

An Active Control System for Improving the Sound Quality of Vehicle Interior Noise

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ABSTRACT

An adaptive feed-forward active control system for improving the sound quality of vehicle engine noise is presented in this paper. Based on the narrow-band and periodic properties of engine noise, an artificial waveform, which was synthesized with sinusoidal components at the fundamental frequency of the engine noise and its harmonics, was adopted as the reference signal. Then these primary noise components were canceled via an adaptive notch filter bank, the coefficients of which were updated using the FXLMS algorithm. The core of the designed system is a new algorithm for improving the quality characteristics of the residual noise by adjusting the gain values of the noise component at each reference frequency. The feasibility and advantages of the designed system were validated through both simulation and practical vehicle tests.

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1. INTRODUCTION

Engine noise, particularly low frequency booming noise, is the main component of the interior noise of mid-sized vehicles [1]. This booming problem is exacerbated by the current trends toward lighter vehicle bodies and more powerful engines. In order to improve comfort levels with respect to interior noise, manufacturers have adopted a number of techniques to control engine noise. These techniques can be classified as either passive or active control methods. Passive control methods, such as sound absorption or sound insulation, have proved effective for controlling high frequency noise [2]; this approach, however, is not always sufficient to control low frequency noise. In addition, the exact mechanism by which the engine excites the vehicle body panels is rather complicated and varies from one car to another. It is extremely difficult to find a mechanical solution that will suit all vehicles. Therefore, in order to control varying low frequency engine noise, adaptive active noise control (ANC) has been implemented by many vehicle manufacturers.

ANC is implemented by producing an "anti-noise" wave through an appropriate array of secondary sources. This wave has identical or directly proportional amplitude to the wave of the original noise, but its polarity is reversed. This creates destructive interference that reduces the amplitude of the perceived noise. The secondary sources are interconnected through an electronic system using a signal processing algorithm specifically chosen for the particular cancellation scheme. Since the 1980s, along with the wide application of large scale integrated circuits and the rapid development of digital signal processing techniques, ANC implementations have improved rapidly. Notably, following the invention of high speed signal processors, adaptive filters were introduced into ANC systems; these

alter control system parameters by tracking real-time changes in environmental noise. With the aid of these adaptive techniques, ANC has been applied widely in practice.

Most applicable ANC systems use the sound pressure level (SPL) of the residual noise as the control objective; a decrease in SPL has been widely accepted as the index for evaluating the performance of the control system. The shortcoming of this index is that it does not take the properties of the human auditory system into account. Human auditory system is very complicated, which may perceive the sounds with same SPL in different ways. In order to evaluate human auditory perceptions of vehicle interior noise, many new indices that represent the subjective perceptions of passengers have been created by researchers and manufacturers for use in studies to improve the comfort levels of vehicle passengers. These new indices are collectively referred to as "sound quality." The concept of sound quality was first introduced by Blauert and Bodden in 1994 [3]. In their work, they emphasize that the general concept of "sound" indicates not only the physical phenomena of the propagation of a wave, but also includes the perceptive process of the human auditory system. They also note that the concept of "quality" denotes the subjective judgments made by humans in perceiving auditory stimuli.

Subjective evaluations, such as jury listening tests, are often applied to evaluate the quality of noises, because human auditory perceptions cannot be directly measured with current techniques. Although subjective evaluation is a straightforward approach for evaluating sound quality, it has several disadvantages, including the high cost of time and manpower, strict requirements for test environments and procedures, and low resolution capability. A fast, simple approach for evaluating sound quality is often required for real world applications,

so the development of objective evaluation methods is encouraged. Many studies have proven that subjective sound quality is closely related to certain objective metrics which can be directly measured or calculated [4]. These metrics, which are derived from a combination of psychological reaction mechanisms and human acoustical perceptions, are called sound quality metrics (SQMs). At this time, there are a variety of SQMs, some of which have been well defined, but very few of which have been standardized. Vehicle manufacturers who conduct sound quality evaluations often develop their own metrics as well as using existing ones. Many studies [5, 6, 7] indicate that the sound quality of engine noise is directly related to the SQMs of loudness and sharpness. In the present study, a new index, which we called "sound quality rate" (SQR) and is a function of loudness and sharpness, is proposed to evaluate the sound quality of engine noise. Based on this index, an active sound quality control (ASQC) system was designed.

The ASQC system described here belongs to the category of narrow-band feed-forward control. Based on the periodic properties of engine noise, a waveform that contains multiple orders of harmonics of the fundamental frequency of the engine noise is synthesized to serve as the reference signal. Then each harmonic can be cancelled by a specified adaptive notch filter, the coefficients of which are updated via a filtered-x least mean square (FXLMS) algorithm. The goal of the designed system was not to decrease the SPL of the residual noise, but to adjust its quality characteristics. Active noise equalization (ANE), an active control system that can adjust residual noise by introducing a gain value into the control, was proposed by Kuo et al [8]. In this work, this algorithm was extended to apply to multiple frequencies, and an algorithm for determining the optimal gain of each harmonic frequency, with the goal of minimizing the SQR of the residual noise, was proposed. The feasibility of this ASQC system was proved by a MATLAB simulation, the results of which showed that the SQR of the residual noise indeed decreased. The actual ASQC system was realized in the form of a Visual C++ program, using the Intel NSP library for performing signal processing operations. The practical effects of the designed ASQC system were verified through test vehicle experiments.

2. Basic Theory

2.1 Sound Quality

a. Loudness: Loudness is an auditory perception that reflects the strength of a sound and that is dependent on magnitude and frequency. Unlike SPL, the measurement of loudness takes into account the masking effect, which is in agreement with the characteristics of human auditory perception. Loudness can be calculated using Zwicker's model [9] (DIN 45631, ISO 532B), in which the SPL spectrum is divided into several bands of one-third of an octave each. The total level of each band is corrected by comparing it to equal-loudness contours and then converting it into specific loudness on a scale of critical-band rate. The total loudness is calculated by integrating specific loudness as:

$$N = \int_0^{24\text{Bark}} N' dz \quad (1)$$

where N is the total loudness in sones, N' is the specific loudness in sone/Bark and z is the critical-band rate in Bark. The scale for linear frequency can be converted into the critical-band rate by using the following equation:

$$z(f) = 13.0 \arctan(0.76f) + 3.5 \arctan(f/7.5)^2 \quad (2)$$

b. Sharpness: Sharpness is a measure of the high frequency content of a sound. The greater the proportion of high frequencies, the sharper the sound. Sharpness is a metric that has not yet been standardized, and there are several calculation models in use. Among them, Zwicker and Fastl's model [4] is the most popular. This model calculates the sharpness as the weighted first moment of the specific loudness N' using the following equation:

$$S = c \frac{\int_0^{24\text{Bark}} N' g(z) z dz}{\int_0^{24\text{Bark}} N' dz} \quad (3)$$

where c is a proportionality constant ($c = 0.11$), and $g(z)$ is a weighting function defined as:

$$g(z) = \begin{cases} 1 & 0 \leq z \leq 16 \\ 0.066e^{0.171z} & 16 < z \leq 24 \end{cases} \quad (4)$$

c. SQR: In this work, a subjective jury listening test was performed in order to evaluate the comfort level of passengers with respect to vehicle engine noise. Thirty sample noises were recorded in different vehicles under different running conditions, so they can be regarded as the most representative vehicle engine noises. After being provided the necessary listening training, 20 listeners were asked to listen to the samples in an anechoic chamber. In the test, the comfort level of the listeners was divided into 20 ratings, and each listener was asked to assign a rating to each sample based on his subjective perceptions of the sample. After necessary data validation, the average reported rating of each sample was determined as the subjectively evaluated SQR of the sample. Along with the jury test, the objective SQMs of loudness and sharpness of the test samples were also measured. Results of a correlation analysis on the subjectively evaluated SQR and these two SQMs indicated that the correlations between both loudness and sharpness and the subjectively evaluated SQR are greater than 0.8, indicating that these two SQMs are appropriate metrics by which to evaluate the sound quality of engine noise. The model for predicting the SQR of a sample by its loudness and sharpness was built via a multiple linear regression (MLR) analysis, and the linear equation of this model is shown in Eq. (5).

$$\text{SQR} = 0.217N + 7.764S - 1.374 \quad (5)$$

2.2 Adaptive Active Noise Control

At the present time, there are a variety of available ANC systems. The narrow-band feed-forward ANC system has proven to be the most effective for controlling vehicle engine noise [10]. Figure 1 illustrates an example of a narrow-band feed-forward ANC system. In this diagram, a synchronous signal that relates to the primary noise is sensed before it passes to the control area by a non-acoustic sensor close to the sound source. This non-acoustic sensor is completely unaffected by the secondary noise, and so provides steady and effective control. With the aid of the sync signal, a signal generator generates a reference signal $x(n)$ representing the main characteristics of the primary noise. The ANC controller applies the reference signal $x(n)$ to generate a signal $y(n)$ that drives the cancelling loudspeaker, producing an anti-noise that is 180° out of phase with the disturbance, thereby canceling the unwanted noise. The error microphone is used to measure the residual error $e(n)$, which is minimized by modifying the coefficients of an adaptive filter in the controller.

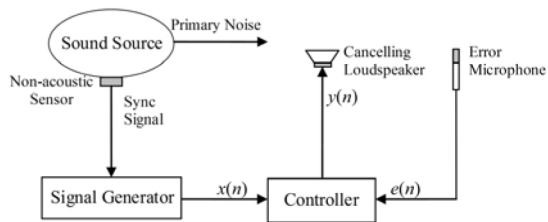


Figure 1. Single channel narrow-band feed-forward ANC system

A large component of engine noise is produced by the combustion of fuel in the engine cylinders, which produces pressure pulses at a rate proportional to the engine speed. Existing research [11] indicates that engine noise can be regarded as the combination of a series of tonal components with the same fundamental frequency f_0 , which can be calculated as

$$f_0 = \frac{nS}{60\tau} \quad (6)$$

where n is the number of cylinders, S is the engine speed (rpm), and τ is the stroke coefficient (for a four stroke engine, $\tau = 2$).

To validate this theory, an experiment was performed in a four-cylinder vehicle to determine the relationship between engine noise and engine speed. In the experiment, the noises generated by the engine at speeds of 1200, 3000, and 4000 rpm were measured inside the vehicle. The calculated fundamental frequencies and their harmonics are shown in Table 1, together with the frequencies at which the peak values occurred in the measured results. From the table, it can be concluded that the calculated fundamental and harmonic frequencies of the engine noise match well with the actual frequencies. Thus if the fundamental frequency is known, the waveform of the engine noise can be synthesized with sine waves as

$$x(n) = \sum_{m=1}^M A_m \sin(\omega_m n) = \sum_{m=1}^M A_m \sin(m2\pi f_0 n) \quad (7)$$

where A_m and ω_m are the magnitude and frequency of the m^{th} order sine wave, and M is the highest order of harmonics to be synthesized. In this work, based on characteristics of the vehicle engine noise, M was set to 5. Based on engine rotational speed as provided by a tachometer attached to the engine, a synchronous waveform was synthesized via a lookup table technique [10] to be applied as the reference signal.

Table 1. Fundamental frequency and harmonics of the engine noise

Engine Speed		f_0 (Hz)	f_2 (Hz)	f_3 (Hz)	f_4 (Hz)
1200 (RPM)	Calculated:	40.00	80.00	120.00	160.00
	Measured:	40.25	80.75	121.25	162.50
3000 (RPM)	Calculated:	100.00	200.00	300.00	400.00
	Measured:	100.25	200.00	308.50	412.25
4000 (RPM)	Calculated:	133.33	266.67	400.00	533.33
	Measured:	135.25	265.50	415.25	540.75

With the synthesized reference signal, an adaptive notch filter can be employed in the FXLMS control system to remove the primary spectral components within a narrow band centered about the reference frequency. A single-frequency FXLMS adaptive notch filter with two adaptive weights is illustrated in Figure 2, wherein $S(z)$ is the secondary-path transfer function from $y(n)$ to $e(n)$, $P(z)$ is the primary transfer function from $x(n)$ to $e(n)$, and $\hat{S}(z)$ is the estimation of $S(z)$. In this work, $\hat{S}(z)$ is estimated via an off-line secondary-path modeling technique [12]. The reference signal is a pure cosine wave

$$x(n) = x_0(n) = A \cos(\omega_0 n) \quad (8)$$

A 90° phase shifter is used to produce the quadrature reference signal

$$x_1(n) = A \sin(\omega_0 n) \quad (9)$$

The weights of the notch filter are updated by the FXLMS algorithm as follows:

$$y(n) = w_0(n)x_0(n) + w_1(n)x_1(n) \quad (10)$$

$$e(n) = d(n) - y'(n) \quad (11)$$

$$w_l(n+1) = w_l(n) + \mu x'_l(n)e(n), \quad l = 0,1 \quad (12)$$

where μ is the convergence factor.