Design and Control of Active Muffler In Engine Exhaust Systems

JINSIANG SHAW
Mechanical Engineering Department
Huafan University
Shihtin 223, Taipei
TAIWAN

Abstract: - This paper presents design and control of active mufflers used in engine exhaust systems. Boundary element method is employed to investigate noise attenuation performances of various active muffler structures. Based on these performance evaluations, an active muffler having only one loudspeaker inclined at 45 degree with the muffler centerline is constructed and tested for active noise control (ANC). The feedback ANC with two controller tuning algorithms, the filtered-x least mean square (FXLMS) algorithm and Godart modified algorithm, is applied independently for engine exhaust noise attenuation. Experimental investigation reveals that feedback ANC with FXLMS algorithm can attain an averaged 23.6 dB noise attenuation for pure tone excitation and over 6 dB noise reduction for motorcycle and automobile exhaust noises. It is also shown that feedback ANC with Godart modified algorithm has faster transient response compared to FXLMS algorithm for a pure tone noise, but has inferior noise attenuation capability than the FXLMS algorithm for the engine exhaust noise at fixed speeds (about 5 dB noise reduction) as well as during run-up tests.

Key-Words: - Active Muffler, Active Noise Control, Engine Exhaust Noise

1 Introduction

Active noise control (ANC) is often applied in various situations for suppressing wanted noise. Noise in a duct [1], engine exhaust systems [2], noise in a cabin [3] are some examples in which ANC is widely applied. Compared to conventional passive noise control, ANC can provide advantages such as improved low-frequency performance, wideband noise suppression, reduction in size and weight in the structure, and adaptability. As is well known, there are three popular control structures for ANC [4], namely narrowband feedforward, broadband feedforward, and feedback ANC. Narrowband feedforward ANC uses a non-acoustic signal related to the primary noise as a signal for synthesizing the reference input, e.g. signals from an accelerometer, a tachometer, or engine ignition signals. On the other side, broadband feedforward ANC measures directly the primary noise near the sound source as the reference signal. One drawback associated with the broadband feedfoward ANC is the so-called acoustic feedback which originates from the control speaker and can cause undesirable effects. These two popular feedforward ANC structures have been extensively investigated in duct noise applications. Instead of using two sensors in the feedforward ANC structures (one sensor for the reference signal, the other sensor for the residue sound level for tuning controller), feedback ANC employs only one error microphone for measuring the residue sound level for feedback.

In this paper, feedback ANC structure will be applied for suppressing engine exhaust noise in motorcycle and automobile. Krause and Weltens [2] summarized results of up-to-date active and semi-active noise control progress in automotive exhaust silencing. Kim et al. [5] employed the narrowband feedforward ANC for suppressing engine exhaust noise in an automobile, in which acceleration signal of engine's cylinder block is used to synthesize a reference signal. Experimental results indicated that a sound reduction of more than 5 dB of exhaust noise in overall sound level can be acquired. Wu and Bai [6], on the other hand, used the broadband feedforward ANC for noise cancellation in engine exhaust systems. A reference microphone is located at the upstream near the engine for measuring the primary noise. Experimental results indicated that reductions of sound level from 3.86 dB to 2.21 dB of exhaust noise were obtained, for fixed engine speed from 800 rpm to 3000 rpm. The purpose of this paper is to employ the third ANC structure, namely feedback ANC, for engine exhaust cancellation and to compare the results with those of the two aforementioned feedforward ANC structures.

2 Design and Simulation of Active Muffler

In this section four active muffler structures, as shown in Figure 1, are to be evaluated for its capability for attenuating noise. These four active muffler structures include using one, two, or three control loudspeakers whose control sound fields can enter into the muffler at either right angle or 45 degree. Boundary element method [7] in SYSNOISE is applied for evaluating each active muffler performance for noise cancellation. The primary noise of a pure tone is generated at the inlet (right end) connecting to engine exhaust tailpipe, while the control sound for anti-noise is optimized for obtaining the minimum residue sound level at the outlet (left end). Figure 2 shows amount of the maximum noise attenuation at different frequency for each active muffler. Table 1 lists the averaged noise reductions in the tested frequency range. From Fig. 2 and Table 1, it is clearly shown that it differs not much which active muffler structure has the best performance. However, the active muffler structure of Fig. 1(second top) with only one control loudspeaker inclined at 45 degree does outperform other structures slightly, and hence is selected as the active muffler used in the following experiments.

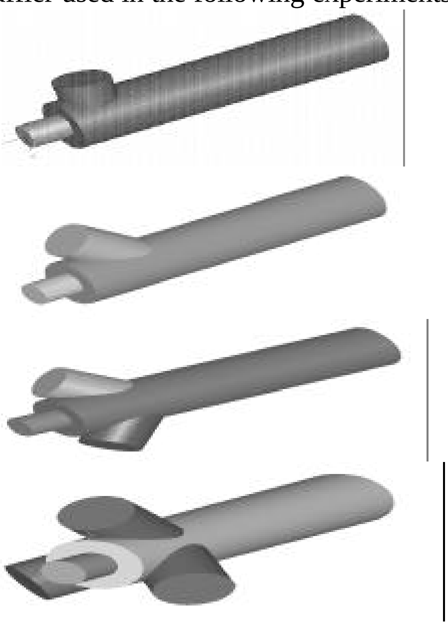


Fig. 1 Active muffler structures

Table 1. Averaged sound attenuations

Structures	Noise Reduction
Fig. 1(top)	84.38 dB
Fig. 1(second top)	86.65 dB
Fig. 1(third top)	86.64 dB
Fig. 1(bottom)	86.45 dB

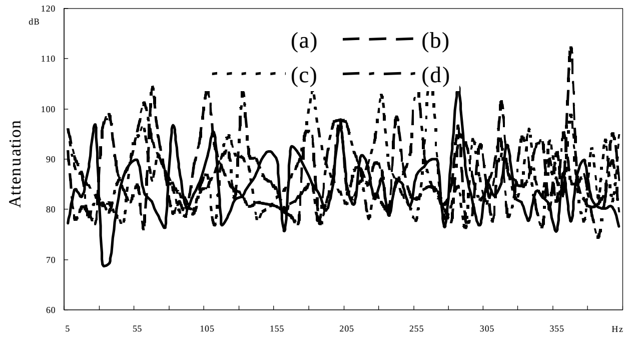


Fig. 2 Noise attenuations: (a)-(d) are for mufflers in Fig. 1 from top to bottom, respectively

3 Experimental Set-up and Control Algorithms

The active muffler of Fig. 1(second top) is chosen for engine exhaust silencing and is attached to the engine exhaust tailpipe which is simply represented by a duct of finite length as shown in Fig. 3. Stainless steel is used to construct the active muffler and the engine exhaust tailpipe. In this study, the engine exhaust noise is to be reproduced by a loudspeaker at the left end. Therefore the effects of flow and temperature existing in practical engine exhaust systems are not considered. The control loudspeaker is mounted at the active muffler for producing anti-noise and an error microphone is place at the outlet of the active muffler for measuring the residue sound level for feedback.

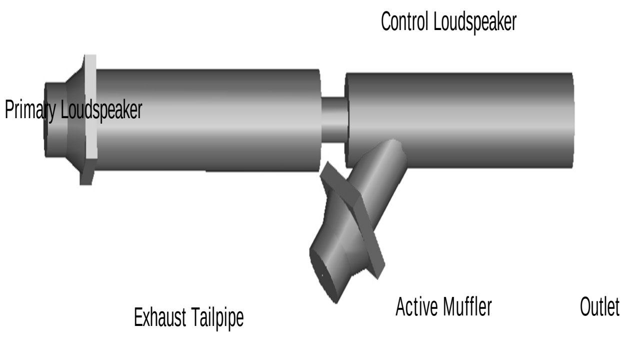


Fig. 3 Experimental set-up for ANC

Block diagram of the feedback ANC with FXLMS and Godart modified algorithms is depicted in Fig. 4. The mathematical model of secondary path from control speaker to the error microphone (the so-called plant model) is identified offline and is represented by an infinite impulse response (IIR) filter with 100 auto-regressive and 75 moving-averaged coefficients. The controller is assumed a finite impulse response (FIR) filter whose coefficients are tuned on line by either FXLMS algorithm or Godart modified algorithm. The FXLMS algorithm [4] is derived by minimizing the cost function *E(n)*:

$$E(n) = \frac{1}{2} e^2(n) \qquad (1)$$

The corresponding tuning law for coefficients of FIR filter controller $w(n)$ is as follows:

$$w(n+1) = w(n) + he(n)\bar{x}(n) \qquad (2)$$

where h is a learning rate controlling rate of convergence of the algorithm. As for the Godart modified algorithm [3], the cost function

$$E(n) = \frac{1}{2}\sum_{k=1}^{k=n} he^2(k) \qquad (3)$$

is minimized. The corresponding tuning law for coefficients of FIR filter controller takes the form:

$$w(n+1) = w(n) + \frac{he(n)P_{n-1}\bar{x}(n)}{1 + h\bar{x}^T(n)P_{n-1}\bar{x}(n)} \qquad (4)$$

$$. \; P_n = P_{n-1} - \frac{hP_{n-1}\bar{x}(n)\bar{x}^T(n)P_{n-1}}{1 + h\bar{x}^T(n)P_{n-1}\bar{x}(n)} . \qquad (5)$$

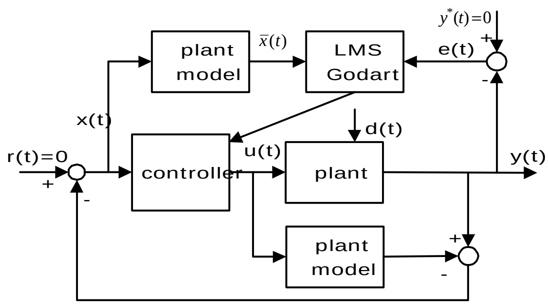


Fig. 4 Block diagram of feedback ANC

The control algorithms of FXLMS and Godart will be implemented in a 586 PC with a sampling rate of 2k Hz. In addition, a low-pass filter with a cutoff frequency at 400 Hz filters out high frequency components of the signals from the error microphone and the control effort after the D/A converter.

4 Experimental Results using Feedback ANC

The experimental set-up of Fig. 3 for evaluating performance of the active muffler will be run in this section. First of all, pure tone excitation is applied at the primary loudspeaker from 20 Hz to 400 Hz at every 5 Hz for testing the validity of the constructed active muffler and the FXLMS algorithm. Fig. 5 shows the resulting noise attenuations in dB at the outlet of the active muffler, thus clearly verifying the noise cancellation capability of the active muffler and the control algorithm. An averaged attenuation of 23.6 dB is obtained. Next, engine exhaust sounds from motorcycle and automobile will be applied for evaluating the performance of the active muffler. Note that the engine exhaust sounds of motorcycle and automobile are first recorded by a recorder placed 1.5 meter behind the exhaust tailpipe with 45 inclined angle and are then replayed by the primary loudspeaker. Fig. 6 and Fig. 7 illustrate performances of the active muffler for attenuating automobile exhaust noise at idle speed of 800 rpm and a fixed speed of 1500 rpm, respectively, in both time and frequency domains. Corresponding response of the active muffler for motorcycle exhaust noise is shown in Fig. 8. Note that solid line and dashed line in the figures correspond to with and without ANC, respectively. For all these engine exhaust noise tested, over 6 dB noise attenuations are obtained.

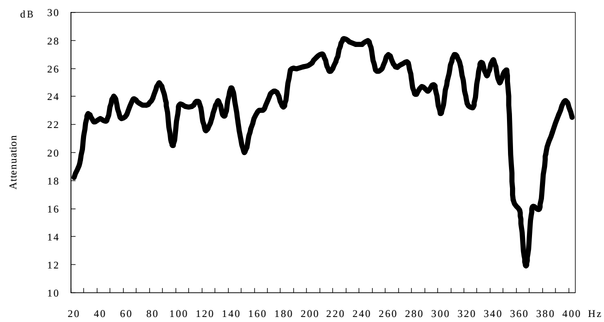


Fig. 5 Noise reductions for pure tone excitation

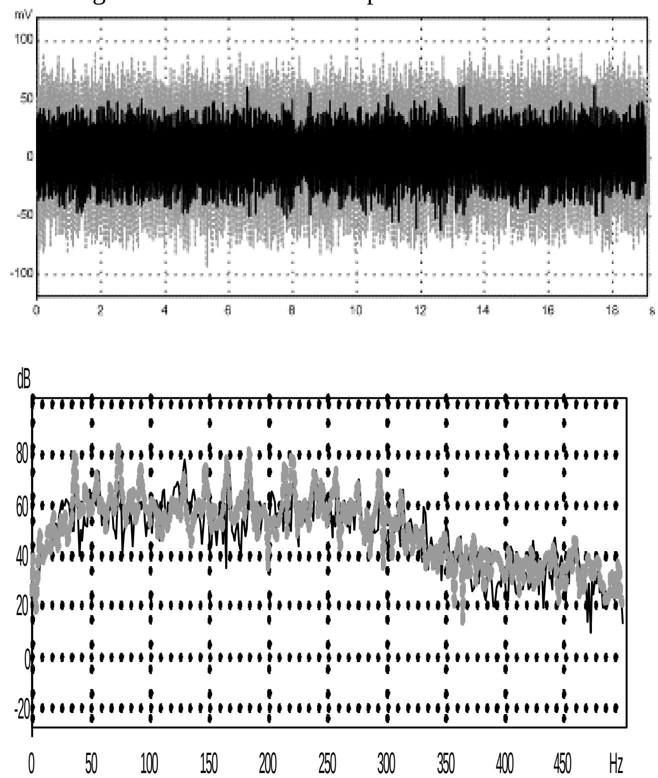


Fig. 6 Time (top) and frequency (bottom) response of ANC of an automobile at 800 rpm.

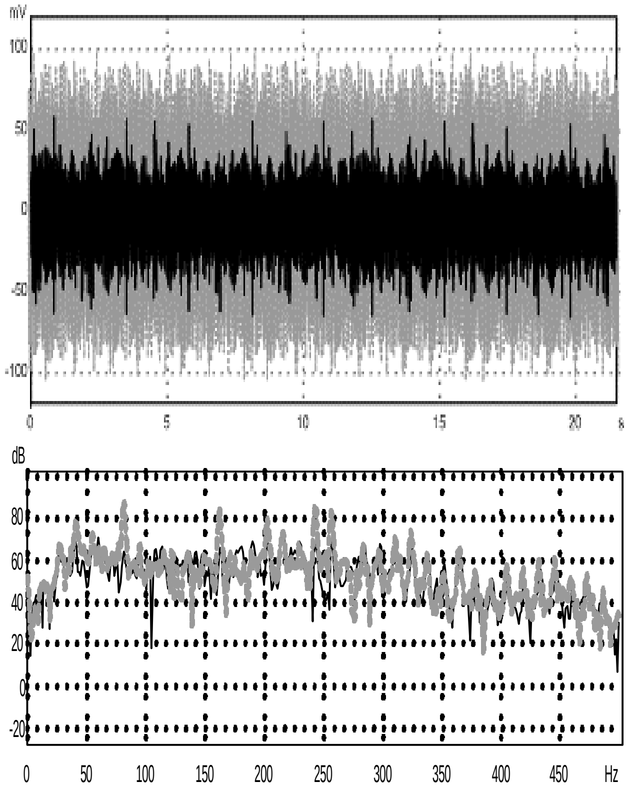


Fig. 7 Time (top) and frequency (bottom) response of ANC of an automobile at 1500 rpm.

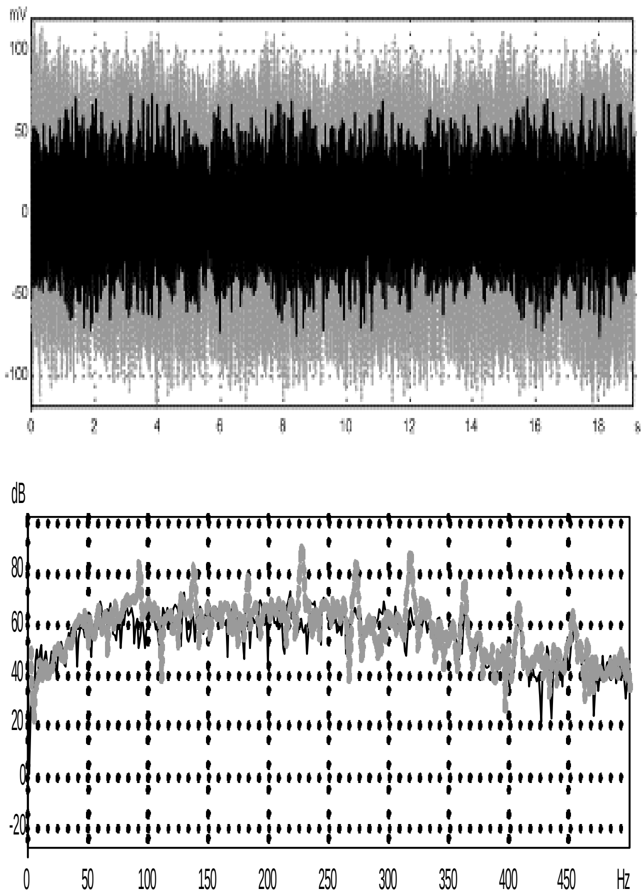


Fig. 8Time (top) and frequency (bottom) response of ANC of an motorcycle at 5280 rpm.

To compare the two control algorithms of FXLMS and Godart for noise reduction, transient response of ANC during the first 5 second run will be examined. Fig. 9 depicts responses for a 100 Hz pure tone excitation, in which Godart algorithm converges slightly faster than FXLMS. In fact, for all the pure tone excitations tested, this statement carries through.

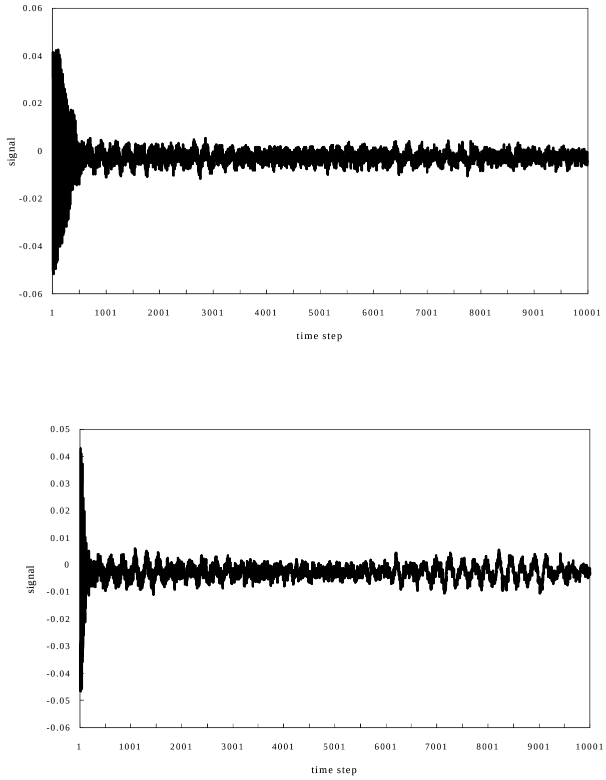
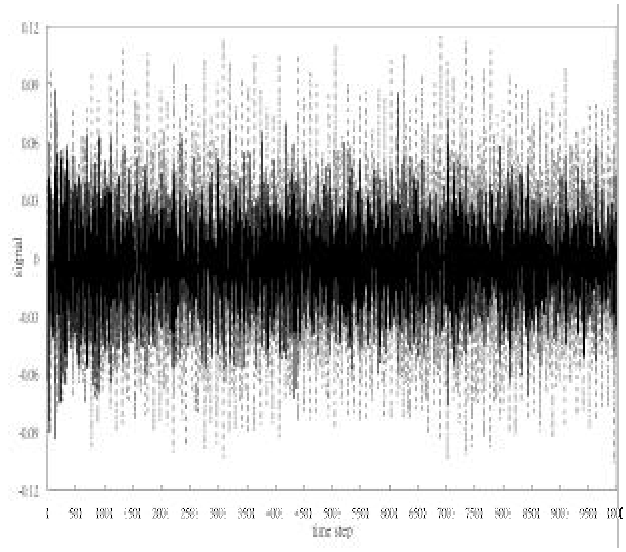


Fig. 9 Transient response of ANC with FXLMS (top) and Godart (bottom) for 100 Hz excitation.

As for the engine exhaust noises, FXLMS and Godart algorithms have comparable convergence rates, as shown in Fig. 10, 11, and 12. However, for steady state response, ANC with FXLMS can obtain over 6 dB noise reductions, while Godart algorithm attains only about 5 dB noise attenuations for these three engine exhaust noises. At last, exhaust noise of an automobile during run-up from 1000 rpm to 1600 rpm in 10 seconds is attenuated by ANC. Fig. 13 illustrates the results indicating ANC with FXLMS outperforms Godart algorithm in noise attenuation. Fig. 14 shows the similar results in the frequency domains



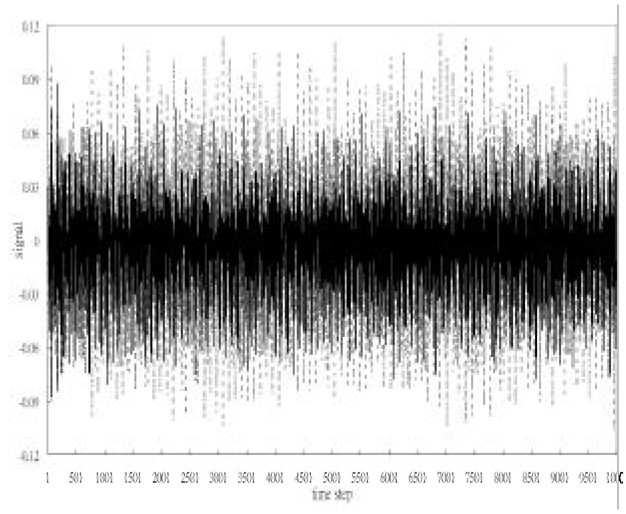
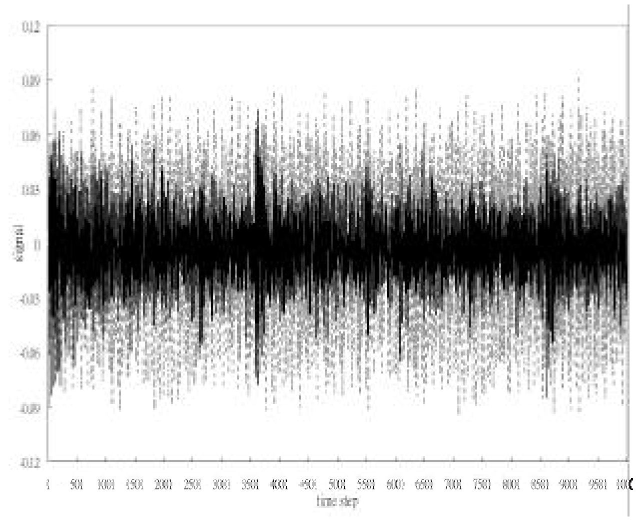


Fig. 10 Transient response of ANC with FXLMS (top) and Godart (bottom) for automobile at 800rpm.



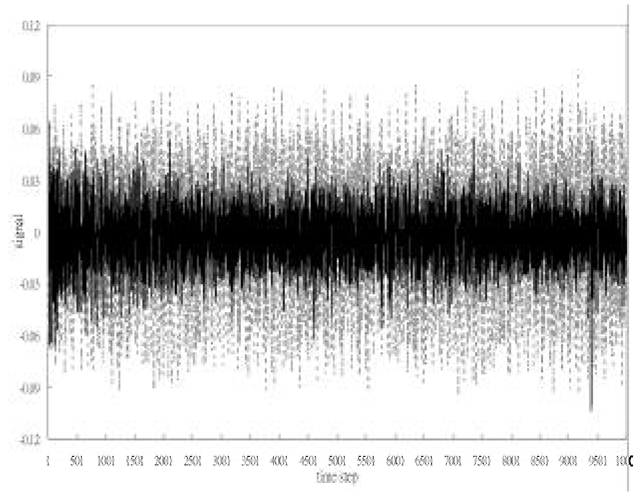
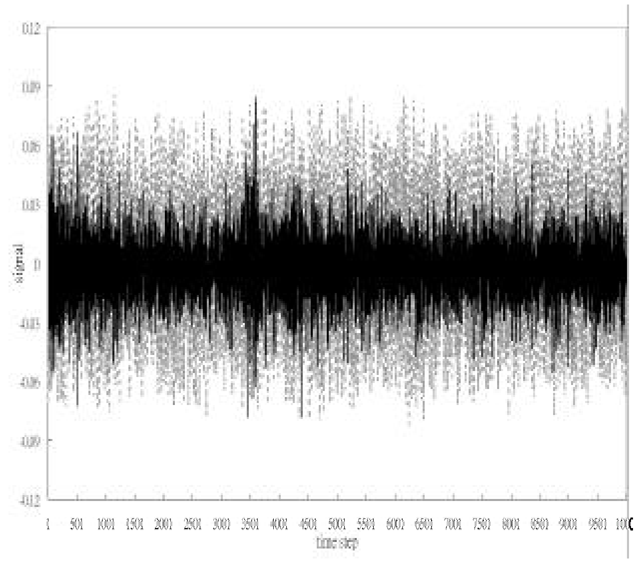


Fig. 11 Transient response of ANC with FXLMS (top) and Godart (bottom) for automobile at 1500rpm.



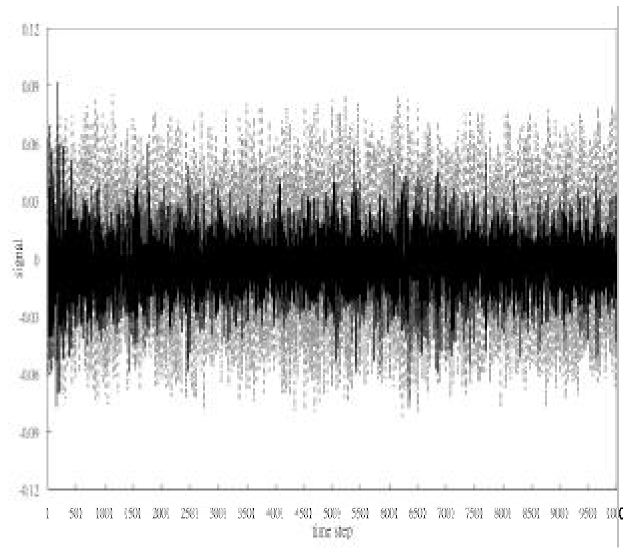


Fig. 12 Transient response of ANC with FXLMS (top) and Godart (bottom) for motorcycle at 5280 rpm.

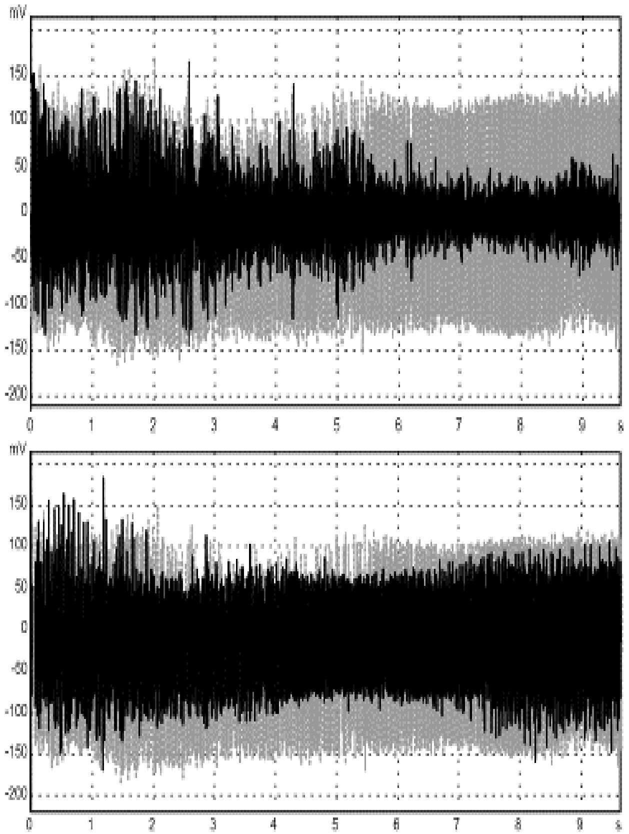


Fig. 13 Transient response of ANC with FXLMS (top) and Godart (bottom) for automobile during run-up.

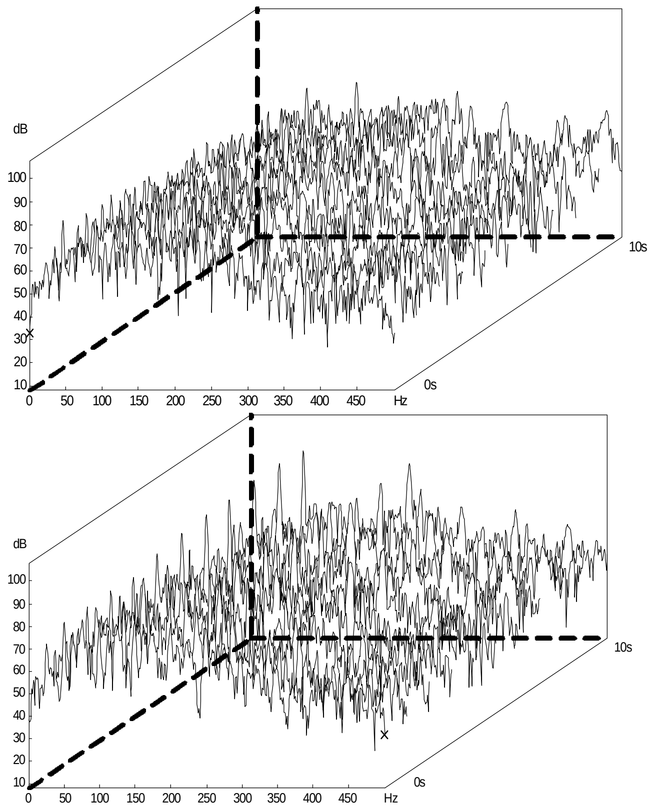


Fig. 14 Frequency response of ANC with FXLMS (top) and Godart (bottom) for automobile during run-up.

5 Conclusions

In this paper, an active muffler with one control loudspeaker inclined at 45 degree with the muffler centerline is developed and tested. The active muffler is attached to engine exhaust systems for exhaust noise attenuation with a goal of attaining broadband noise suppression. Feedback ANC with FXLMS and Godart modified algorithms are independently employed for controller tuning. From experimental results it is clearly shown that although Godart algorithm has a slightly faster transient response than that of FXLMS for a pure tone noise excitation, FXLMS outperforms Godart modified algorithm in terms of noise attenuation in the overall sense for all the noise used in the experiments. Feedback ANC with FXLMS algorithm attained over 6 dB reductions of engine exhaust noise, whereas feedback ANC with Godart algorithm has only 5 dB noise attenuation. Finally, compared to results in references [5] and [6], feedback ANC with FXLMS has a slightly better noise attenuation performance. It is, however, pointed out here that flow and temperature effects are neglected in this study. These effects will be included in the future work.

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