

Development of Feedback-Based Active Road Noise Control Technology for Noise in Multiple Narrow-Frequency Bands and Integration with Booming Noise Active Noise Control System

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ABSTRACT

When a vehicle is in motion, noise is generated in the cabin that is composed of noise in multiple narrow-frequency bands and caused by input from the road surface. This type of noise is termed low-frequency-band road noise, and its reduction is sought in order to increase occupant comfort. The research discussed in this paper used feedback control technology as the basis for the development of an active noise control technology able to simultaneously reduce noise in multiple narrow-frequency bands. Methods of connecting multiple single-frequency adaptive notch filters, a type of adaptive filter, were investigated. Based on the results, a method of connecting multiple filters that would mitigate mutual interference caused by different controller transmission characteristics was proposed. This method made it possible to implement controllers with amplitude and phase characteristics in multiple narrow-frequency bands corresponding to design values, and to achieve the target noise-reduction. Additionally, in feedback-based road noise control, the amplitude of the control output signal changes drastically depending on the frequency characteristics of the road surface. When this technology was integrated with the already-commercialized booming noise control system, a method to adjust the range of each controller output automatically was applied, achieving integration while balancing noise reduction performance under normal conditions with control stability when the vehicle passes over a large-input surface.

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INTRODUCTION

When a vehicle is driven, noise composed of various frequency components is generated in the cabin. [Figure 1](#) shows in-cabin sound pressure level (SPL) spectra when a vehicle is driven over two different rough concrete road surfaces at a constant speed. Noise of 200 Hz and below caused by input from the road surface is termed low-frequency-band road noise, and is composed of noise in multiple narrow frequency bands. This is an uncomfortable noise that produces a feeling of pressure, and it would be desirable to reduce it simultaneously in all the frequency bands in which it occurs. Active noise control (ANC) is attracting attention as a technology able to reduce noise without a significant increase in mass. A variety of technologies have been proposed based on ANC, and technologies already in use as products include an ANC technology for the reduction of drumming noise, a type of low-frequency-band road noise[1,2], an ANC technology for the reduction of engine booming noise originating in combustion in the engine[3,4], and an integrated ANC technology that simultaneously reduces drumming and engine booming noise[5]. The integrated ANC technology applies a

single-frequency adaptive notch (SAN) filter, a type of adaptive filter, in feedback control in order to realize a controller able to achieve targeted noise attenuation performance for a single type of narrow-frequency-band noise. The use of feedback control makes it possible to reduce noise using fewer sensors than feedforward control, for which a noise source signal is needed. However, there are few examples of the design of feedback-based controllers for the simultaneous reduction of noise in multiple narrow frequency bands. The research discussed in this paper therefore newly developed a feedback-based ANC technology able to simultaneously reduce noise in multiple narrow frequency bands using SAN filters. The research also developed an output range adjustment mechanism that makes it possible to adjust the output range to help prevent distortion of the additive signal composed of the respective control outputs when the control is integrated with engine booming noise control. These technologies, which will be discussed in this paper, were employed in the next model products of Honda vehicles.

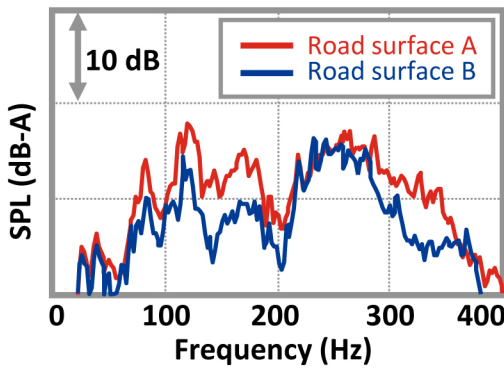


Figure 1. Characteristics of interior noise

CONTROL METHOD

Fundamental Principle of Feedback-Based ANC

Figure 2 shows a block diagram for standard feedback-based ANC. Feedback-based ANC corresponds to disturbance suppression control in the field of control engineering. Terming the transfer function from the speaker output to the microphone Plant C , the base noise Disturbance, and the Residual Noise detected by the microphone the Error Signal e , the Controller G was designed with the Target Value r set at zero. The relationships between these parameters can be expressed by the following formula.

$$\frac{e}{d} = \frac{1}{1 + C(j\omega) \cdot G(j\omega)} \quad (1)$$

Equation (1) is termed a sensitivity function, and expresses the frequency response characteristic of disturbance suppression. In Equation (1), ω is angular velocity; using frequency, f , $\omega = 2\pi f$. Focusing on the denominator in the right-hand term of Equation (1), when $G(j\omega)$ is set to ensure that $C(j\omega) \cdot G(j\omega)$ is 1, sensitivity can be expressed by Equation (2).

$$\frac{e}{d} = \frac{1}{2} \quad (2)$$

This shows that at frequency f , noise is reduced by 6 dB. By contrast, when $C(j\omega) \cdot G(j\omega)$ approaches -1 , because the denominator approaches 0,

$$\frac{e}{d} \rightarrow \infty \quad (3)$$

This is synonymous with an unlimited amplification of noise, and represents divergence of control. Generally, $C(j\omega)$ and $G(j\omega)$ change with frequency, f , and it is desirable to set $G(j\omega)$ to help ensure that $1 + C(j\omega) \cdot G(j\omega)$, the denominator, does not approach the zero point.

The design of a controller for feedback control with the acoustic characteristic of the vehicle as the plant will be considered. The acoustic characteristic of the vehicle includes the output characteristic

of the speakers, the detection characteristic of the microphone, and the acoustic characteristic from the speakers to the microphone. Dead time, the delay time due to the distance from the speakers to the microphone, is included. Given this, and because of the existence of a resonance characteristic originating in the structure of the speakers and a reverberation characteristic originating in the fact that the vehicle cabin is an enclosed space, the acoustic characteristic of the cabin is normally a high-frequency plant that includes dead time. Figure 3 shows an example of an acoustic characteristic with an audio speaker positioned at the vehicle door as the input and a control microphone positioned on the roof as the output. The peaks and troughs of the amplitude characteristic indicate high frequency, and the characteristic that changes as the frequency increases indicates delay due to dead time. Methods for the design of feedback controllers include the loop-shaping method, the Smith method, and the H_∞ control method[7,8].

However, these are basically methods for the design of low-frequency controllers for low-frequency plants. In the reports referenced above, the frequency bands for control were focused on exclusively; the plants were approximated using low-frequency models, and the control effects of combinations of these control design methods were examined. While simulations showed that control effects would be obtained in the specified frequency bands, the reports indicate a decline in the disturbance suppression characteristic and an amplification of disturbance in actual vehicles due to modeling error. Given this, it was considered that the design of a controller that realized the designed frequency characteristics for multiple narrow frequency bands simultaneously would represent a challenge.

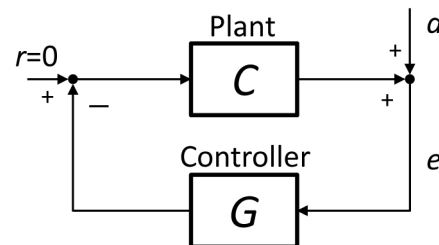


Figure 2. Block diagram of feedback control

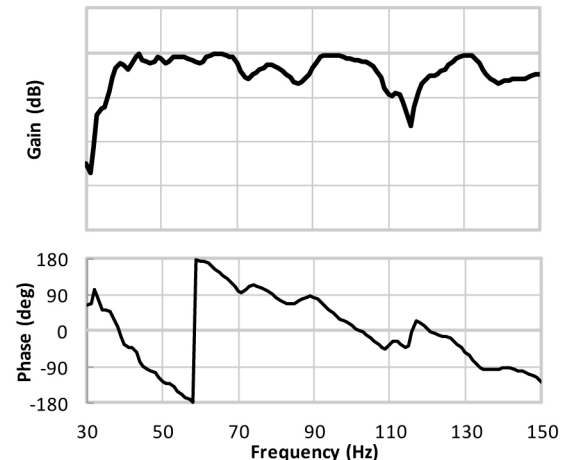


Figure 3. Acoustic characteristic of automobile audio speaker

Feedback-Based ANC using SAN Filters

Feedback-based ANC using SAN filters has been proposed as a method of reducing noise in specific narrow frequency bands[5]. This system is made up of a signal extractor that focuses on signals in the specified narrow frequency bands, a reference signal generator for which amplitude and phase have been adjusted, and a conditioner that outputs the figure obtained by multiplying the coefficients of adaptive filter from the signal extractor by the conditioned reference signal. Figure 4 shows a block diagram of the system.

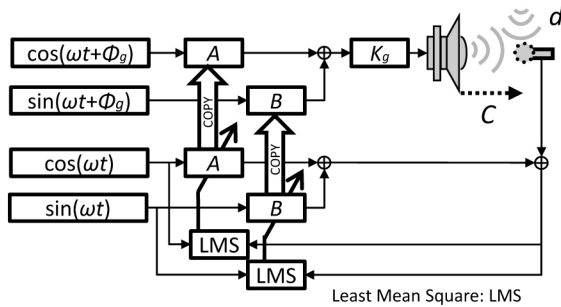


Figure 4. Block diagram of SAN feedback control

Here, A and B are the coefficients of adaptive filter for extracting the signal, ω is the angular velocity of the frequency being focused on, Φ_g is the phase adjustment characteristic, and K_g is the amplitude conditioner.

The update formulas for adaptive filters A and B are expressed as follows.

$$A_{n+1} = A_n - \mu \cdot e \cdot \cos(\omega t) \quad (4)$$

$$B_{n+1} = B_n - \mu \cdot e \cdot \sin(\omega t) \quad (5)$$

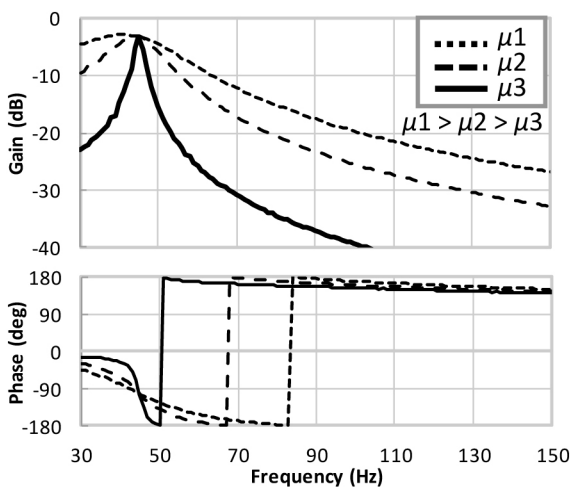


Figure 5. Frequency response of SAN feedback controller

Here, μ is a coefficient that expresses the degree of updating of the adaptive filters, known as the step size parameter. These formulas make it possible to easily set the target frequency for isolation and adjust phase and amplitude, and to make these adjustments with a low calculation load and a minimal delay. Figure 5 shows the

frequency characteristic of a controller based on this method. As Figure 5 indicates, the amplitude of the passing frequency during signal extraction can be adjusted by changing μ . In designing the controller, the amplitude of the passing frequency, the phase characteristic, and the amplitude characteristic were adjusted independently, using μ , Φ_g , and K_g , respectively, and Φ_g and K_g were determined uniquely from Equation (1), the acoustic characteristic, and the target level of noise reduction.

Multiplexing of SAN Filters in Feedback-Based ANC Control

The research discussed in this paper focused on a method of attenuating simultaneously to noise in multiple narrow frequency bands by means of feedback-based ANC using SAN filters. It was decided to connect the SAN filter signal extractor and amplitude phase conditioner in parallel. For the sake of simplicity, the coefficient of the adaptive filter that extracts the signal is termed W , the reference signal x , the degree of adjustment of phase Φ_g , the degree of adjustment of amplitude K_g , and the corrected reference signal, the phase of which has been adjusted by Φ_g , x' . Figure 6 shows a block diagram of the system.

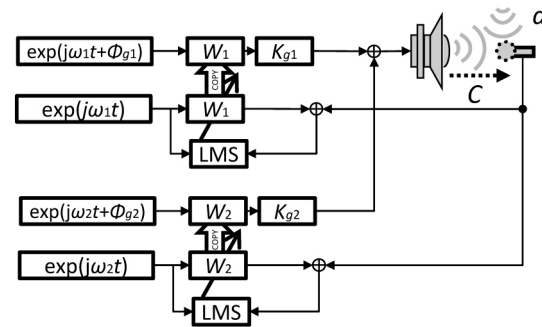


Figure 6. Block diagram of parallel SAN feedback control

The relationship between these parameters and the variables in the block diagram shown in Figure 4 can be expressed as follows.

$$W = A + j \cdot B \quad (6)$$

$$x = \cos(\omega t) - j \cdot \sin(\omega t) = e^{-j\omega t} \quad (7)$$

$$\begin{aligned} x' &= \cos(\omega t + \Phi_g) - j \cdot \sin(\omega t + \Phi_g) \\ &= e^{-j\omega t - \Phi_g} \end{aligned} \quad (8)$$

Simple calculation is possible using these formulas because the overall controller characteristic is the sum of the characteristics of the two SAN filter feedback-based ANC controllers. Controllers were designed with their center frequencies as 45 and 125 Hz and the targets for reduction of the center frequencies as -4 dB, and the frequency response characteristics of the controllers were