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ACTIVE NOISE CONTROL OF ROAD BOOMING NOISE WITH CONSTRAINT MULTIPLE FILTERED-X LMS ALGORITHM

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INTRODUCTION

In this paper, we present a fast converging ANC(Active Noise Control) algorithm to attenuate road booming noise inside a passenger car. MFX (Multiple Filtered-X) LMS algorithm has been a basic feedforward control algorithm in active control of road booming noise application. It is well known that 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. It will be shown that such problem can be solved to some extents by incorporating CFX (Constraint Filtered-X) LMS algorithm[1,2] and its extension to multiple reference, multiple error, multiple output case; CMFX (Constraint Multiple Filtered-X) LMS algorithm.

CONSTRAINT FILTERED-X LMS ALGORITHM

FX LMS algorithm suffers slow convergence of weight because it is derived assuming time invariantness of the weight during weight update; $w_i(k) \approx w_i(k-j)$ for j of within FIR order of error path. This problem becomes worse as the delay of error path increases. The 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

given x(k), e(k) *at k step*	
filtered-x signal	$fx(k) = \sum_{j=0\sim Lh} h_j x(k-j)$
constraint error	$\varepsilon(k) = e(k) - \sum_{j=0\sim Lh} h_j y(k-j) + \sum_{i=0\sim L} \dot{w}_i(k)\, fx(k-i)$
weight update	$w_i(k+1) = w_i(k) - 2\mu\, \varepsilon(k) fx(k-i)$
control output	$y(k) = \sum_{i=0\sim L} w_i(k) x(k-i)$

Table 1. Constraint Filtered-X LMS algorithm

in Table 1.

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 estimated error path model $H(z)$. 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 $w_i(k) \approx w_i(k-j)$ which is done in FX LMS. Moreover, as the CFX LMS behaves like LMS whose input is $fx(k)$, the convergence parameter μ can be normalized between 0 and 1 by using $\mu/\left(fx^2(k)+fx^2(k-1)+\cdots+fx^2(k-L)\right)$ instead of μ. At the cost of increased computation, CFX LMS offers improved convergence characteristics compared with the conventional FX LMS.

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. we can place multiple control sources and error microphones to enlarge the quiet zone or increase noise reduction level. Therefore, we need to investigate CMFX LMS algorithm.

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

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

$$\varepsilon_m(k) = d_m(k) + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{j=0}^{Lh}\sum_{i=0}^{L} h_{mkj} w_{kni}(k) x_n(k-i-j) \ , \qquad (2)$$

where $x_n(k)$ is n-th reference, w_{kni} is i-th coefficient of control filter $W_{kn}(z)$

given $x_n(k)$, $e_m(k)$, *n=1,2,...,N, m=1,2,...,M at k step*	
filtered-x signal	$fx_{mkn}(k) = \sum_{j=0}^{Lh} h_{mkj} x_n(k-j)$
constraint error	$\varepsilon_m(k) = e_m(k) - \sum_{k=1}^{K}\sum_{j=0}^{Lh} h_{mkj} \bar{y}_k(k) + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{i=0}^{L} w_{kni}(k) fx_{mkn}(k-i)$
weight update	$w_{kni}(k+1) = w_{kni}(k) - 2\mu \sum_{m=1}^{M} \varepsilon_m(k) fx_{mkn}(k-i)$
control output	$y_k(k) = \sum_{n=1}^{N}\sum_{i=0}^{L} w_{kni}(k) x_n(k-i)$

Table 2. Constraint Multiple Filtered-X LMS algorithm

whose input is n-th reference and output is fed to k-th control speaker, and $h_{mkj}(z)$ is j-th coefficient of error path $H_{mk}(z)$ located between k-th control speaker to m-th error microphone. Weight w_{kni} 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 results is shown in Table 2. The signal $fx_{mkn}(k)$ is a filtered signal of $x_n(k)$ through the error path model $H_{mk}(z)$. CMFX LMS algorithm is different from MFX algorithm only in using $\varepsilon_m(k)$ instead of $e_m(k)$.

HARDWARE-IN SIMULATION RESULTS

We chose ANC system of four references, one secondary speaker, and one error microphone with adaptive filter length 300 for all filters(four weight filters and one error path model). For hardware-in simulations, we recorded 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 while driving two types of road: rough concrete road and turtle-back road with driving speed of 50km/h. Test car was SONATA II of HYUNDAI which has 2000cc engine. The simulation was carried out playing the record tape. Fig.1 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 which is considered as d(k). Sampling frequency was 1000Hz, and we assumed the real error path is z^{-8} whose corresponding acoustic distance is 270cm when sampling frequency is 1000Hz. We carried out simulations using a DSP board equipped with TMS320c40 chip.

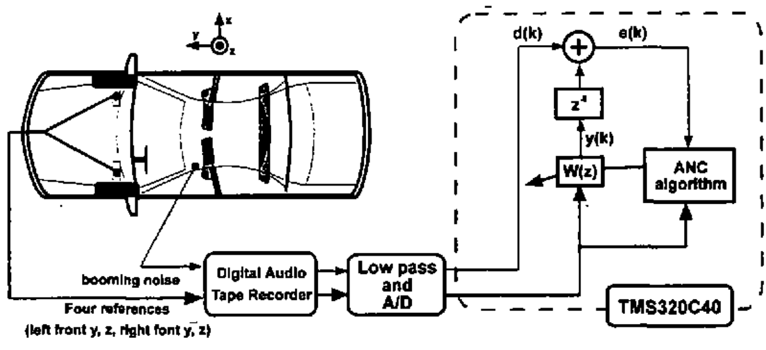
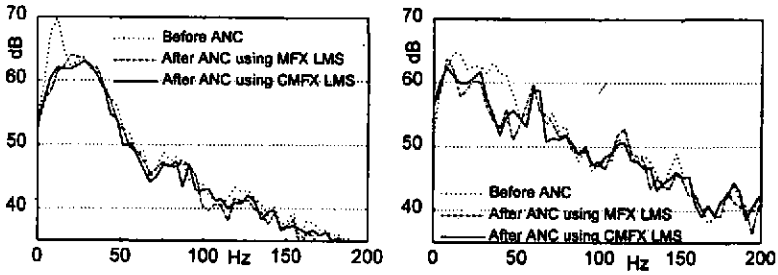


Fig.1 Experimental setup for hardware-in simulation

Fig.2 shows spectrum of e(k) before ANC(dotted line) and after ANC using MFX LMS(dash-dotted line) and CMFX LMS(solid line). Seeing the spectrum of noise level before ANC as shown in Fig.2, the test car originally seems to well isolate or absorb the road booming noise of greater than 150Hz. Frequency ranges of only under 100Hz appears road booming components while driving. With the best chosen set of parameters for both ANC algorithms, they showed similar attenuation level for the two types of road surface. It is worth noting that the range of μ (in normalized sense) to maintain the performance close to that of Fig.2 was much wider in CMFX LMS than in MFX LMS. Fig.3 shows sum of $e^2(k)$ during the first 1000 steps of adaptation as μ varies for turtle-back road. Consequently, CMFX LMS can increase the convergence speed by using larger μ without loss of steady state performance.



(a) Rough concrete road

(b) Turtle-back road

Fig.2 Hardware-in simulation results for two types of road conditions

CONCLUSIONS

The use of MCFX LMS algorithm for active attenuation of the road booming noise inside a passenger car caused by multiple inputs due to independent vibration of wheels are investigated. Though the MCFX LMS did not show much enhanced performance compared to the MFX LMS in steady state, we could confirm that MCFX LMS offers much wider range of convergence parameter for equal reduction of noise level, and faster convergence speed.

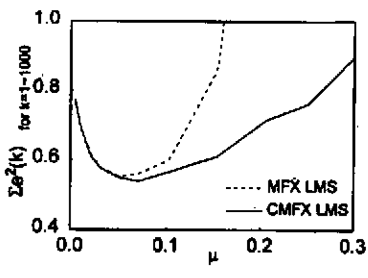


Fig.3 Squared sum of e(k) along μ for turtle-back road

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