Active Control of Road-Booming-Noise with Constraint Multiple Filtered-X LMS Algorithm

*Shi-Hwan Oh, *Hyoun-Suk Kim, *Young-Jin Park

Abstract

Vibration generated by the non-uniform road profile propagates though each tire and the suspension and finally generates structure born noise in the interior of the passenger vehicle. In this paper, the road-booming-noise which has strong correlation with the vibration signals measured at the suspension system was compensated. Active noise control of the road-booming-noise is rather difficult to achieve because of its non-stationary characteristics. CMFX LMS (Constraint Multiple Filtered-X Least Mean Square) algorithm, which can track non-stationary process rather well, is applied. Comprison of the proposed method and the conventional MFX LMS (Multiple Filtered-X Least Mean Square) algorithm is made through the hardware-in-the-loop simulation and the feasibility of the proposed method is demonstrated with the experiment.

I. Introduction

Several studies have been carried out to reduce the interior road noise in a car with feedforward control scheme [1~4]. MFX (Multiple Filtered-X) LMS algorithm was a basic control algorithm in those studies. In practice, The attenuation of road-booming-noise is one of the most difficult control applications with adaptive signal processing. Because the dominant characteristic of road-booming-noise is time varying, a control algorithm with fast convergence should be needed in this application. It is well known that the delay of the error path decreases the upper limit of convergence speed in FX (Filtered-X) LMS algorithm and so does in MFX LMS algorithm. So, it is hard to achieve the satisfactory control performance with MFX LMS algorithm. The other characteristic is that the road-booming-noise is generated from individual four wheels, thus multi-input multi-output algorithm should be also used.

In this paper, a fast converging ANC (Active Noise Control) algorithm was proposed to attenuate road-booming-noise inside a passenger car. It is shown that such problem can be solved to some extents by incorporating CFX (Constraint Filtered-X) LMS algorithm [5,6] and its extension to multiple reference, multiple error, multiple output case [7], i.e., CMFX (Constraint Multiple Filtered-X) LMS algorithm. Simulation and experiment are performed to show the effectiveness of the CMFX LMS algorithm.

II. Constraint Filtered-X LMS algorithm

FX LMS algorithm suffers from slow convergence of weight because it is derived assuming time-invariant of the weight during the weight updating process; $w_i(k) \simeq w_i(k-j)$ for j of within FIR order of the error path model. This problem becomes worse as the delay of error path increases. CFX LMS algorithm that deals with single reference signal $x(k)$, single control output $y(k)$ to secondary speaker, and single error signal $e(k)$ from a microphone located at the quiet zone of interest is described in Figure 1. The control output $y(k)$ and the conatraint error $\varepsilon(k)$ can be expressed as

$$y(k) = \sum_{i=0}^{L} w_i(k) x(k-i), \tag{1}$$

$$\varepsilon(k) = e(k) - \sum_{j=0}^{Lh} \hat{h}_j y(k-j) + \sum_{i=0}^{L} w_i(k) fx(k-i). \tag{2}$$

The ith adaptive filter weight $w_i(k)$ is updated by the following equation in order to minimize the squared error $e^2(k)$,

$$w_i(k+1) = w_i(k) - 2\mu\varepsilon(k) fx(k-i), \tag{3}$$

where

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$$fx(k) = \sum_{j=0}^{Lh} \hat{h}_j x(k-j), \qquad (4)$$

The terminology 'filtered-X' means the filtered signal of the reference $x(k)$. The cost function of CFX LMS algorithm is square of constraint error $\varepsilon(k)$ that is modified from the ordinary error signal $e(k)$. Adaptive filter $W(z)$ is adjusted by the constraint error $\varepsilon(k)$ and the $fx(k)$ signal which is a filtered reference input through the estimated error path model $\hat{H}(z)$. The constraint error $\varepsilon(k)$ that is introduced as a quantity to be minimized in this algorithm offers an exact instantaneous gradient because it does not assume $w_i(k) \simeq w_i(k-j)$ which holds in FX LMS algorithm. Moreover, as the CFX LMS algorithm behaves like LMS algorithm whose input is $fx(k)$, the convergence parameter μ can be normalized between 0 and 1 by using $\mu / \sum_{i=0}^{i=L} fx^2(k-i)$ instead of μ. At the cost of increased computation, CFX LMS offers improved convergence characteristics compared with the conventional FX LMS algorithm. The detail meaning of the constraint error and the stability analysis are described in references [5,8,9].

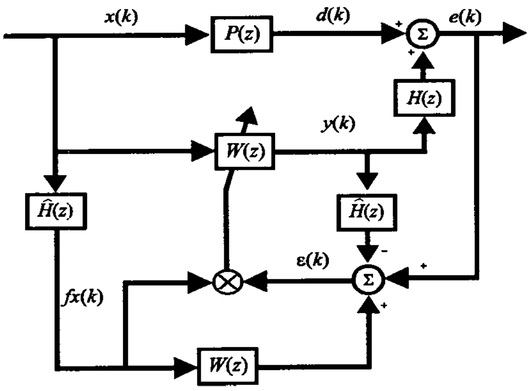


Figure 1. Block diagram of constraint Filtered-X LMS algorithm.

III. Constraint Multiple Filtered-X LMS algorithm

When the noise to be attenuated is caused by several independent inputs, it is necessary to deal with multiple reference signals to actively control the undesired noise $d(k)$. This is the case for road-booming-noise measured inside a car. Each of the four wheel vibrations due to irregular road surface excitation can be considered as independent noise sources. Multiple control sources and error microphones can be placed to enlarge the quiet zone or increase noise reduction level. Therefore, the CMFX LMS algorithm needs to be investigated.

Let's consider an ANC system having N references, K control speakers, and M error microphones. Such multiple system has $M \times K$ number of multiple error paths. In this case, the m-th error $e_m(k)$ and constraint error $\varepsilon_m(k)$ are

$$e_m(k) = d_m(k) + \sum_{n=1}^{N} \sum_{k=1}^{K} \sum_{j=0}^{Lh} \sum_{i=0}^{L} h_{mkj} w_{kni}(k-j) x_n(k-i-j), \qquad (5)$$

$$\varepsilon_m(k) = d_m(k) + \sum_{n=1}^{N} \sum_{k=1}^{K} \sum_{j=0}^{Lh} \sum_{i=0}^{L} h_{mkj} w_{kni}(k) x_n(k-i-j) \qquad (6)$$

Where $x_n(k)$ is n-th reference, $w_{kni}(k)$ is i-th coefficient of control filter $W_{kn}(z)$ whose input is n-th reference and output is fed to k-th control speaker, and $\hat{h}_{mkj}$ is j-th coefficient of $\hat{H}_{mk}(z)$ which is the model of $H_{mk}(z)$ located between k-th control speaker and m-th error microphone. Weight $w_{kni}(k)$ of CMFX LMS is updated by steepest descent method and the constraint error $\varepsilon_m(k)$ can be calculated by modifying $e_m(k)$ as in CFX LMS case. Derivation of CMFX LMS algorithm that tries to minimize the cost function $\varepsilon_1^2(k) + \varepsilon_2^2(k) + \cdots + \varepsilon_M^2(k)$ is straightforward and the algorithm is summarized as follows:

$$y_k(k) = \sum_{n=1}^{N} \sum_{i=0}^{L} w_{kni}(k) x_n(k-i) \qquad (7)$$

$$fx_{mkn}(k) = \sum_{j=0}^{Lh} \hat{h}_{mkj} x_n(k-j) \qquad (8)$$

$$w_{kni}(k+1) = w_{kni}(k) - 2\mu \sum_{m=1}^{M} \varepsilon_m(k) fx_{mkn}(k-i) \qquad (9)$$

k-th control output is expressed in (7) and the adaptive filter located between k-th speaker and n-th reference is (9). The signal $fx_{mkn}(k)$ in (8) is a filtered signal of $x_n(k)$ through the error path model $\hat{H}_{mk}(z)$. CMFX LMS algorithm is different from MFX algorithm only in using $\varepsilon_m(k)$ instead of $e_m(k)$.

IV. Hardware-in-the-loop Simulation Results

ANC system with four references, one secondary speaker, and one error microphone with adaptive filters of 256 taps for all filters (four weight filters and one

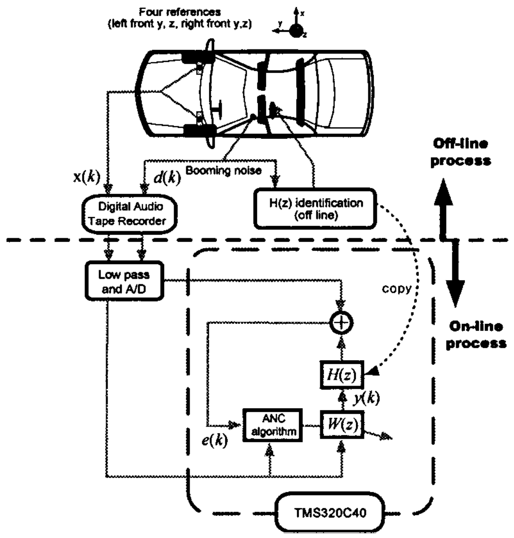
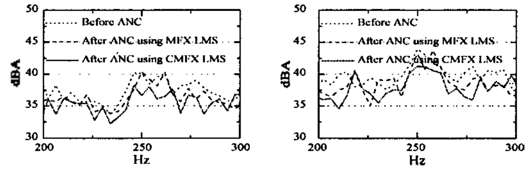


Figure 2. Experimental setup for hardware-in-the-loop simulation.

error path model) was selected. For hardware-in-the-loop simulations, four acceleration signals (y and z directions of two front wheels) with acoustic pressure signal from a microphone near the head rest of driver seat [10,11] were recorded while driving the turtle-back road with driving speed of 40 and 60km/h. Test car was SONATA II of HYUNDAI, which has 2000cc engine. The simulation was carried out playing the record tape. Figure 2 illustrates the overall experimental setup. Four reference signals are low-pass-filtered with cut-off frequency of 300Hz and then A/D converted with microphone signal that is considered as d(k). Sampling frequency was 1000Hz, and the error path models are estimated from the test car in off-line. Simulation is carried out using a DSP board equipped with TMS320c40 chip. The convergence coefficient was 0.12 for MFX LMS algorithm and 0.19 for CMFX LMS algorithm. Figure 3 shows the spectrum of e(k) which is twenty-time averaged and A-weighted before ANC (dotted line), after ANC using MFX LMS algorithm (dashed line) and CMFX LMS algorithm (solid line). It is easily found that the road-booming-noise for the test car is dominant near 250Hz. With the best chosen set of parameters for both ANC algorithms, they showed similar attenuation level for the two speed of turtle-back road surface. Figure 4 shows normalized mean square error during the first 1000 steps of adaptation, i.e., $\sum_{k=1}^{1000} e^2(k)/\sum_{k=1}^{1000} d^2(k)$ as μ varies for turtle-back road. It is worth noting that the range of μ (in normalized sense) to reduce the error signal in Figure 4 was much wider in CMFX LMS algorithm than in MFX LMS algorithm and. It can be also found that the transient mean square error with CMFX LMS algorithm is smaller than that of MFX LMS at the same μ. Consequently, CMFX LMS can increase the convergence speed by using larger μ without much degradation of steady state performance.



(a) Turtle-back road (40Km/h)

(b) Turtle-back road (60km/h)

Figure 3. Hardware-in-the-loop simulation results for two different speeds of turtle-back road.

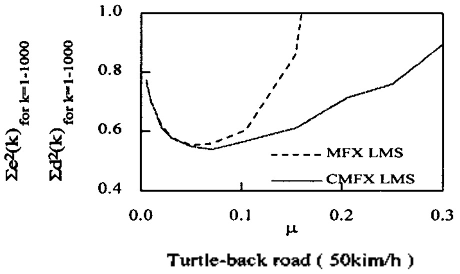


Figure 4. Transient mean square error (normalized) vs. for turtle-back road (50km/h).

V. Experiments

Unlike the hardware-in-the-loop simulations, active control of road-booming-noise was performed with the signals detected from the driving car in real-time process. Experimental setup was same with the hardware-in-the-loop simulation except the reference and the error signals were connected directly to the DSP board without recorder. The control speaker was located behind the driver seat and the error microphone was attached the loop near the driver's head.

Figure 6 shows the spectrum before and after ANC driving the rough asphalt road and the turtle-back road respectively. Each spectrum was twenty-time averaged while driving same road profile. The control result with MFX LMS algorithm was not plotted because the road-booming-noise was not attenuated with the algorithm at all. Error spectrum has several irregular peaks because the engine noise and the exhaust noise were also detected with the error microphone. Comparing Figure 3(b) and Figure 6(b), the experimental results are somewhat different from simulation results. It is caused by the fact that the road-booming-noises are non-stationary. The road-booming-noise driving the rough road with constant 60km/h was attenuated about 2~5dB with constraint multiple Filtered-X LMS algorithm. But the error signal was not reduced for driving the turtle-back road. In the A-weighted error spectrum before control with driving the turtle-back road in experiment, the road booming component are relatively smaller than the other frequency range. It is natural that the low frequency level is much larger than the road booming region in the original spectrum. Thus, the road booming component was less attenuated than the other frequency band.

In real, the original error signals before A-weighting were used in the control algorithms. Thus, CMFX LMS and MFX LMS algorithm try to minimize the error signal with larger weights for low frequency than the road booming component because one of the characteristics of MFX (CMFX) LMS algorithm is to attenuate the larger power frequency band more than the other bands. If the reference signal or the error signal is band-pass filtered, the controllers are expected to reduce the booming noise component efficiently.

VI. Conclusion

Road-booming-noise of a vehicle is naturally time varying signal due to the change of vehicle speed and road profile and caused by multiple input due to the independent vibration of wheels. Little sound attenuation of non-stationary road-booming-noise is achieved by conventional MFX LMS algorithm because of its characteristics.

Because CFX LMS offers much wider range of convergence parameter for equal reduction of noise level and faster convergence speed, CMFX LMS algorithm for active attenuation of the road-booming-noise inside a passenger car was investigated. Through the simulation results, CMFX LMS could attenuate 2~5dB of the road-booming-noise, which was not obtained with the conventional MFX LMS algorithm. It shows the effectiveness of the proposed algorithm compared to MFX LMS algorithm. And the experimental result also shows the feasibility of the CMFX LMS algorithm in practical application. But the control results are not satisfactory to recognize the attenuation of noises, further studies and experiments will be performed in order to get a better performance.

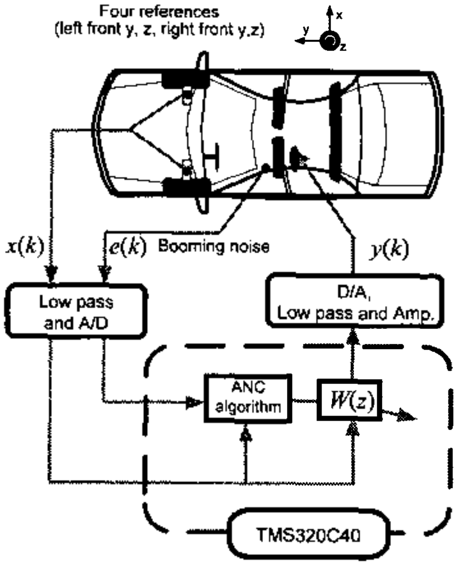
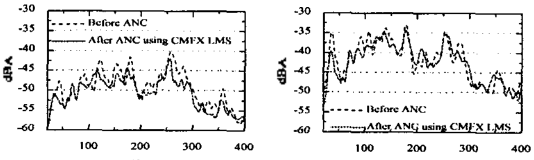


Figure 5. Experimental setup for real time control with driving roads.



(a) Rough road (60Km/h) (b) Turtle-back road (60km/h)

Figure 6. Experimental results for two different road profiles.

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