Active Noise Control for Muffler

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Abstract—This paper presents an active noise control (ANC) system for muffler. An ANC muffler is built to verify the performance and the experiment is conducted in real-time. Experiment results compare three narrowband ANC methods: direct, parallel and direct/parallel forms; with synthesized engine noises for fixed and changing engine speed. Active noise equalizer (ANE) is also experimented and presented in this paper to tune the engine sound.

I. INTRODUCTION

Traveling by cars can be really convenient and helpful for most people. Sun and rain protection, big space, and timesaver are the main reasons why cars are preferred. However, they contribute not only air pollution, but also noise pollution, especially the engine exhaust noise. According to Environment Protection Authority (EPA) regulation, the car noise level may not exceed 90 dB [1]. Noise level at 90 dB may only be listened up to two hours thirty minutes [2] and exposure to high noise level for long duration can cause permanent hearing loss.

Conventionally, the engine exhaust noise is suppressed by a passive muffler system in which the noise propagation is broken up by baffles and passageways, or absorbed in sound-deadening material [3]. However, using sound absorbing material in muffler leads to back pressure to the engine, degrading engine power delivery and increasing fuel consumption. Moreover, passive muffler is effective only at reducing high frequency sound, whereas the engine noises usually have their main power at low frequencies. These problems can be solved by using electronic muffler based on ANC techniques.

This paper presents electronic muffler using the ANC system, dealing with synthesized engine noises for both fixed and changing engine speed. This paper also presents the ANE to tune engine noise becoming good engine sound.

II. ENGINE EXHAUST NOISE ANALYSIS

This section analyzes the engine exhaust noise of accelerating or decelerating engine speed. Acoustic sensor cannot last long in high-temperature environment of the engine exhaust; thus, non-acoustic sensor which measures the engine speed is commonly used to obtain the fundamental frequency of engine noise. A sine wave generator is used to create the reference signal which includes the harmonics of the primary noise [4].

Engine-generated noise is dominated by harmonically related components having frequencies that vary as a function of the engine rotational speed. The dominant harmonic components will depend on the number of cylinders, due to the differing firing patterns [3]. Since RPM is related to frequency of the noise:

\[
f_{\text{vehicle}} = \frac{n \cdot C}{30 \cdot S} \tag{1}
\]

where \(n\) is the engine RPM, \(C\) is the number of cylinders, \(S\) is the number of cycles, and \(f_{\text{vehicle}}\) is the fundamental frequency of the engine noise [5]. This paper uses a four-cylinder engine, so both \(C\) and \(S\) are 4. For 2400 rpm, the fundamental frequency is 80 Hz, 20 Hz (fundamental frequency divided by the number of cycles) gap for each harmonic frequencies until 700 Hz (focus on low-frequencies) is reached. For 3600 rpm, the fundamental frequency is 120 Hz, 30 Hz gap for each harmonic frequencies until 700 Hz is reached. The primary noise and reference signal are synthesized using multiple sinewave generator and generated by digital signal processor board. Figure 1 shows the generated signal for 3600 rpm.

To obtain the noise of accelerating or decelerating engine speed, each of 2400 rpm harmonic frequencies is swept to 3600 rpm harmonic frequencies in 12 seconds as shown in Fig. 2.

III. ACTIVE NOISE CONTROL FOR MUFFLER

ANC system cancels the primary noise based on the principle of superposition; specifically, an anti-noise of equal amplitude and opposite phase is generated and combined with the primary noise, thus resulting in the cancellation of both noises. The narrowband feedforward ANC system uses non-acoustic sensor to synthesize the reference input. This technique is only effective for periodic noise, such as engine noise, because the fundamental driving frequency is the only reference information available [3].

A. Direct Form

As shown in Fig. 3, a non-acoustic sensor is used to obtain the rotation of the engine. By using digital signal processing, the reference signal which consists of multiple-harmonic noise components is generated by converting the rotation to frequency. As long as a reference signal is available that includes every sinusoidal component of the interference, a narrowband ANC system will provide effective cancellation [3]. However, it’s difficult for the adaptive filter to deal with low-energy frequency because of a huge energy differences between the harmonics. The block diagram of direct form ANC is shown in Fig. 3, where the reference input is a sum of \(K\) sinusoids:
\[ x(n) = \sum_{k=1}^{K} A_k \cos(\omega_k n) \] ..............(2)

where \( A_k \) and \( \omega_k \) are, respectively, the amplitude and the frequency of the \( k^{th} \) sinusoid.

As shown in Fig. 3, the residual noise \( e(n) \) is expressed as:
\[ e(n) = d(n) - y'(n) = d(n) - s(n) + y(n) \] ..............(3)

where \( s(n) \) is the impulse response of secondary path \( S(z) \) at time \( n \), * denotes linear convolution. The adaptive filter output \( y(n) \) is computed as:
\[ y(n) = \sum_{l=0}^{L-1} w_l(n) x(n-l) \] ..............(4)

where \( w_l(n) \) is the \( l^{th} \) coefficient of the adaptive filter \( W(z) \).

The adaptive filter weight is updated by the FXLMS algorithm:
\[ w_l(n+1) = w_l(n) + \mu x'(n-l) e(n), l = 0, 1, ..., L - 1 \] .............(5)

where \( \mu \) is the step size that determines the convergence speed of the algorithm, \( L \) is the filter length of the adaptive filter \( W(z) \), and \( x'(n) \) is a filtered version of the reference input signal. Thus:
\[ x'(n) = \sum_{m=0}^{M-1} \tilde{S}_m(n) x(n-m), m = 0, 1, ..., M - 1 \] .............(6)

where \( \tilde{S}_m(n) \) is the \( m^{th} \) coefficient of the secondary-path estimation filter \( \tilde{S}(z) \) at time \( n \), \( M \) is the filter length of the secondary-path estimation filter \( \tilde{S}(z) \).

B. Parallel Form

This method is based on FXLMS algorithm which divides the signal obtained from the non-acoustic sensor into multiple reference signals:
\[ x_k(n) = A_k \cos(\omega_k n), k = 1, 2, ..., K \] ..............(7)

where \( A_k \) and \( \omega_k \) are, respectively, the amplitude and the frequency of the \( k^{th} \) sinusoid.

Each reference signal contains a single harmonic and its own adaptive filter to generate the anti-noise. By doing so, the parameter of each adaptive filter can be adjusted according to the primary noise. These adaptive filters are connected in parallel as shown in Fig. 4 and the canceling signal is a sum of the adaptive filter outputs:
\[ y(n) = \sum_{k=1}^{K} \sum_{l=0}^{L-1} w_{k,l}(n) x_k(n-l) \] ..............(8)

where \( w_{k,l}(n) \) is the \( l^{th} \) coefficient of the adaptive filter at \( k^{th} \) harmonic. The adaptive filter weight is updated by the FXLMS algorithm:
\[ w_{k,l}(n+1) = w_{k,l}(n) + \mu_k x_k'(n-l) e(n) \] ..............(9)

where \( l = 0, 1, ..., L - 1; k = 1, 2, ..., K \) and \( \mu_k \) is the step size. Each reference signals goes through secondary-path estimation filter \( \tilde{S}(z) \):
\[ x'_k(n) = \sum_{m=0}^{M-1} \tilde{S}_m(n) x_k(n-m), k = 1, 2, ..., K \] .............(10)

C. Direct/Parallel Form

The idea is to separate a collection of many harmonically related sinusoids into mutually exclusive sets that individually have frequencies spaced out as far as possible [3]. For example, there are 20 harmonic frequencies for the changing synthesized engine noise in this paper, \( f_1, f_2, ..., f_{20} \), then four sets of staggered frequencies could be formed as:
\[ \{ f_1, f_5, f_9, f_{13}, f_{17} \} \]
\[ \{ f_2, f_6, f_{10}, f_{14}, f_{18} \} \]
\[ \{ f_3, f_7, f_{11}, f_{15}, f_{19} \} \]
\[ \{ f_4, f_8, f_{12}, f_{16}, f_{20} \} \]

Each sets is processed by its own corresponding adaptive filters. The output signals from each adaptive filter are summed to obtain a cancelling signal. The block diagram is similar to Fig. 4, except that each \( x_k(n) \) contains one or more sinusoidal components.

D. Active Noise Equalizer

By using active noise equalizer (ANE), the amplitude of each harmonic frequencies can be controlled. A block diagram of narrowband active noise equalizer system for controlling periodic noise is shown in Fig. 5.

The gains \( \beta \) and \((1 - \beta)\) are inserted to enable adjustment of the residual noise. The signal \( e'(n) \) acts as a pseudoeonrr signal to ‘trick’ the LMS algorithm so that it will converge to an optimum solution to minimize \( e'(n) \), while the actual residual noise \( e(n) \) has the desired amplitude. Thus:
\[ e(n) = d(n) - (1 - \beta) y(n) = \beta d(n) \] ..............(11)

where the system output \( e(n) \) contains residual component of the narrowband noise whose amplitude can be continuously, linearly, and totally controlled by adjusting the gain value \( \beta \) [3].

IV. EXPERIMENTAL SETUP

The prototype is based on Jing Tong Co., Ltd. #291545 model and built by using acrylic as shown in Fig. 6. The size is 450mm (L) * 290mm (W) * 150mm (H). Figure 7 shows the experimental setup from the side view. Error microphones are located on the left side of the muffler and secondary loudspeakers are located in the middle. The primary loudspeaker is to play the primary noise which is synthesized and generated by digital signal processor. Anti-noise drives the secondary loudspeaker to cancel out the noise coming out from the muffler and the residual noise is picked up by the error microphones.
V. EXPERIMENT RESULTS AND ANALYSIS

The performance of ANC system is evaluated by real-time experiments using synthesized engine noises for fixed and changing engine speed.

A. Fixed Engine Speed

The performance of the ANC system is evaluated using engine noise at 3600 rpm as primary noise. As discussed in Section II, each harmonic frequencies is generated by different signal generators, mixed, and played through the primary loudspeaker. Figure 8 depicts the magnitude spectra of signal measured at the error microphone before and after noise cancellation by using direct form (a), parallel form (b), and direct/parallel form (c).

The average cancellation of direct, parallel, and direct/parallel is, respectively, 10 dB, 28 dB, and 13 dB.

B. Changing Engine Speed

Accelerating engine speed causes the engine noise to change. Similar to the first case, but now each harmonic frequencies is swept, reaching the maximum frequencies at 12th second.

Figure 9 shows the spectrogram that representing the transition of signal measured at the error microphone after noise cancellation, compared to before the cancellation shown in Fig. 2.

C. Active Noise Equalizer

By adjusting $\beta$, the sound of engine noise can be tuned. In this case, the noise of accelerating engine speed drives the primary loudspeaker and the parameter of ANE is based on the parallel form ANC. The first sixth harmonics are maintained ($\beta = 1$), while the others are cancelled ($\beta = 0$).

Compared to Fig. 9(b) which all harmonics are cancelled, Fig. 10 shows that the spectrogram of the lower frequencies are maintained whereas the higher frequencies are cancelled.

VI. CONCLUSIONS

This paper implemented ANC system for muffler to cancel engine exhaust noise. The characteristics of engine exhaust noise for fixed and changing engine speed were analyzed. Both ANC and ANE system performance were done by real-time experiments using synthesized engine noise for fixed and changing engine speed. Experiment results showed that the electronic muffler can reduce the noise levels well.

REFERENCES

**Fig. 4.** Parallel form narrowband ANC system.

**Fig. 5.** Block diagram for multiple-frequencies active noise equalizer.

**Fig. 6.** Electronic muffler, (a) reference model (b) prototype for experiment

**Fig. 7.** Muffler apparatus.

**Fig. 8.** The performance of narrowband ANC system for fixed engine speed (a) direct form (b) parallel form (c) direct/parallel form.
Fig. 9. The performance of narrowband ANC system for changing engine speed (a) direct form (b) parallel form (c) direct/parallel form.

Fig. 10. The performance of ANE system.