EQUALIZED ALGORITHM FOR A TRUCK CABIN ACTIVE NOISE CONTROL SYSTEM

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1 INTRODUCTION

The noise inside a truck cabin is caused by various sources such as the engine, transmission, wheel vibrations, wind, and some other external sources. In general, the interior noise of vehicles is composed of two components: one is synchronized with the engine rotation or other periodic noise, while the other is caused by stochastic sources [1]. For most midsized trucks with an in-line four-cylinder engine, periodic noise is the dominant part of the internal noise. Such periodic noise is a combination of the harmonic noise components, also known as noise orders. Furthermore, the order frequency range is relatively low, typically below 500 Hz. That makes Active Noise Control (ANC) effective in attenuating the order-related noise. The most commonly used strategy is narrowband feedforward ANC with a Filtered-x Least Mean Squares (FXLMS) algorithm [1]. The FXLMS algorithm, first derived by Widrow in 1981, has been used successfully for many applications, such as broadband noise in an enclosure [2], single frequency noise in a duct [3], multiple frequency noise in a helicopter [4], and time-varying noise in a tractor [5].

As the speed of truck engine changes, the order frequencies change continuously during operation. That compromises the overall performance of the ANC system because the FXLMS approach exhibits the frequency-dependent convergence behavior. Although several variations to the FXLMS algorithm have been developed in an effort to overcome the performance degradation, their drawback is that they either increase the computational burden of the algorithm or add the algorithm's complexity. Recently, a new approach known as the Eigenvalue Equalization Filtered-x Least Mean Squares (EE-FXLMS) algorithm has been developed by Thomas et al. [6], and already been proven effective to overcome the frequency dependent performance, and to improve the overall performance in the desired frequency range [6], [7], [8]. More importantly, the implementation of the equalized algorithm is straightforward and only minor modifications are needed to the existing FXLMS algorithms.

In this paper, a narrowband feedforward ANC system for a truck cabin is presented. A normal FXLMS algorithm and an equalized FXLMS algorithm based on the former case are implemented, and the performance of the approaches is compared experimentally.

2 THE ACTIVE NOISE CONTROL SYSTEM

Based on a real truck cabin provided by Dongfeng Motor Company (DFL) from China, the recordings of the noise data at all relevant driving speeds are measured and analyzed [9]. According to the results, at each gear, the most dominant periodic component throughout the range is the 2nd order, the firing frequency of the engine. There are also other two orders which are clearly detectable orders in the spectra, the 4th and the 6th orders. As suggested [8], the orders 2, 4 and 6 are attenuated consequently as much as possible in the practical ANC system. For the periodic noise caused by an engine, narrowband feedforward techniques are effective in reducing repetitive noise. Instead of using an acoustic reference sensor, a tachometer is employed to provide information about the engine speed. Thus, the reference signal will not be affected by the outputs of the secondary sources. This is useful for the practical attenuation in a real vehicle cabin since ANC will not be affected by vehicle warnings, radio or speech. Furthermore, in order to achieve an adequate attenuation of the noise in both the driver's and co-driver's positions, a multi-channel ANC system is needed.

In principle, the number of secondary sources needed to obtain perfect sound cancellation in the enclosure is the same as the number of acoustic modes being excited [1]. As shown in Figure 1, a 3-channel narrowband feedforward ANC system with the tachometer input is constructed [9]. The realization of the ANC system is done with loudspeakers and microphones, with an additional subwoofer to handle the low frequency components. The control algorithms developed with Simulink are implemented on a Texas Instruments TMS320C6713 DSP processor. The control unit in use has been specially developed for an Active Noise Profiling (ANP) system [10].

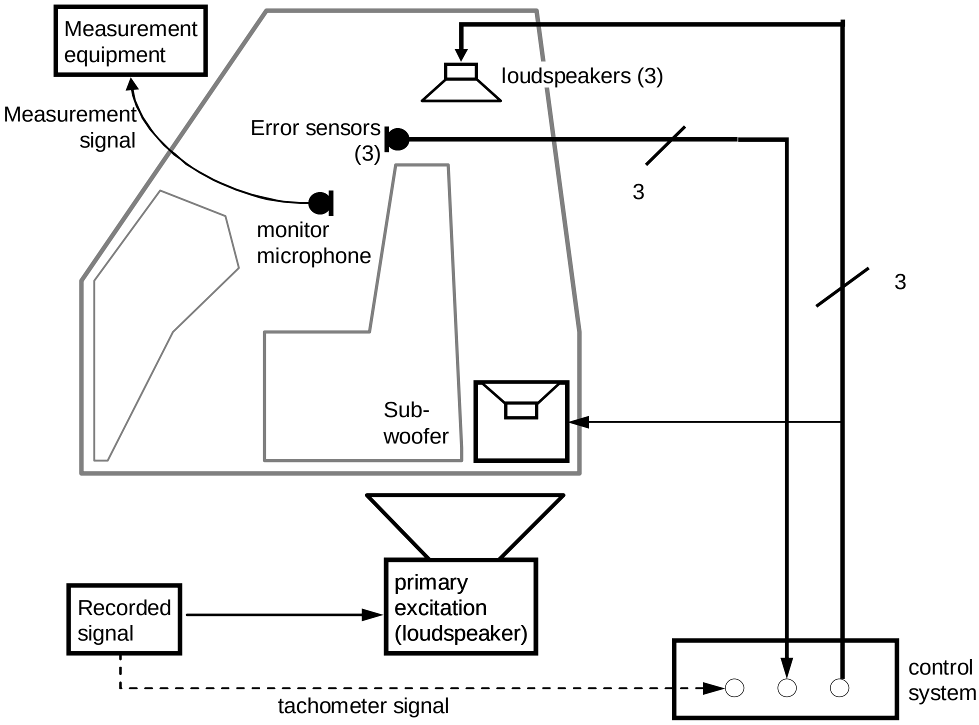

Figure 1. The simplified diagram of the ANC system inside the truck cabin [9].

3 PRINCIPLE OF THE FXLMS ALGORITHM

A 3-channel narrowband feedforward ANC system was constructed to attenuate the noise inside the truck cabin. As for the narrowband implementation all 3 order references are generated from a tachometer signal $x(n)$, the ANC system has 3 references, 3 secondary sources, and 3 error sensors. From the control point of view, the system is a 3x3x3 Multi-Reference Multiple Input – Multiple Output (MR-MIMO) system.

A simplified block diagram of this MR-MIMO ANC system is illustrated in Figure 2. The variable t is used as a discrete time index and the variable z is used as a discrete frequency domain index. A single-reference signal $x(t)$ is used for all the three adaptive filters. Vector $e(t)$

represents the outputs of the error microphones and $y(t)$ is the actual output of the filters driven by the reference input signal. The matrix $\hat{\boldsymbol{S}}$ is formed by the estimates of the secondary paths from the secondary loudspeakers to the error microphones and $x'(t)$ is the filtered reference signal.

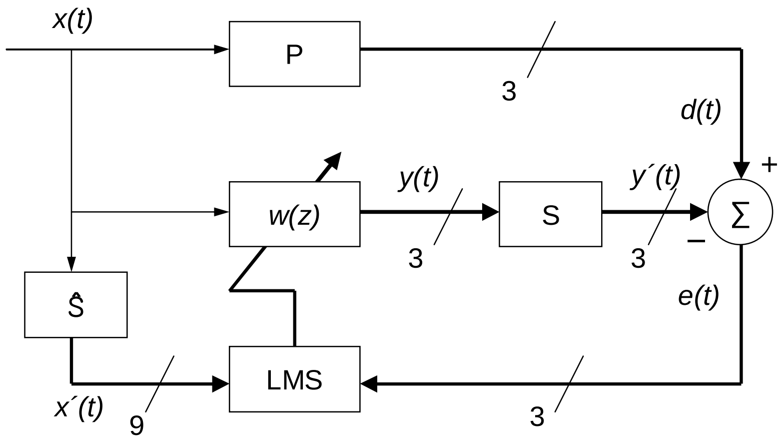

Figure 2. Simplified block diagram of the 3-channel ANC system.

The control filter updated equation for the vector $\boldsymbol{w}$ can be expressed as

$$\boldsymbol{w}(t+1)=\boldsymbol{w}(t)-\mu\boldsymbol{X}'(t)\boldsymbol{e}(t) \tag{1}$$

This equation can also be partitioned into 3 equations as

$$\boldsymbol{w}_k(t+1)=\boldsymbol{w}_k(t)+\mu_k\sum_{m=1}^{3}x'_{km}(t)\boldsymbol{e}_m(t), \qquad k=1,2,3 \tag{2}$$

where μ_k is the step size of the kth filter, vectors $\boldsymbol{e}_m(t)$ and $\boldsymbol{w}_k(t)$ are defined as

$$\boldsymbol{e}_m^{\ T}(t)=[e_m(t),e_m(t-1),\ldots,e_m(t-L+1)] \tag{3}$$

$$\boldsymbol{w}_k^{\ T}(t)=\left[w_{k0},w_{k1},\ldots,w_{k(L-1)}\right] \tag{4}$$

and L is the length of the adaptive filters.

The filtered reference signal vectors of the reference matrix $\boldsymbol{X}'(t)$ are defined as

$$x'_{km}(t)=\hat{s}_{mk}(t)*x(t)=\sum_{i=1}^{L}\hat{s}_{mk,i}(t)x(t-i), \quad m,k=1,2,3 \tag{5}$$

4 EQUALIZED ALGORITHM

As the periodic noise is time-varying, to achieve a reasonable reduction of the noise inside the truck cabin, a fast algorithm to adapt the adaptive filter coefficients is essential to provide a cancelling signal that tracks under rapidly changing conditions. One of the main treatments to get the optimal convergence speed is to adjust the step sizes of the filters. But, because of the frequency-dependent convergence behavior of the FXLMS algorithm, it is difficult to get a fast convergence speed in the overall frequency range without the system becoming unstable. This can be understood better with the autocorrelation matrix of the filter-x signal, which is largely a function of the estimate of secondary paths. The autocorrelation matrixes of the filtered-x signal of different filters are defined as

$$\boldsymbol{R}_{km} = E\left[\boldsymbol{x}'_{km}(t)\boldsymbol{x}'^{T}_{km}(t)\right], \qquad k, m = 1,2,3 \tag{6}$$

As already mentioned in Reference [1], the range of the chosen step sizes of the control system is limited by the following equation

$$0 < \mu_k < \frac{2}{\lambda_{\max}}, \qquad k = 1,2,3 \tag{7}$$

and the Mean Square Errors (MSE) time constant of the adaptive process can be bounded as

$$\tau_{mse} \le \frac{\lambda_{\max}}{\lambda_{\min}} T \tag{8}$$

where $\lambda_{\max}$ and $\lambda_{\min}$ are the maximum and minimum eigenvalues of the autocorrelation matrix for the filtered-x signal in the overall target frequency range. Thus, the convergence speed of the FXLMS algorithm is dependent on the maximum eigenvalue and the eigenvalue spread (the ratio of the maximum to minimum eigenvalues) of the autocorrelation matrix ***R***. Since it is difficult to get a precise estimate of the secondary paths, the eigenvalues $\lambda_{\max}$ and $\lambda_{\min}$ are also difficult to calculate. In order to reduce the spread of eigenvalues, some equalization process needs to be done to the filtered reference signals. In Reference [6], the equalized FXLMS algorithm removes the variance in the eigenvalue by changing the magnitude coefficients while preserving the phase of $\hat{S}(z)$. Another approach uses genetic algorithm to find the magnitude coefficients that give the least variation in eigenvalues of the autocorrelation matrix [8].

As a straightforward way, the equalized FXLMS algorithm was used to flatten the magnitude coefficients. After an offline system identification process, the equalization is also done offline before the real-time ANC operation. For multi-channel systems, the process is repeated for each estimate of the secondary paths. The plots in Figure 3 show the magnitudes and phases of the original and modified secondary path estimates. The peak magnitude is reduced to 1/15 of the original and the overall magnitude has been considerably flattened, while the phase remains almost the same. This decreases the maximum eigenvalue and also the eigenvalue spread. As a result, the step sizes of adaptive filters may be increased and the robustness and stability of the ANC system is improved. Furthermore, as an offline process, it adds no computational burden to the standard algorithm when the ANC system is running.

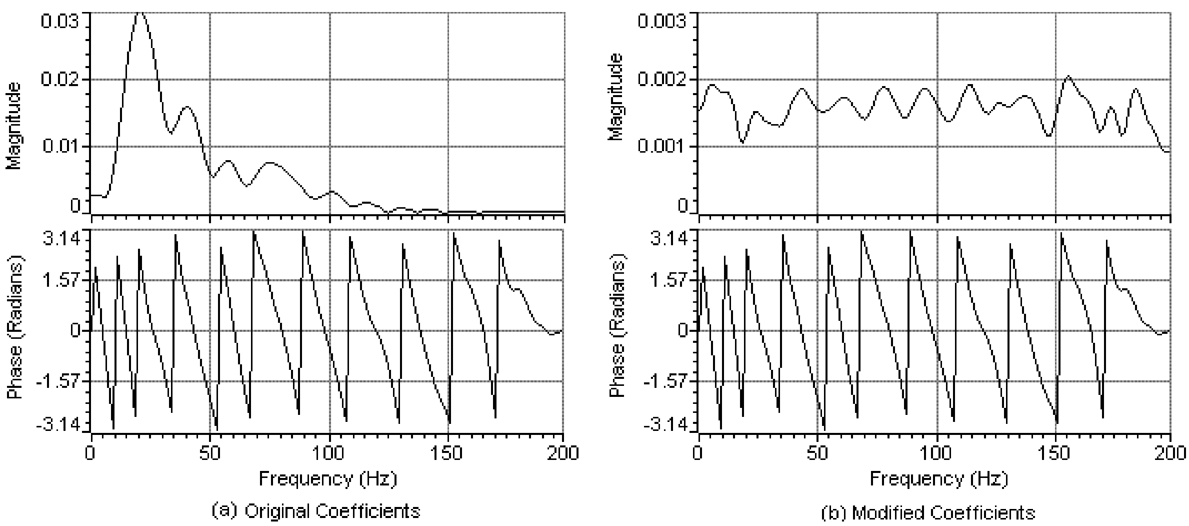

Figure 3. Original and modified coefficients of the secondary path estimate.

5 EXPERIMENTAL RESULTS

Based on the constructed 3-channel ANC System, the experiments with both algorithms with the noise recorded inside the real truck cabin were carried out. The recordings were made at several engine rotational speeds, from 600 RPM to 3000 RPM. Control system was set to attenuate the dominant orders 2, 4 and 6. Table 1 shows the optimal step sizes for the equalized FXLMS algorithm can be even 20 times larger than for normal FXLMS algorithm. With the larger step sizes the faster convergence speed can be achieved, which is important while attenuating the time-varying noise in practice.

Table 1. The normalized optimal step size of the algorithms in different RPM.

Step size / RPM / Algorithm	600	930	1560	1920	2400	3000
Normal Algorithm	1	1	1	1	1	1
EE Algorithm	18	18	20	17	16	15

Figure 4 shows the measured SPLs with a monitor microphone at driver's position at 1560 RPM. The green curve represents the noise without the ANC treatment. The purple and blue curves represent the treated noise with the normal FXLMS algorithm and the equalized algorithm, respectively.

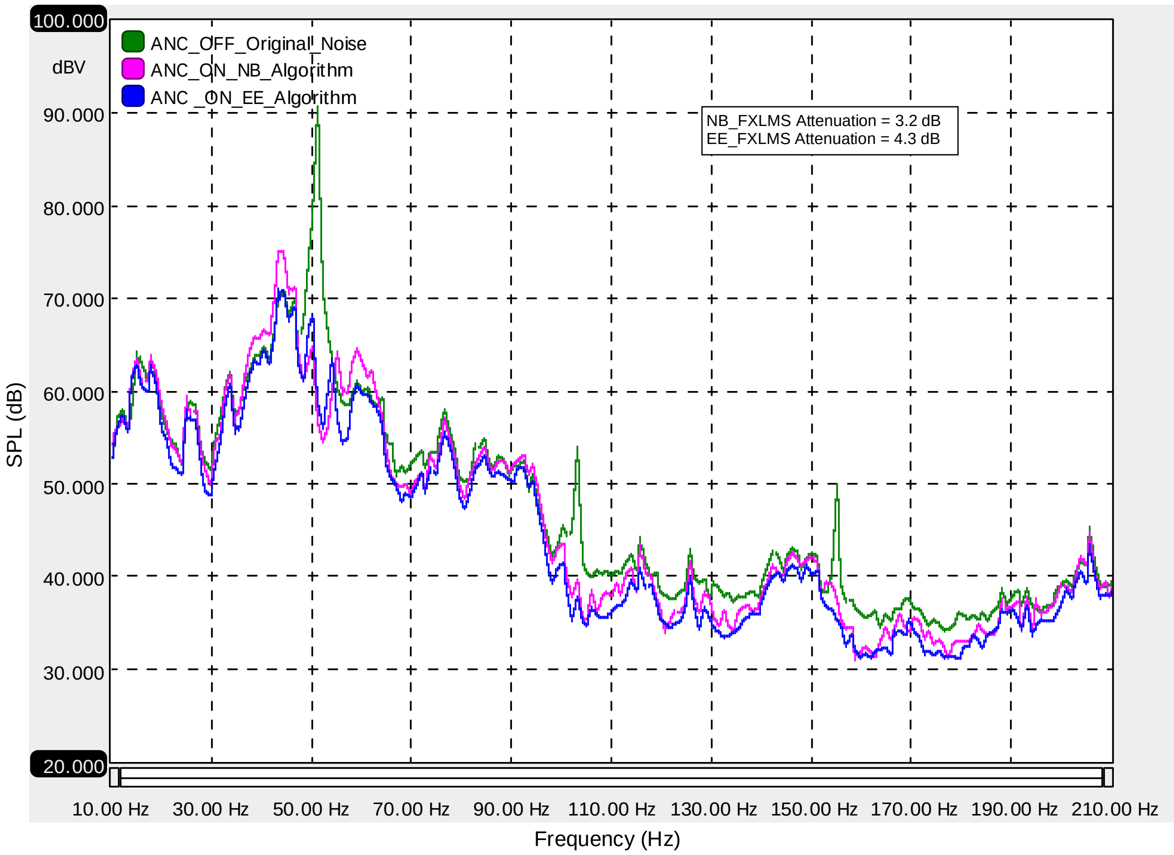

Figure 4. The attenuations of different algorithms for the ANC system at 1560 RPM.

As shown in Figure 4, the frequencies of the 2nd, 4th and 6th orders are at 52 Hz, 104 Hz and 156 Hz, respectively. Both algorithms have achieved large attenuations at these frequencies. Especially at 52 Hz, the attenuations are more than 20 dB. At the overall frequency range from 10 Hz to 210 Hz, the achieved attenuation by the normal FXLMS algorithm is 3.2 dB, and the attenuation of the equalized FXLMS algorithm reaches 4.3 dB. On average, the equalized FXLMS algorithm performed 1.1 dB better than the normal one.

6 CONCLUSIONS

Based on the constructed 3-channel ANC system for a truck cabin, the optimal performances of two different FXLMS algorithms are evaluated with the recorded noises. In comparison to the normal FXLMS algorithm, the equalized algorithm has the faster convergence speed and improved noise attenuation. Especially, the equalized algorithm has achieved 15-times faster convergence speed and 1 dB better performance than the normal FXLMS algorithm. Moreover, the equalized algorithm did not increase the online computational load. Because of the improved performance, the equalized FXLMS algorithm is more effective than the normal FXLMS algorithm for the practical use in truck cabins.

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