Modeling and Implementation of Engine Noise Cancellation System using Digital Adaptive Filter in a car environment

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Abstract

Engine management systems play a vital role in present day automotive systems. The design of Electronic Control Unit in engine management systems involves using self adaptive filters to changing real-time environments. The performance and life of an engine depends on air-fuel regulation, revolution per minute (rpm) mechanism and noise control strategies. Generally, the noises generated from engine, tires, belts and braking systems reduces the overall performance of various systems in a car. The government legislation to regulate automobile exhaust emissions under the authority of Environment Protection Agency in different countries also motivates the car manufacturers to concentrate in engine management systems. Engine noise cancellation thus becomes a vital mechanism providing a thrust to improve the national average fuel economy. This paper presents various engine noise cancellation methods in a car and designs an active engine noise cancellation System using digital adaptive filters. The proposed method is implemented using ARM CORTEX M4 processor and the performance parameters like Convergence factor, Mean Square Error and stability of the system is analyzed and discussed using MATLAB simulation results.

Keywords: *Engine Noise, Adaptive Filters, LMS Filters, ARM Processors, MATLAB, ECU, Automotive Electronics*

1. Introduction

Noise is an unwanted signal which is present in all environments. Vehicle noise can be categorized as driving noise, aerodynamic noise and rolling noise. Vehicle engine noise forms an important parameter for commercial success of OEM Companies. The filter used in air intake system, exhaust system, blow-off valves, turbo waste gate, and engine gear drives during revolutionary speed, belt drives and braking systems contribute to the vehicle engine noise. The above noises can be modeled depending on its frequency spectrum or time characteristics. Such noises fall into two categories of noises-White noise and Colored noise.

A white noise can be defined as an uncorrelated random noise process with equal power on all frequencies. The autocorrelation function of a continuous-time zero-mean white noise process is a delta function [1, 2]. Many car noises in real-time falls in non-white spectrum and time varying. A white noise passing through a channel is colored by the shape of the frequency response of the channel. The noise from car engine is non-stationary and varies with speed, road surface conditions and air flow mechanism. Such noises is a random signal which cannot be predictable but can be analyzed with well-defined statistical values such as maximum and minimum mean, variance and power spectrum[2].

2. Automobile Noise control Mechanism

The automobile industries uses two broad categories of noise control methods- Passive Noise Control method and active Noise control method.

2.1 Passive noise control method:

In olden day cars, mufflers and car damping materials are used to cancel out the engine noise by isolating vehicle occupants from engine and road noise. Mufflers are connected within the exhaust system in Combustion engines. They damp the sound produced by the engine using same piping used for silent exhaust gases. The fiber insulation is used to cancel the engine noise [3, 4]. The major limitation of mufflers is an increase in back pressure which highly decreases the engine efficiency and increases the weight of the automobile. Various types of mufflers used are Vector, Spiral baffle and aero turbine muffler. Most of the cars uses spiral shaped mufflers. A passive mount used to minimize the engine noise due to vibrations is shown in figure 1.

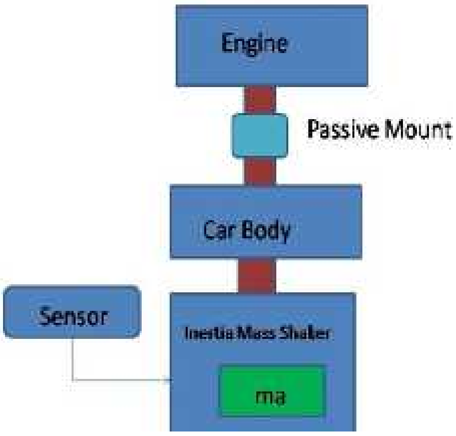


Figure 1: Passive Control Method

The passive Noise control methods are used to attenuate the noises from exhaust pipes, resonators and catalyst converters. There are various types of mufflers like combinational mufflers and Reactive Mufflers. The engine noise is measured and found to be of low frequency type typically around 90 to 150 Hz. So, Reactive mufflers are highly used to control such noises. Table 1 lists out the typical attenuation levels of noises using mufflers taken from Chevrolet petrol engine vehicle.

Table 1
Sound Level (dB)

Weight/load(kg)	Without using Muffler	Using Muffler
0	50.1	42.1
1	63.3	57.3
3	64.9	60.1
5	69.2	60.6

Table 2
Fuel Consumption with time factor to intake around 25 ml in seconds

Weight/load(kg)	Without using Muffler	Using Muffler
0	65	67
1	60	62
3	58	59
5	56	60

The values listed above are taken for different load conditions including no load condition (weight is zero).The fuel consumption and engine efficiency increases with the use of Mufflers which is listed through numerical values in Table 2.

During running conditions, the engine may be operated at different speeds depending on the road surface conditions. There will be minimum noise pollution when the engine is operating in its average usual speed of 3000 rpm.So, the effort must be taken to reduce the engine noise around 2000 rpm to 3000 rpm.It is inferred from the Table 1 and Table 2 that the engine performance can be increased to about 3% and also noise level can be minimized to about 3 dB to 7 dB with the use of mufflers depending on the load conditions.

2.2 Active noise control method:

Engine and power train mounts are designed by optimizing between vibration isolation and engine movement [5]. The basic idea behind active noise cancellation strategy is to superimpose the unwanted noise or vibrations with an anti-noise signal exactly of same magnitude and a phase difference of 180 degrees. It uses an Electronic control unit which performs engine management by getting input from various sensors and analyzing them using digital signal processing techniques [5].

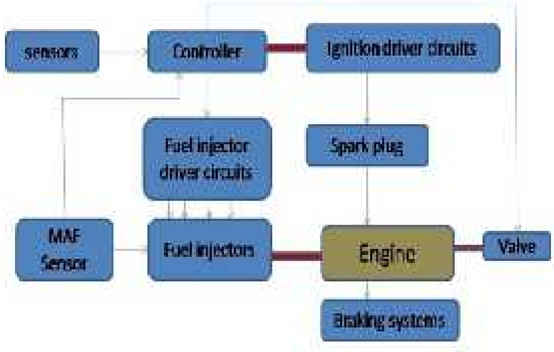


Figure 2: Engine Management System

A simple electronic engine management system is shown in figure 2. Active methods have wider advantages with the cost of electronic integrated chips reducing in present day market. They also increase fuel efficiency and life of an engine. They provide a better solution for manufacturing lighter luxurious cars [6,7]. Figure 3 shows a typical active engine noise control method.

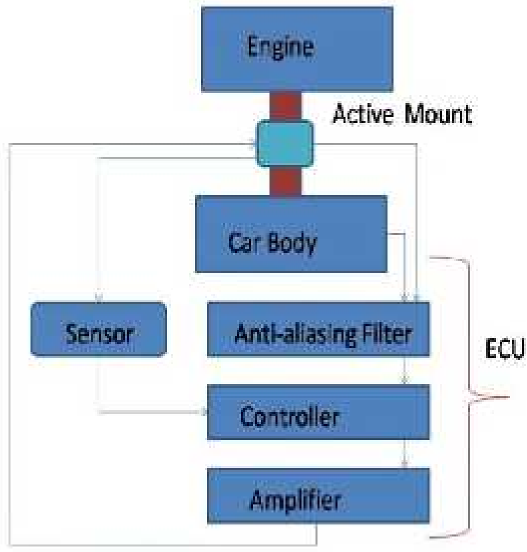


Figure 3: Active Control Method

3. The proposed method

The existing Noise Cancellation techniques in cars use mufflers, sound damping materials and active control methods to cancel out the engine noise. The proposed method uses digital adaptive filters to cancel the engine noise in a non-stationary environment. The noise signal generated in real-time is modeled as a Random signal and various adaptive algorithms like Least Mean Square (LMS) and variants are used to perform noise cancellation [8,9]. The engine noise cancellation mechanism using Adaptive filters is shown in figure 4.

It consists of a primary signal and a reference signal correlated with engine noise. The reference signal is used as an anti-noise signal to cancel the engine noise. Since this process happens in a real-time environment ie.when the car is moving, adaptation is performed using the current inputs obtained from the sensors and the filter weights are updated to minimize the error signal [10,11]. Mathematically, the algorithm is defined as,

$$y(n) = \sum_{i=0}^{M-1} w_k(n) * x(n-i) \qquad \text{------ (1)}$$

$$e(n) = d(n) - y(n) \qquad \text{----- (2)}$$

$$w_k(n+1) = w_k(n) + 2\text{«} * e(n) * x(n-i) \qquad \text{----- (3)}$$

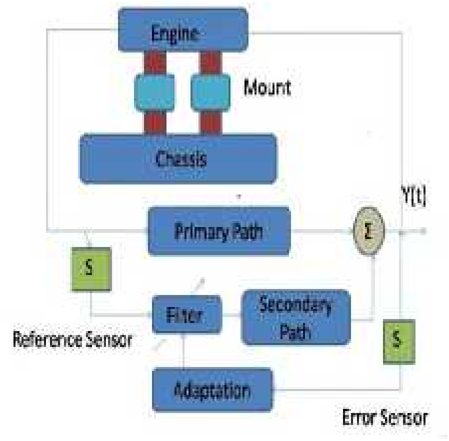


Figure 4: ANC system using Digital Adaptive filter

The tap inputs, x (n), x (n-1),……, x (n-M+1) is the reference signal x(n) with M-1 delay elements. The primary signal is d (n), the error signal is e (n) and w_k (n) is the tap weight at nth iteration. The parameter μ is the scaling factor step size parameter which controls stability and convergence speed. For proper convergence and stability of the filter, the initial conditions of the filter should have non-zero values and the step size parameter values should take values always less than one [12, 13]. The step-size condition is given by,

$$0 < \text{«} < \frac{1}{N\{inputsignalpower\}} \qquad \text{------ (4)}$$

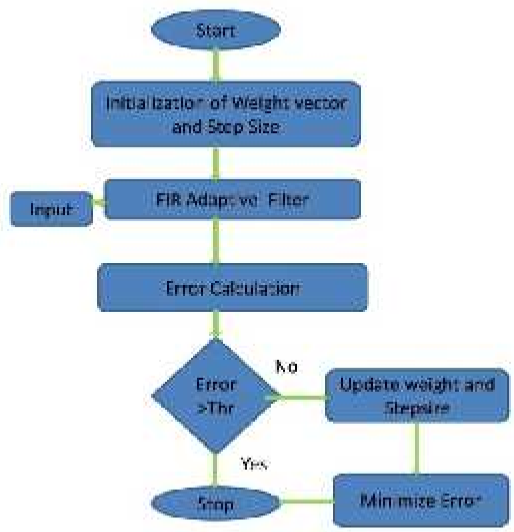


Figure 5: Flowchart of adaptation process

The adaptation algorithm processed is described using a flowchart as given in fig 5.

4. Simulation Results and Discussion

The proposed Adaptive Engine noise canceller is designed and simulated using MATLAB. Initially, the randomness of the engine noise is captured using microphone and analyzed [14, 15]. The condenser microphones are used for automotive applications where noise signal is captured and converted to electrical signal. The signal thus obtained is processed using digital signal processing techniques and given to the digital adaptive filter. The general block diagram of microphone used in noise cancellation is given in figure 6[16,17].

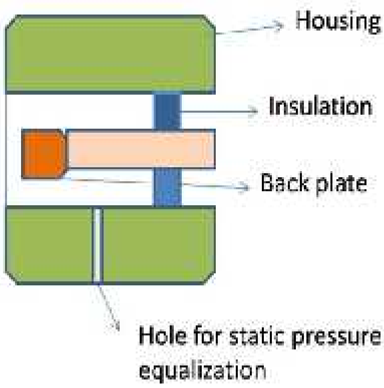


Figure 6: Schematic of a Condenser Microphone

The Correlation function and the power spectrum of the Random engine noise is illustrated in figure 7 and 8. The proposed system uses a step size value of 0.002 and filter order of 5.The performance factors like mean square error, convergence and stability of the system is analyzed and shown in figure 9.

Table 3
Mean Square Error analysis

No. of iterations	MSE(dB)
1000	-6
5000	-15
10000	-19

The simulation results prove that the active engine noise cancellation system converges at a faster rate and becomes stable. The mean square error is highly minimized when the number of iterations is increased as displayed in Table 3.

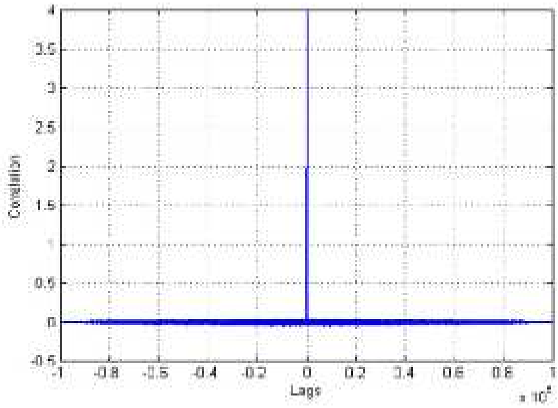


Figure 7: Autocorrelation function of Automobile Engine Noise

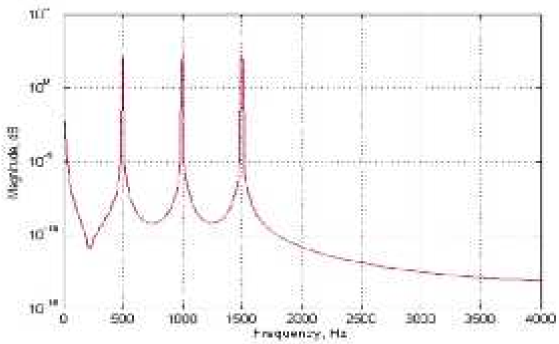
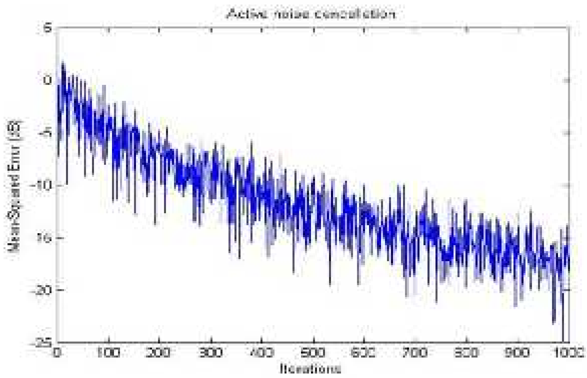
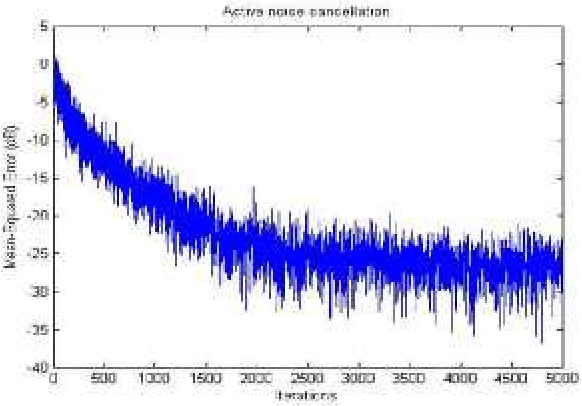


Figure 8: Power spectrum of a random engine noise

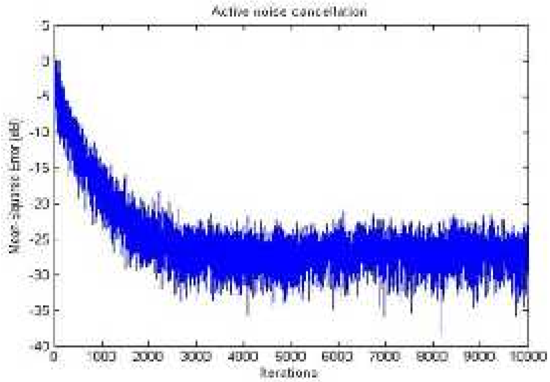


9(a) MSE I=1000 iterations

The Mean Square error analysis is illustrated for 1000, 5000 and 10000 iterations respectively.



9(b) MSE I=5000 iterations



9(c) MSE I=10000 iterations

Figure 9: Mean Square error of the proposed ANC system

The reduction in Noise level using Adaptive filtering is performed by capturing the engine noise signal inside the car cabin using microphones. Since a feed forward system is used, a reference signal is taken which is a signal that is highly correlated with the occurring noise signal usually captured from loud speakers. It is given to the adaptive filter for noise reduction and its performance characteristics are studied. Table 4 lists out the Numerical values for noise reduction in db using the Active noise control method.

Table 4

Sound Level (dB)

Weight/load(kg)	using Muffler	Using Muffler
0	50.1	40.3
1	63.3	54.1
3	64.9	56
5	69.2	58.1

It is inferred from the table that the noise reduction of about 10 db to 11 db is possible using Active Noise Reduction method compared to the Passive method of using mufflers. Also, minimizing the use of mufflers will reduce the overall weight of the cars.

5 . System Implementation

The proposed Adaptive Noise Canceller is implemented using ARM Cortex-M4 based processor (FM4 S6E2CCA) [figure 10]. The Cypress FM4 board (FME-176L-S6E2CC-ETH Starter Kit) is a low cost development platform featuring a 200MHz ARM Cortex-M4 based processor (FM4 S6E2CCA)[14]. It connects to a host PC via a USB cable using a CMSIS programming and debugging tool (CMSIS-DAP).It uses a floating point unit to process the digital data. It is also equipped with THUMB instruction set to perform 16 bit operations. The Keil MDK-ARM development environment, running on the host PC enables software written in C to be compiled, linked and downloaded to run on the FM4 S6E2CCA[18,19,20]. The Filter coefficients are generated using MATLAB and is given to the ARM CORTEX processor to obtain the frequency response of the system. The Implementation and Experimental setup of Adaptive Noise Canceller is shown in figure 11.

Figure 10: ARM CORTEX M4 Evaluation Board

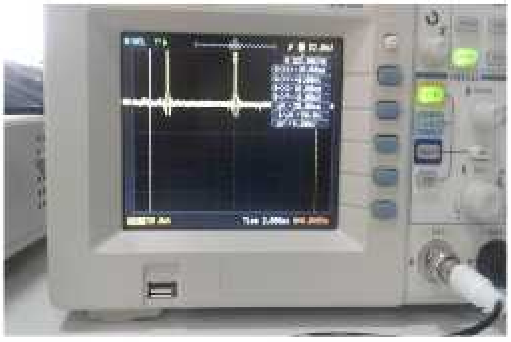


Figure 11: Implementation of ANC System

6. Conclusion and Future work

The Digital Adaptive Engine Noise Canceller is designed and implemented using ARM CORTEX M4 based processor and the performance parameters like convergence factor, Stability and Mean square error are discussed. It is clearly proved from the simulation results that the proposed system is highly efficient, fast convergent, stable system in a changing real-time car environment. The above system can be further enhanced by optimizing the word length for filter coefficients using a fixed or floating point processor which can be described using a hardware descriptive language.

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Bibliography

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