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Research Article

Integration of Bass Enhancement and Active Noise Control System in Automobile Cabin

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With the advancement of digital signal processing technologies, consumers are more concerned with the quality of multimedia entertainment in automobiles. In order to meet this demand, an audio enhancement system is needed to improve bass reproduction and cancel engine noise in the cabins. This paper presents an integrated active noise control system that is based on frequency-sampling filters to track and extract the bass information from the audio signal, and a multifrequency active noise equalizer to tune the low-frequency engine harmonics to enhance the bass reproduction. In the noise cancellation mode, a maximum of 3 dB bass enhancement can be achieved with significant noise suppression, while higher bass enhancement can be achieved in the bass enhance mode. The results show that the proposed system is effective for solving both the bass audio reproduction and the noise control problems in automobile cabins.

1. INTRODUCTION

Noise control and the high-quality bass reproduction in automobile cabins are two interrelated problems. The later can be difficult due to the high-level noise present and the size of the loudspeakers that can be installed inside the cars. Traditional passive noise control techniques are only efficient at high frequencies. For the low-frequency engine noises, passive techniques become costly and bulky, which are not suitable for the use in automobile cabins. Due to its effectiveness in reducing low-frequency noise, the active noise control (ANC) [1] technique has received much attention since 1980s [2, 3].

On the other hand, with the advancement of multimedia digital signal processing (DSP) technologies, high-quality audio reproduction is becoming possible for the automobiles. However, there are many challenges in reproducing high-quality bass in cars due to the limited space and acoustic properties, and the low-frequency noise present in the cabins.

The ANC techniques generally produce good performance in canceling the narrowband engine noise. However, it does not offer complete control over the engine noise in cabins. In some practical applications, it prefers to enhance some preselected noise components to extract important sound information. For example, the driver may want to know how the engine is working when driving. Due to its flexibility of amplifying or attenuating noises with predetermined levels at certain frequencies, active noise equalizer (ANE) [4] systems and other similar algorithms [5–7] have potential applications.

High-quality audio reproduction in cabins can be difficult due to the engine noise and low-frequency performance of the loudspeakers. With the flexibility of ANE system, we propose a novel method to solve this problem. Instead of trying to cancel the engine noise entirely, the proposed integrated system equalizes the engine-noise harmonics based on the bass information to enhance the low- frequency part of audio signal. The main challenges are to track the frequencies of engine harmonics and to tune these harmonics to match the bass components of audio signal.In order to integrate active noise control with bass enhancement, the proposed system uses frequency-sampling filter (FSF) [8] and multifrequency ANE [4] to tune the engine harmonics, and convert the annoying low-frequency noise into desired audio bass components.

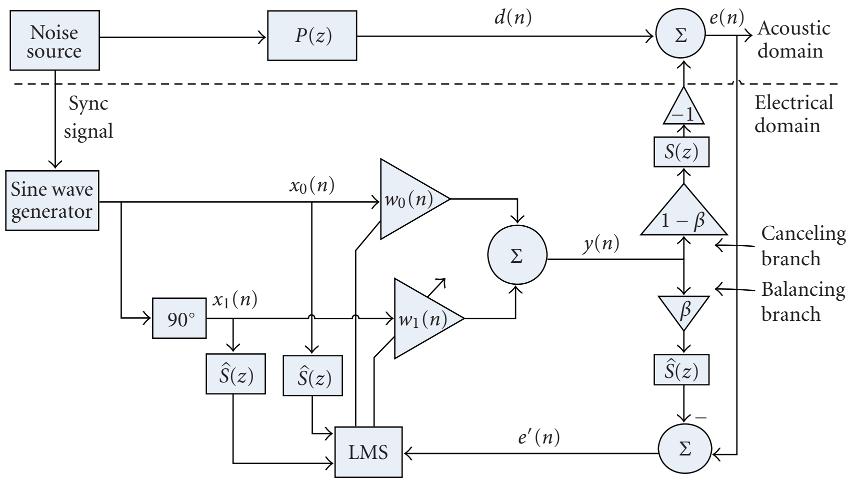

Figure 1: Block diagram of single-frequency ANE system.

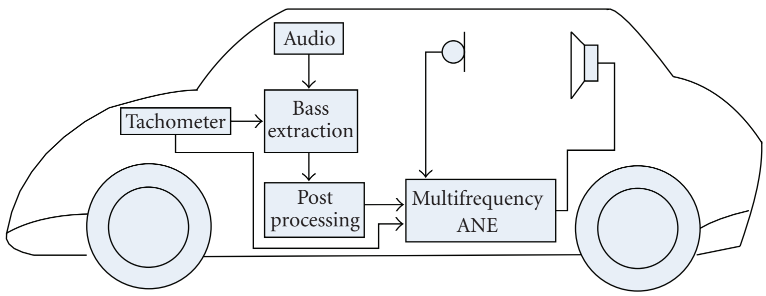

Figure 2: System block diagram inside the automobile cabin.

The remainder of this paper is structured as follows. Section 2 presents the narrowband ANE system, followed by a description of the proposed system in Section 3. Simulation results under different driving conditions are given in Section 4, and Section 5 concludes this paper.

2. NARROWBAND ACTIVE NOISE EQUALIZER

The single-frequency narrowband ANE [4] system is based on an adaptive notch filter using the filtered-X least mean square (FXLMS) [1] algorithm. As shown in Figure 1, the secondary output is split into two branches: the canceling branch and the balancing branch. A pseudoerror $e'(n)$ is used to trick the adaptive filter to converge to a desirable state determined by the user. The pseudoerror can be expressed as

$$e'(n) = d(n) - y(n)^{*}s(n). \tag{1}$$

After convergence, the pseudoerror approaches zero. However, the actual residual noise $e(n)$ converges to

$$e(n) = d(n) - (1-\beta)y(n)^{*}s(n) \approx \beta d(n), \tag{2}$$

where β is known as the gain factor determined by the user.

Depending on the gain factor β, ANE can be classified into four operation modes [4]:

(i) cancellation mode ($\beta = 0$): ANE functions as the conventional narrowband ANC;

(ii) attenuation mode ($0 < \beta < 1$): the amount of attenuation is determined by β. Therefore, it is possible to retain some portion of the noise at the selected frequency;

(iii) neutral mode ($\beta = 1$): the noise passes through the ANE system without attenuation;

(iv) enhancement mode ($\beta > 1$): the ANE functions as an amplifier that enhances the noise component with amount determined by β.

3. PROPOSED SYSTEM IN AUTOMOBILE CABINS

A proposed system in car cabins that integrates bass enhancement and active noise equalizer is shown in Figure 2. This system can be divided into three subsystems: (i) the "bass extraction" block extracts bass components from the car audio system based on the engine speed; (ii) the "postprocessing" block processes; these bass components to match with frequencies of engine harmonics; and (iii) the "multifrequency ANE" block implements a multifrequency ANE that enhances desired low-frequency audio components using equalized engine harmonics. A detailed overview of these subsystems is described as follows.

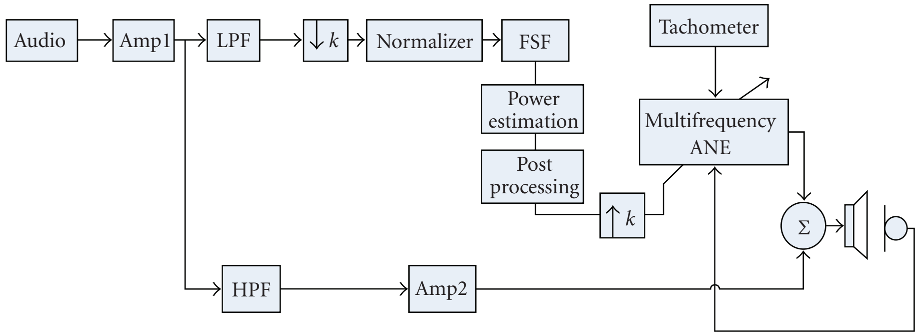

FIGURE 3: Audio signal extraction block diagram.

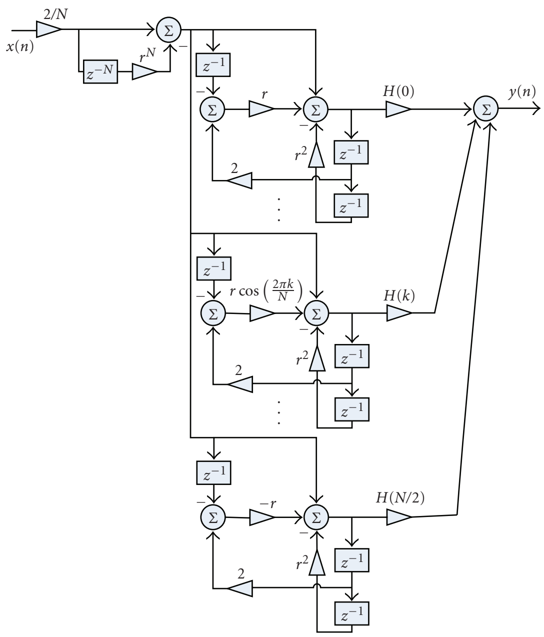

FIGURE 4: Frequency-sampling filter block diagram.

3.1. Bass extraction

The audio signal components that will be enhanced are those close to the engine-noise components, which are related to the engine revolutions per minute (RPM). Because the engine RPM is time varying, the engine-noise components change accordingly, thus the filters must self-configure according to the engine RPM to extract the desired audio signal components. In other words, the filter's center frequency should be tuned by the engine RPM.

As shown in Figure 3, the audio signal is passed through a low pass filter with a cutoff frequency at 500 Hz, and the audio signal is decimated to a lower sampling frequency of 1.5 kHz. Therefore, a lower computational load is achieved for processing bass information of the audio signal.

To utilize engine noise for enhancing bass reproduction, extraction of the audio signal at frequencies of engine harmonics is needed. This requires a bank of passband filters align with predominant engine harmonics. Fast online reconfiguration and computational efficiency are important considerations for designing the filter bank. The FSF is chosen to meet these requirements. It is based on sampling a desired amplitude spectrum to obtain the corresponding filter coefficients. The number of FSF channels equals to the number of predominant engine-noise harmonics, where each channel corresponds to one engine harmonic. As shown in Figure 4, the unique characteristic of the FSF structure allows recursive implementation of finite-impulse response filters, leading to both computational efficiency and fast online reconfiguration. The transfer function of the FSF is expressed as

$$H(z) = \frac{2}{N}\left(1 - r^L z^{-N}\right)\sum_{k \le N/2}(-1)^k H(k)\frac{1 - r\cos(2\pi k/N)z^{-1}}{1 - 2r\cos(2\pi k/N)z^{-1} + r^2 z^{-2}}, \tag{3}$$

where N is the filter length, $H(k)$ is frequency sample value at channel k, and r is a radius of pole that is slightly less than unity. Equation (3) shows that the FSF has N parallel bandpass filters with center frequencies at $2\pi k/N$, where $k = 0, 1, \ldots, N-1$. Therefore, the parameter N controls center frequencies of all bandpass filters. The following sections further describe how to design an FSF for a particular engine.

3.1.1. Engine RPM and the fundamental frequency of engine noise

This section investigates the fundamental and firing frequencies of a 4-stroke engine. A sampling frequency of 1.5 kHz is selected for the FSF processing block. This sampling frequency restricts the range of engine noise to 600 Hz. For a 4-stroke engine, the fundamental frequency is the product of the firing frequency and number of the cylinders, where the firing frequency is

$$\text{firing frequency} = \frac{1}{2} \times \frac{\text{RPM}}{60}\ \text{Hz}. \tag{4}$$

The fundamental frequency of engine noise is the fourth harmonic of the firing frequency. Depending on the engine noise profile, the harmonics selected can be different. When higher frequency harmonics are selected, this range will be

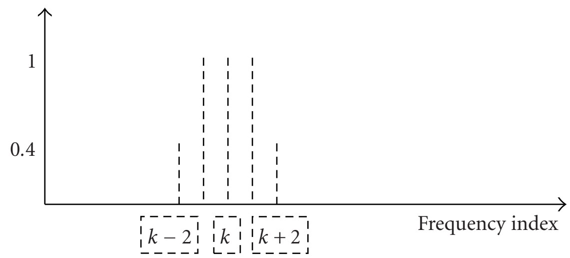

Figure 5: Diagram of FSF filter setting for fundamental engine noise frequency.

lowered accordingly. For most cars and with the objective of bass enhancement, the sampling frequency of 1.5 kHz is reasonable.

3.1.2. Parametric factor

There are two methods in determining the main parameters to control the filtering and center frequencies of FSF. One is to set the filter length N as a constant value and change each of the frequency sample values $H(k)$. However, this approach requires changing multiple sample values during online filter reconfiguration. On the other hand, if we first set the relative frequency samples at certain values, it is possible to achieve the reconfiguration by changing only the FSF filter length N. For example, when we set the filter $H(k)$ at $k = 10$ to coincide with the fundamental frequency of noise, the filter length can be derived as

$$\frac{\mathrm{Fs}}{N} \times 10 = \frac{1}{2} \times \frac{\mathrm{RPM}}{60} \times 4 \Longrightarrow N = \left[\frac{\mathrm{Fs} \times 10 \times 30}{\mathrm{RPM}}\right]. \quad (5)$$

When the RPM is 2500, the corresponding filter length is 180. It is also important to point out that the FSF does not incur a higher computational load when the filter length increases. This is because most frequency samples $H(k)$ are zero and only few frequency samples defined in the passband require computation.

3.1.3. Transition band sample value

Rabiner et al. proposed some typical values for the coefficients in the transition band [9]. In the case of designing the FSF for handling typical RPM from 1000 to 2500, the filter length ranges from 180 to 450. If three samples are used to define the frequency samples in the passband, the optimum value for transition band is found to be 0.4 [10] The illustration is shown in Figure 5.

3.1.4. Selecting suitable filter length/frequency resolution

As the sampling frequency Fs is 1500 Hz, the frequency resolution for FSF is Fs/N. According to the relationship:

$$\frac{\mathrm{Fs}}{N} \times k = \frac{1}{2} \times \frac{\mathrm{RPM}}{60} \times 4, \quad (6)$$

where k is the sample index that is selected to align at the engine noise frequency. As a result, index k controls the resolution of the filter. Therefore, the optimal resolution is determined by the frequency range of the engine noise. Offline calibration is required for different engines to select the proper value of k, which is set to the center frequency of fundamental engine noise, and correspondingly determine the frequency resolution.

3.2. Postprocessing

The signal power estimation is performed before sending to postprocessing block. The process can be expressed as

$$P_x(n) = \lambda P_x(n-1) + (1-\lambda)x^2(n), \quad (7)$$

where $P_x(n)$ is the signal power, $x(n)$ is the current sample, and λ is known as the smoothing parameter or forgetting factor, typically set between 0.9 to 0.999. There are many options for the postprocessing block. Users can perform different kinds of equalization. This paper proposes two schemes. The bass enhancement scheme is designed for higher amplification of equalized engine noise, and the noise cancellation scheme is designed for more engine noise reduction.

3.2.1. Bass enhancement scheme

The bass enhancement scheme emphasizes on the enhancement of bass components in the audio signal. Using the power estimation results obtained from previous block, the gain factors β_i, $i = 1, 2, \ldots, Ns$ in the ANE systems can be the calculated as

$$\beta_i = \sqrt{P_i} \times \alpha, \quad i = 1, 2, \ldots, Ns, \quad (8)$$

where P_i is the power of the FSF's output that corresponding to the engine harmonic frequency, and α is a constant that controls the volume of the sound in order to mix the tuned engine noise with the original audio output. Users can tune α to different levels of bass enhancement. The variable Ns is the number of predominant engine noise harmonics which is dependent on the particular engine type. If the in cabin loudspeakers are incapable in reproducing the signal at engine noise fundamental frequency, the perception of bass can still be enhanced by other harmonics due to the famous "missing fundamental" phenomenon.

In order to set the value of α that determines β_i, it is important to derive the relationship between the sound pressure level of the audio signal and engine noise. In typical audio system, the sound pressure level ranges from 50 dB to 80 dB. On the other hand, the engine noise level in a cabin ranges from 45 dB to 75 dB [9]. For a 16-bit audio signal, which is normalized to unit, the sound pressure level is stated as

$$\mathrm{SPL}_A = 96\,\mathrm{dB} + 10\log_{10}x^2(n)\,\mathrm{dB}. \quad (9)$$

This equation sets the maximum sound pressure level SPL_A to 96 dB when the amplitude of $x(n)$ equals to 1.

To calibrate the value of factor α, it is assumed that if the signal SPL_A is 60 dB, the engine noise should be neither

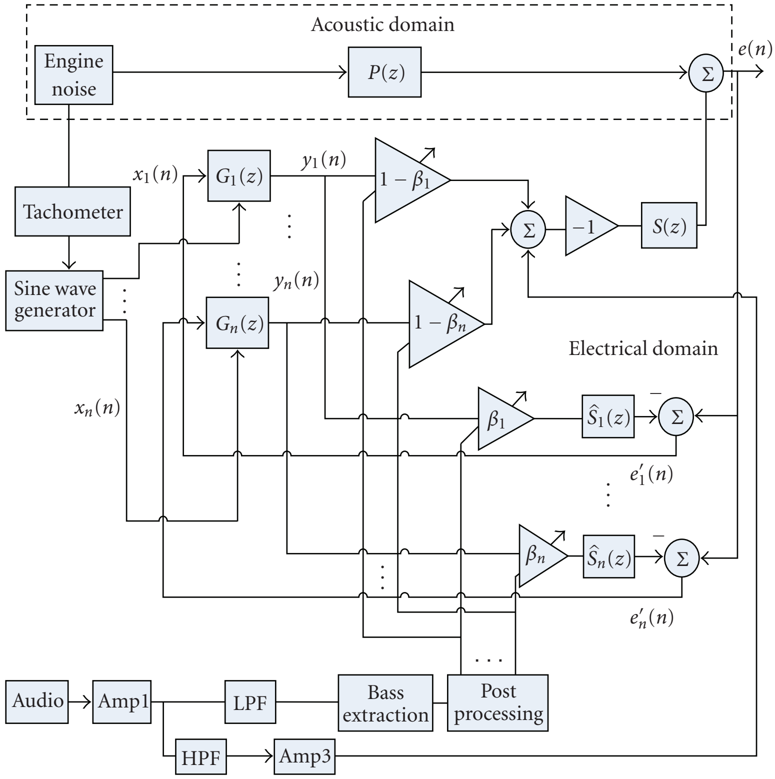

Figure 6: System block diagram of the multifrequency ANE.

amplified nor attenuated. According to (9) and setting SPL_A to 60 dB, the amplitude of the signal is computed as

$$A_A = 10^{(\mathrm{SPL}_A - 96)/20} \approx 0.016. \tag{10}$$

The power of the signal is approximately 1.28×10^{-4}. Setting β to 1 results in $\alpha \approx 88$.

3.2.2. Noise cancellation scheme

It can be seen from the previous scheme that by tuning the factor α, higher enhancement at the low frequency can be achieved. However, at the same time, the timbre of the original signal will also change. To fulfill the needs of enhancing bass reproduction while maintaining a balanced timbre with significant noise cancellation, we propose another scheme known as the noise cancellation scheme.

In this scheme, when engine noise is louder than the audio signal, a proper equalized engine noise is used to enhance the audio signal. In order to maintain a better timber, this scheme does not allow any amplification of the engine noise, or the gain factors for engine noise harmonics should be always smaller than one. The rationale behind this scheme is to make the amplitude of the engine harmonics equals to the corresponding amplitude of the audio signal at that frequency. In this way, when there is audio signal present at the engine noise harmonics, the ANE system amplifies the amplitude of the engine noise to produce a 3 dB enhancement of audio signal.

When the engine noise is lower than the audio signal, we keep or cancel the engine noise harmonics depending on whether the audio signal is present or not. As a result, the gain factor for the ANE system is either one or zero. The maximum gain of 3 dB is achieved when the engine noise level equals the audio signal level. Therefore, to achieve the desired gain adjustment in Section 2, a new gain scheme is proposed as follows:

$$\beta = \begin{cases} e^{(\mathrm{SPL}_A - \mathrm{SPL}_E)/\gamma}, & \mathrm{SPL}_O < \mathrm{SPL}_A < \mathrm{SPL}_E, \\ 1, & \mathrm{SPL}_O < \mathrm{SPL}_E < \mathrm{SPL}_A, \\ 0, & \mathrm{SPL}_A < \mathrm{SPL}_O, \end{cases} \tag{11}$$

where SPL_A is the sound pressure level of audio at the corresponding engine noise harmonic frequency, SPL_E is the sound pressure level of the engine noise harmonic, SPL_O is used as a threshold and is set to 45 dB, and γ is a constant governing the equalization between the gain factor and difference between the sound pressure level of audio signal and engine noise.

To equalize the engine noise when $\mathrm{SPL}_O < \mathrm{SPL}_A < \mathrm{SPL}_E$, the gain factor β is chosen such that

$$\beta A_E = A_A, \tag{12}$$

where A_E is the amplitude of the engine noise and A_A is the amplitude of the audio signal. Substituting (9) and (11) into

(12), we have

$$A_E e^{(\mathrm{SPL}_A - \mathrm{SPL}_E)/\gamma} = A_A,$$
$$e^{(\mathrm{SPL}_A - \mathrm{SPL}_E)/\gamma} = \frac{10^{(\mathrm{SPL}_A - 96)/20}}{10^{(\mathrm{SPL}_E - 96)/20}}. \quad (13)$$

Taking logarithm of both sides, we obtain

$$\left(\frac{\mathrm{SPL}_A - \mathrm{SPL}_E}{\gamma}\right)\log_{10}e = \frac{\mathrm{SPL}_A - 96}{20} - \frac{\mathrm{SPL}_E - 96}{20}. \quad (14)$$

This results in

$$\frac{\log_{10}e}{\gamma} = \frac{1}{20}, \quad (15)$$

and $\gamma \approx 8.6859$.

According to this gain factor scheme under a loud engine noise condition, it is expected to achieve both reduction of engine noise and a 3 dB bass enhancement at certain frequencies.

3.3. *Multifrequency ANE system*

To perform the active control of the engine noise, we designed a multifrequency ANE system consisting of several independent single-frequency ANE systems connected in parallel. Each single-frequency ANE is tuned to the corresponding harmonic frequency of the engine noise. The overall block diagram of the multichannel ANE is shown in Figure 6. The number of the single-frequency ANE system is determined by the number of the selected predominant engine noise harmonics. Each ANE block has its own gain factor tuned to the power of the related audio component. When the audio signal is changing with time, the equalization of the low-frequency signal responds accordingly.

4. SIMULATION RESULTS

Performance of the proposed system is evaluated by both a synthesized engine noise and a recorded in cabin engine noise (Toyota Crown at passenger seat with the engine running at around 2600 RPM). The reference signal is generated using cosine wave with the center frequency at the corresponding engine noise harmonic. Kim and Park showed in [11] that the self-generated reference could achieve good performance in ANC applications. Figures 7 and 8 show the spectrogram and power distribution of the engine noise, respectively. For this recorded engine noise, we select two predominant frequency components and an FSF is used to extract the bass audio information.

The audio signal used for the simulation is "Hotel California" by The Eagles (live version). The sound clip was taken from the start of the track, which consists of a bass drum with some audience noise. This track makes it easier to focus on the bass. The sound clip and simulation results wave files are available at [12].

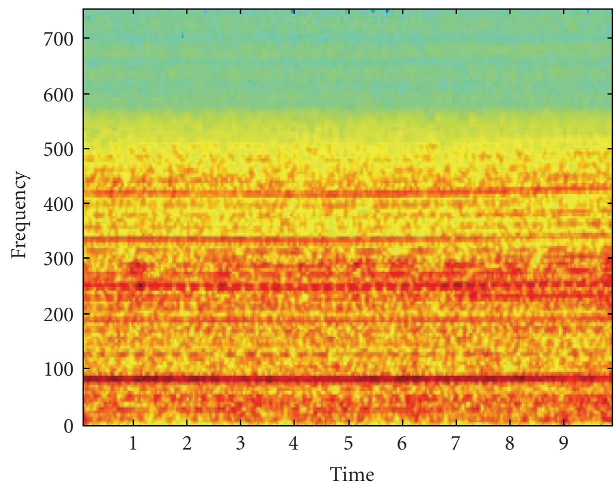

Figure 7: Spectrogram of the recorded engine noise.

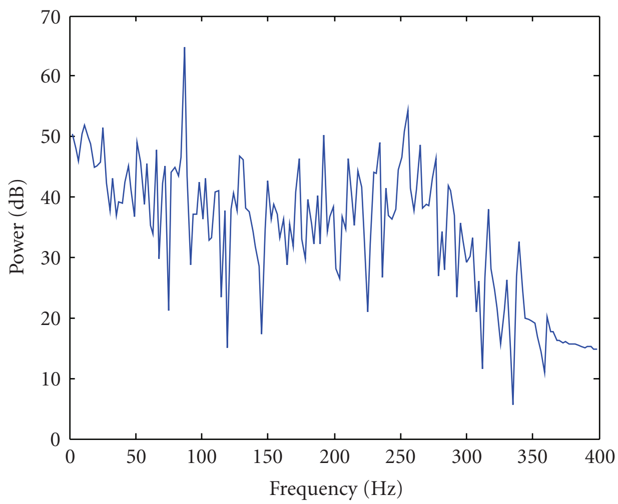

Figure 8: Power distribution of the recorded engine noise.

4.1. *Bass enhancement scheme*

The results shown in Figures 9 and 10 are the spectrograms that show bass components of audio signal before and after the process, respectively. The predominant engine noise harmonics are attenuated (marked as circles in diagrams) when the audio is absent, and tuned according to the gain factor shown in Figure 11, when the audio is present.

To display the tuned engine noise more clearly, the spectrogram of the tuned engine noise is shown in Figure 12. It is observed that the tuned engine noise has a similar spectrogram distribution as the audio signal.

The proposed system is also evaluated using synthesized engine noise to test the effectiveness at defined harmonics. In the following simulation, the synthesized engine is running at 3000 RPM, with its predominant harmonic frequencies at 100, 200, 300, and 400 Hz. As seen from Figure 13, the engine noise components at 100, 300, and 400 Hz are attenuated by 5, 8, and 15 dB. However, a 3 dB enhancement is achieved at 200 Hz. The equalized engine noise is equalized to enhance

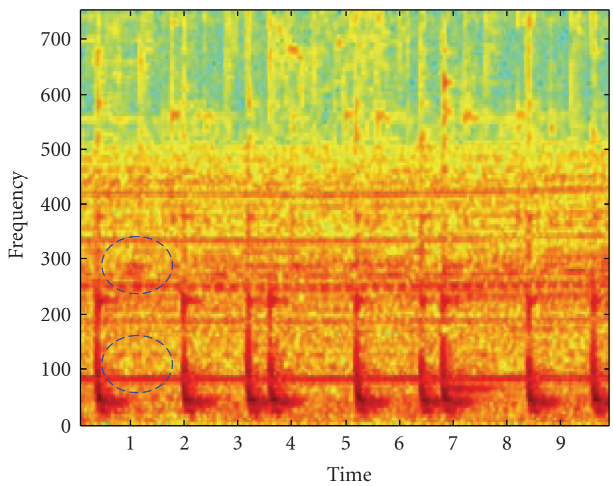

FIGURE 9: Spectrogram of the sound in cabin when system off.

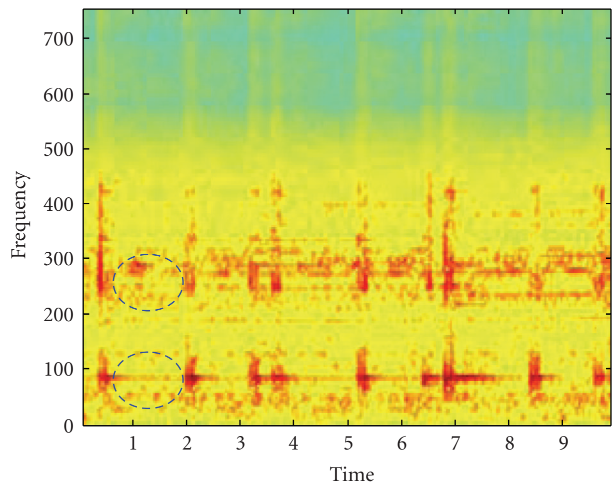

FIGURE 12: Spectrogram of the tuned noise.

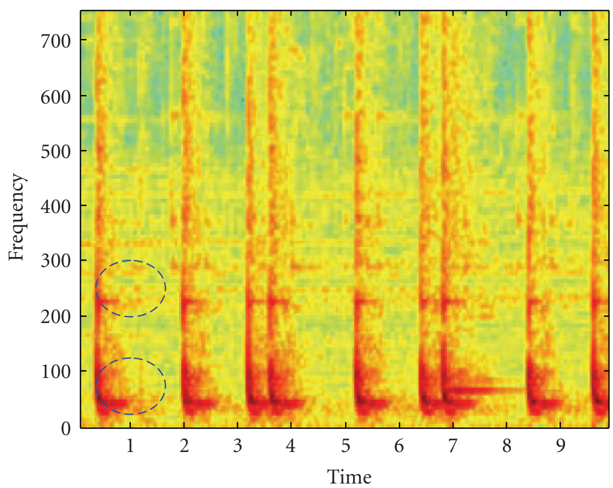

FIGURE 10: Spectrogram of the sound in cabin when system on.

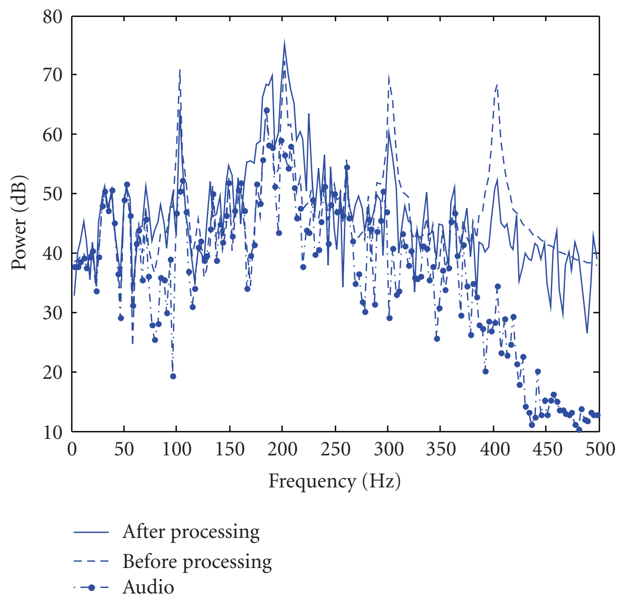

FIGURE 13: Bass enhancement scheme with synthesized engine noise.

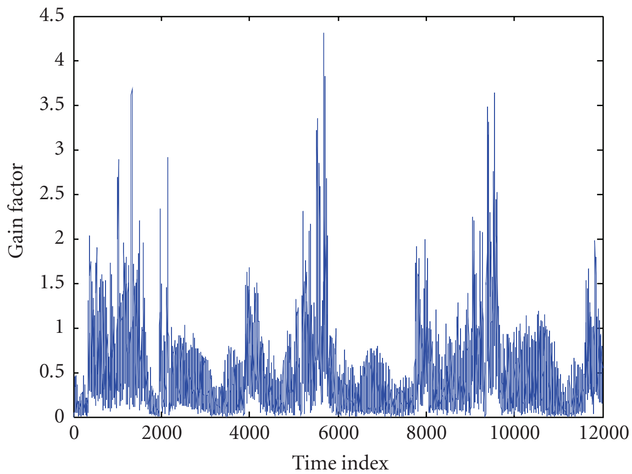

FIGURE 11: Gain factor for fundamental frequency.

the bass component of the audio signal. The gain factor value for the 200 Hz harmonic over the duration of simulation is shown in Figure 14.

4.2. Noise cancellation scheme

In this simulation, we investigate the performance of the proposed system under noise cancellation scheme. The system is tested with the recorded engine noise (running at 2600 RPM) and with SPL of 75 dB. The spectrogram of this engine noise is similar with those under bass enhancement mode.

The tested audio file is extracted from a short speech clip. We simulate the case when the driver is listening to news or

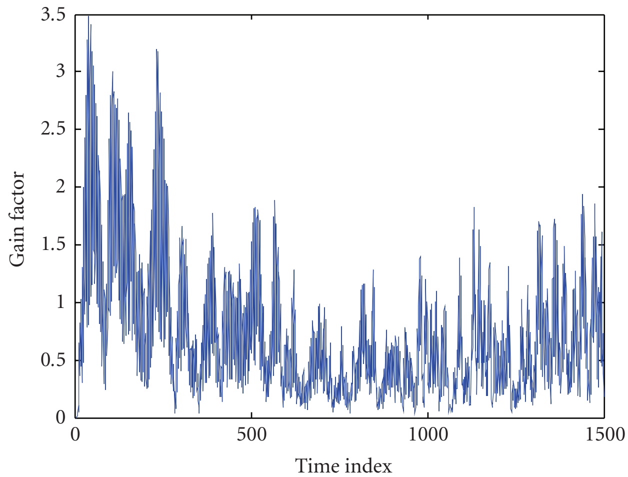

Figure 14: Gain factor (at 200 Hz) in bass enhancement scheme.

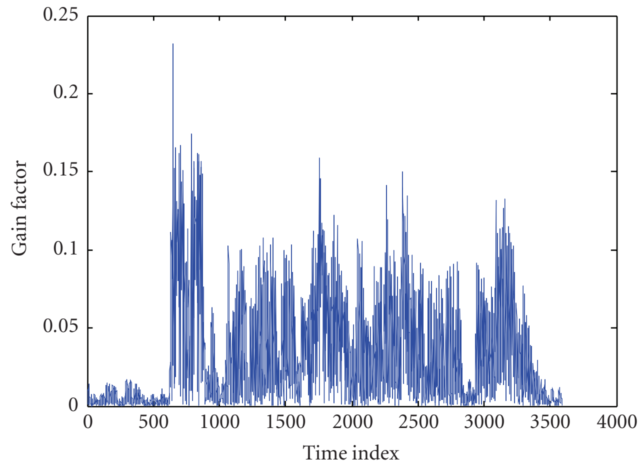

Figure 16: Gain factor using noise cancellation scheme.

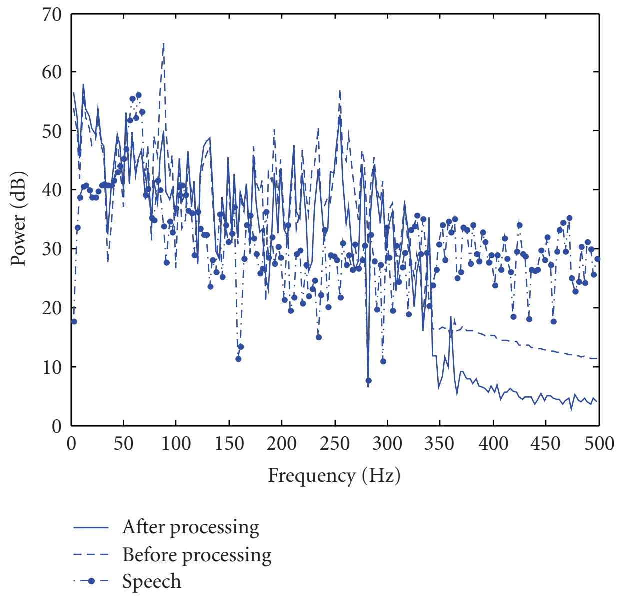

Figure 15: Engine noise before and after processing.

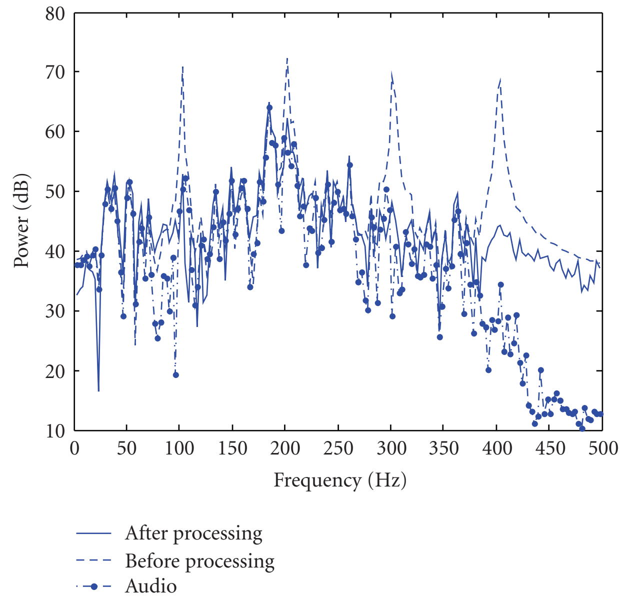

Figure 17: Noise cancellation scheme with synthesized engine noise.

making a phone call. The system adapts to cancel the engine noise to achieve a better SNR for speech perception in the car cabin. Engine noise before and after processing is shown in Figure 15. It can be clearly observed that the most prominent engine noise harmonics are reduced by 6 dB. Gain factor for the fundamental frequency over the period of simulation is shown in Figure 16.

Similar to the bass enhancement scheme, we evaluate the system using audio signal and the synthesized engine noise. As seen from Figure 17, the engine noise components are significantly reduced, especially at 400 Hz since there is very little audio component. The gain factor value for 200 Hz harmonic over the duration of simulation is shown in Figure 18. Compared with the result obtained in bass enhancement scheme, it clearly shows that the gain factor value is confined in the range of 0 to 1, and engine noise is never been amplified.

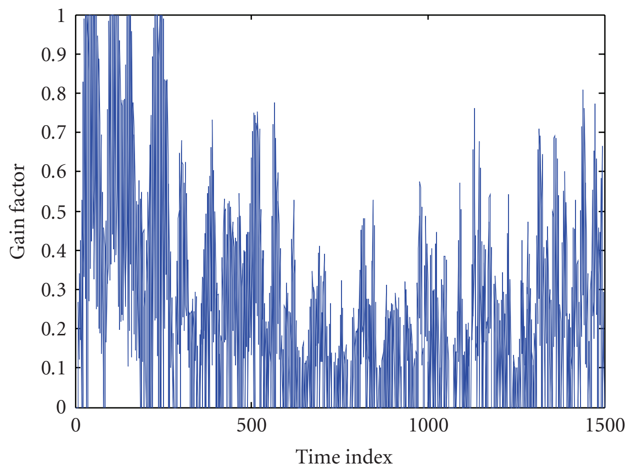

Figure 18: Gain factor (at 200 Hz) in noise cancellation scheme.

5. CONCLUSION

Instead of canceling the engine noise entirely, this paper presented a system that utilizes the engine noise to enhance the bass reproduction of audio signal in automobile cabins. The proposed system integrated bass extraction, audio signal processing, and active noise equalization to enhance desired bass signal and reduce noise. Several engine noises and audio signals are used to evaluate the performance of integrated audio and active noise equalization system. Simulation results showed that the proposed system can achieve audio bass reproduction and noise reduction inside the car cabins.

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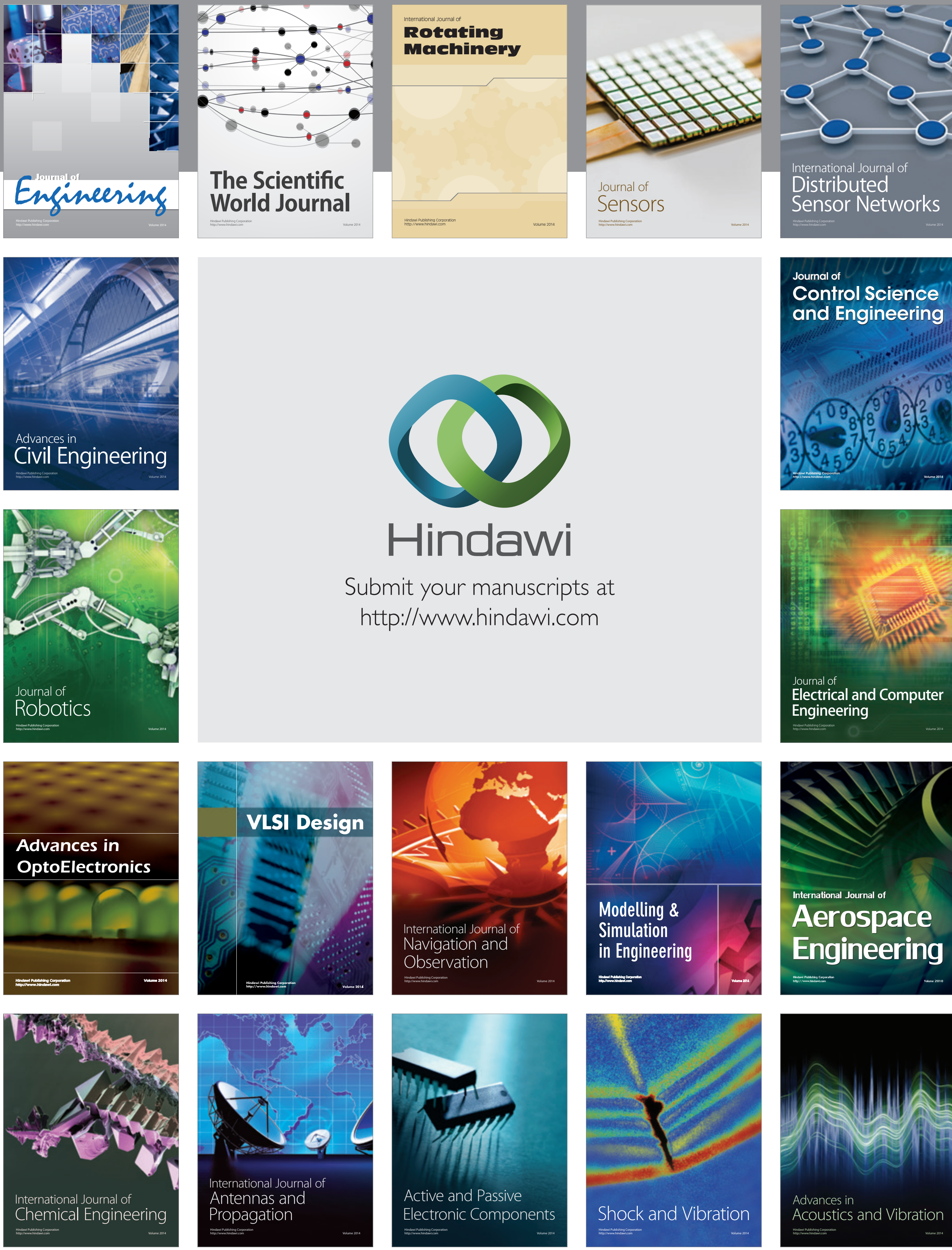
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