated, in which the rotational speed of engine crank shaft increases from 1500 rpm to 5500 rpm in ten seconds. The time history of engine rotational speed is shown in Figure 3.

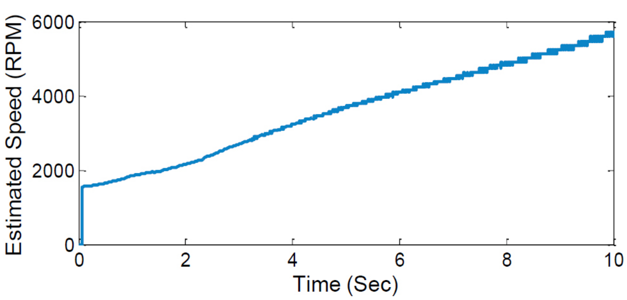

Figure 3. Estimated engine speed from the tachometer signal.

For demonstration purposes, the objective of this simulation is to enhance the 2nd order response to certain predetermined target value, and to reduce the 3rd order response as much as possible. In order to fulfill the objective, the gain factor (β) for the 2nd order response is time varying and needs to be updated constantly throughout the simulation. One can expect the 2nd order response to be enhanced to the target value if the algorithm converges fast enough. For the 3rd order response, gain factor of 0 is used. As a result, the AST works like a traditional ANC system for the 3rd order response and one can expect the 3rd order response to be attenuated to background noise level. There is no target value associated with ANC system because ANC system tends to attenuate the response to background noise level as much as possible. Time history of the 2nd and the 3rd order responses are shown in Figure 4 (a) and (b) respectively. Black solid line represents the base line response when the AST system is deactivated; red dash line represents the tuning result using proposed ANF-IMLMS algorithm and blue dotted line is the result for adaptive notch filter with conventional FXLMS (ANF-FXLMS) algorithm.

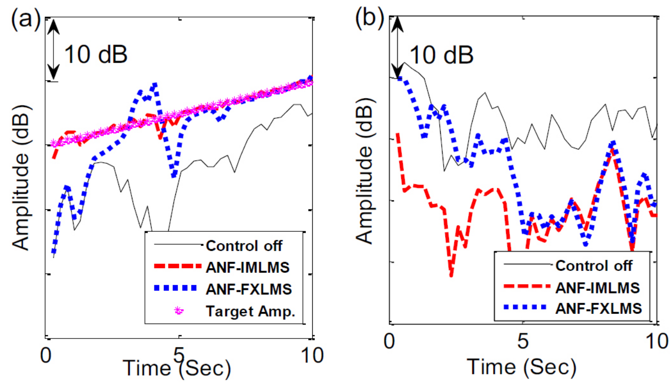

Figure 4. Comparison of controlled response between proposed ANF-IMLMS algorithm and conventional ANF-FXLMS algorithm: (a) 2nd order (b) 3rd order.

As can been from Figure 4 (a), with the proposed system, the 2nd order response is enhanced to the target value throughout the entire time band. However, for system with conventional ANF-FXLMS algorithm, there is hardly any enhancement for the first two seconds, and there is a little overshoot at around the 4th second. The reason is that for the first two seconds, the engine speed is lower than 3000 rpm, which corresponds to 100 Hz for the second order response, while the magnitude response of the secondary path is very small under 100 Hz. As speed increases, one can expect more enhancements for the 2nd order response and also expect the conventional system to become more stable. Similar phenomenon can be observed for the 3rd order response as shown in Figure 4 (b). System with the conventional ANF-FXLMS algorithm needs about five seconds to converge, while the proposed system with ANF-IMLMS is able to attenuate the 3rd order response to background noise level through the entire time band.

Figure 5 shows the frequency spectrum of baseline response and controlled results using time block data generated from 4.5th second to 5.0th second. It's noted that at around the 5th second, the conventional system can enhance the 2nd order and attenuate the 3rd order to some extent. However, the performance is not as good as the proposed system. Results demonstrate that, due to the variation of magnitude response of secondary path, the step size is not sufficient for the conventional system at lower speed while large enough at higher speed, which leads to a frequency dependent convergence behavior of the conventional system. It's obvious that the proposed AST system with ANF-IMLMS algorithm can achieve faster convergence and more balanced result at various orders as compared to the system with conventional ANF-FXLMS algorithm.

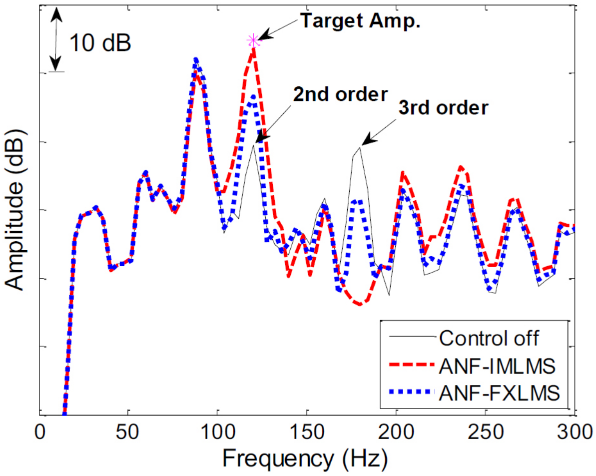

Figure 5. Comparison of frequency spectrum of controlled results between proposed ANF-IMLMS algorithm and conventional ANF-FXLMS algorithm using data generated from 4.5^{th} second to 5.0^{th} second.

SUMMARY/CONCLUSIONS

This paper proposes a fast active sound tuning system for vehicle powertrain response using adaptive notch filter with inverse model least mean square (ANF-IMLMS) algorithm. It can nullify the effect of secondary path on algorithm's convergence, which is typically seen in traditional AST systems. Therefore, the proposed system exhibits faster convergence speed and more balanced results as compared to the traditional system. Moreover, the proposed system requires less computational time since the convolution process required for tradition system is eliminated. Numerical simulations are conducted to verify the performance, applying a time-varying powertrain response. Results show that the proposed system has obvious improvement with better spectrum shaping capability.

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