

Fast Active Sound Tuning System for Vehicle Powertrain Response

Ji Xu, Guohua Sun, and Tao Feng
University of Cincinnati

Mingfeng Li
NIOSH Pittsburgh Res Lab

Teik Lim
University of Cincinnati

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.

CITATION: Xu, J., Sun, G., Feng, T., Li, M. et al., "Fast Active Sound Tuning System for Vehicle Powertrain Response," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(3):2015, doi:10.4271/2015-01-2220.

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].

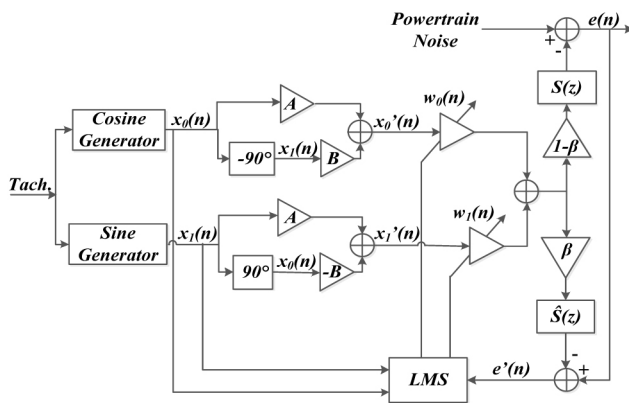


Figure 1. Block diagram of proposed active sound tuning system using ANF-IMLMS algorithm.

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:

$$x_0(n) = a_i \cos(2\pi n f_i / f_s) = a_i \cos(f_i' n) \quad (1)$$

$$x_1(n) = a_i \sin(2\pi n f_i / f_s) = a_i \sin(f_i' n) \quad (2)$$

where a_i is the amplitude of the i th order reference, f_i is the i th 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 (ω) can be represented by its gain (g) and phase shift (Θ):

$$S(j\omega) = g * e^{j*\Theta} \quad (3)$$

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

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

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

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:

$$e'(n) = d(n) - y(n) \quad (6)$$

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:

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

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]:

- Cancellation mode: $\beta=0$, the AST system is identical to ANC system configured with ANF-IMLMS algorithm
- Attenuation mode: $0 < \beta < 1$, the AST system reduces portion of undesired frequency, the amount of reduction depends on β
- Neutral mode: $\beta=1$, the system has no effect at all
- Enhancement mode: $\beta > 1$, 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