

Development of Feedback Active Noise Control Technology for Noise in Multiple Narrow Frequency Bands by Multiplexing of Single-frequency Adaptive Notch Filters

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ABSTRACT

When vehicles are in motion, noise made up of noise in multiple narrow frequency bands, originating in input from the road surface, is generated in the cabin. This type of noise is termed low-frequency-band road noise, and it is desirable to reduce it in order to increase occupant comfort. The research discussed in this paper used feedback control technology as a base in 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 studied. Based on the results, a method of connecting multiple filters that would mitigate mutual interference between controller transfer characteristics was proposed. This method made it possible to realize controllers with amplitude and phase characteristics in multiple narrow frequency bands corresponding to design values, and to obtain the target noise-reduction characteristic.

1. Introduction

When a vehicle is in motion, noise made up of various frequency components is generated in the cabin. Figure 1 shows the in-cabin sound pressure level (SPL) power spectra when a vehicle is driving at a constant speed over two types of rough concrete road surface. Noise of 200 Hz and below that originates in road surface input is termed low-frequency-band road noise, and is made up of noise in multiple narrow frequency bands. This is unpleasant noise that makes vehicle occupants feel uneasy, and it is desirable to reduce it simultaneously in all frequency bands. Active Noise Control (ANC) technology has attracted attention as a technology making it possible to reduce noise without significantly increasing vehicle weight. A variety of types of ANC technologies have been proposed, and a number are already in use, including an ANC technology that reduces drumming noise, a type of low-frequency-band road noise⁽¹⁾⁻⁽³⁾; an ANC technology that reduces engine booming noise originating in combustion⁽⁴⁾⁻⁽⁷⁾; and an integrated ANC technology that simultaneously reduces drumming noise and engine booming noise⁽⁸⁾. This integrated ANC technology employs a single-frequency

adaptive notch (SAN) filter, a type of adaptive filter, in feedback control to realize a controller that achieves the target noise attenuation performance in relation to noise in a single narrow frequency band. The use of feedback control makes it possible to reduce noise with fewer sensors than feed-forward control, which necessitates a noise source signal. However, there are few examples of the design of controllers able to simultaneously reduce noise in multiple

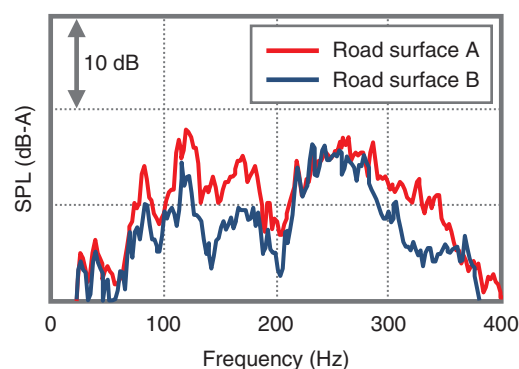


Fig. 1 Characteristics of interior noise

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narrow frequency bands using feedback control. The research discussed in this paper therefore newly developed a feedback-type ANC technology able to simultaneously reduce noise in multiple narrow frequency bands using multiple SAN filters, and applied the technology in a new model.

2. Control Method

2.1. Basic Principle of Feedback-type ANC

Figure 2 shows a block diagram of the generally applied feedback-type ANC. In terms of control engineering, feedback-type ANC corresponds to disturbance suppression control. With the transfer function from speaker output to microphone as plant C , the base noise as disturbance, d , and residual noise detected by the microphone as the error signal, e , the controller, G , is designed to realize a target value, r , of zero. The relationships between these parameters can be expressed by the following equation:

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

Equation (1) is termed a sensitivity function, and it expresses the frequency characteristic of disturbance suppression. Here, ω is angular velocity. Using the frequency, f , ω can be expressed as $\omega = 2\pi f$. Focusing on the denominator of the right-hand term of Eq. (1), to provide an example, if $G(j\omega)$ is set to make $C(j\omega) \cdot G(j\omega)$ 1, then sensitivity is expressed by Eq. (2):

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

This shows a 6 dB reduction in noise of frequency f . By contrast, when $C(j\omega) \cdot G(j\omega)$ approaches -1, because the denominator approaches zero,

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

This is synonymous with an infinite increase in the amplitude of noise, and means divergence. Generally, $C(j\omega)$ and $G(j\omega)$ each change in response to the frequency, f , but it is desirable to set $G(j\omega)$ to attempt to ensure that the denominator, $1 + C(j\omega) \cdot G(j\omega)$ does not approach zero.

Here, the design of controllers for feedback control

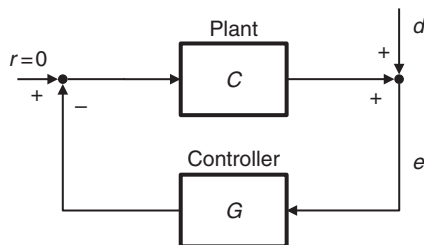


Fig. 2 Block diagram of feedback control

using the vehicle's acoustic characteristic as the plant will be considered. The acoustic characteristic of the vehicle will be assumed to include the speaker output characteristic, the microphone detection characteristic, and the acoustic characteristic from the speaker to the microphone. Taking into consideration dead-time, the delay time due to the distance from the speaker to the microphone, the resonance characteristic originating in the structure of the speaker, and reverberation originating in the fact that the vehicle cabin is a closed space, the acoustic characteristic in the cabin is generally a numerous order plant incorporating dead-time. Figure 3 shows an example of a vehicle acoustic characteristic with an audio speaker positioned at the door as the input and a microphone for control use positioned at the roof as the output. The crests and troughs of the amplitude characteristic display a high-frequency order, and the change in the characteristic as frequency increases is delayed by dead-time. A variety of methods are available for the design of controllers for feedback control, including the loop-shaping method, the Smith method, and the H_∞ control method⁽⁹⁾⁻⁽¹¹⁾. However, these methods assume low-frequency-order controllers for low-frequency plants. The reports referenced above focus exclusively on the frequency bands that represent the control targets and approximate the plant in low-frequency-order models, examining the control effect in combination with the controller design methods. As an issue of this method, the reports indicate that while a control effect is obtained in the simulation in the specific frequency band that is focused on, in the actual vehicle modeling error results in a decline in the disturbance suppression characteristic and an increase in the amplitude of disturbance. Given this, it can be considered challenging to expand these methods and realize a controller that would display a design frequency characteristic enabling it to simultaneously respond to multiple narrow frequency bands.

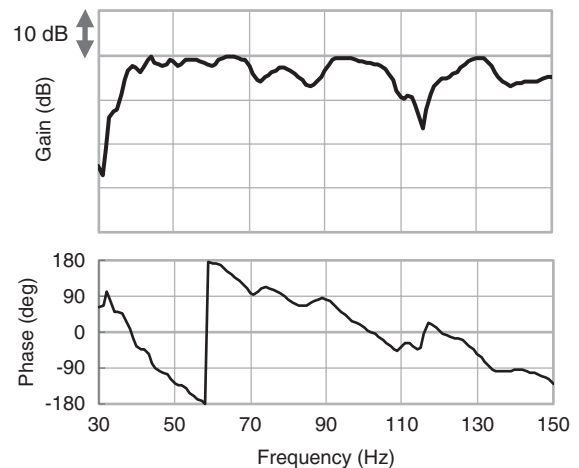


Fig. 3 Acoustic characteristic of automobile audio speaker

2.2. Feedback-type ANC using Multiple SAN Filters

Feedback-type ANC employing single SAN filter has been proposed as a method of reducing noise in a specific narrow frequency band⁽⁸⁾. This system is made up of a signal extractor that focuses on the signal of the specific narrow frequency band, a reference signal generator with conditioned amplitude and phase, and a conditioner that multiplies the adaptive filter coefficient obtained from the signal extractor by the conditioned reference signal to produce output. Figure 4 shows a block diagram of the system.

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

The update equations for adaptive filters A and B are expressed as follows:

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

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

Here, μ is termed the step size parameter, and is the coefficient that adjusts the degree of updating of the adaptive filters. The merit of this method is that the setting of the target frequency for extraction and the conditioning of phase and amplitude are easy, and these procedures can be realized with low computational load and low delay. Figure 5 shows the frequency response characteristic of a controller using this method. As the figure shows, it is possible to adjust the amplitude of the frequency-passing signal extraction by changing μ . In controller design, the amplitude of the passing frequency is adjusted by μ , the phase characteristic is adjusted by Φ_g , and the amplitude characteristic is independently adjusted by K_g , and Φ_g and K_g are uniquely calculated based on Eq. (1), the acoustic characteristic, and the target amount of reduction of noise.

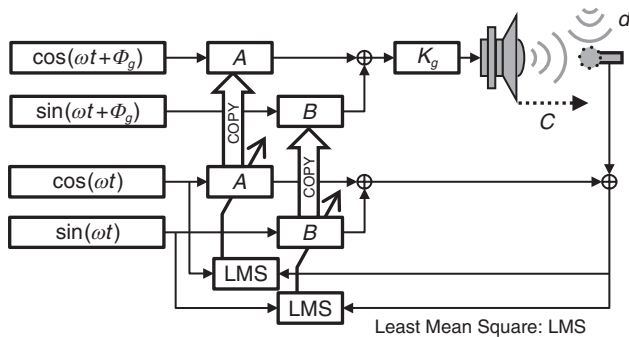


Fig. 4 Block diagram of SAN feedback control

2.3. Multiplexing Frequencies using Feedback-type ANC employing Multiple SAN Filters

The research discussed here studied a method of simultaneously reducing noise in multiple narrow frequency bands using feedback-type ANC employing multiple SAN filters. The first consideration was that the SAN filter signal extractor and the amplitude and phase conditioner could simply be connected in parallel. For the sake of simplicity, the adaptive filter coefficient for signal extraction will be 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, x' the phase of which has been adjusted by Φ_g . Figure 6 shows a block diagram.

The relationship between these variables and the variables shown in the block diagram in Fig. 4 is expressed as follows:

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

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

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

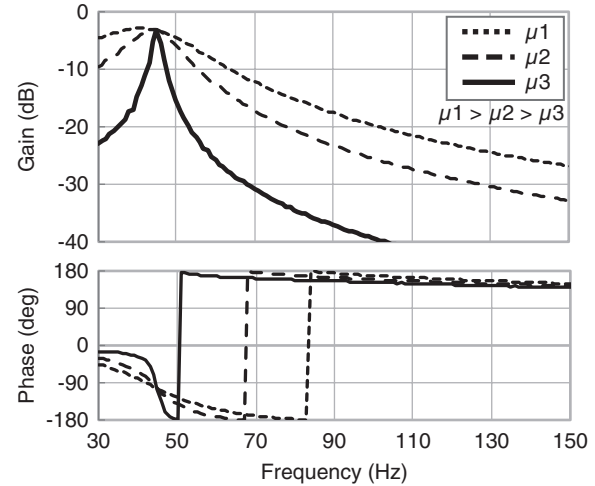


Fig. 5 Frequency response of SAN feedback controller

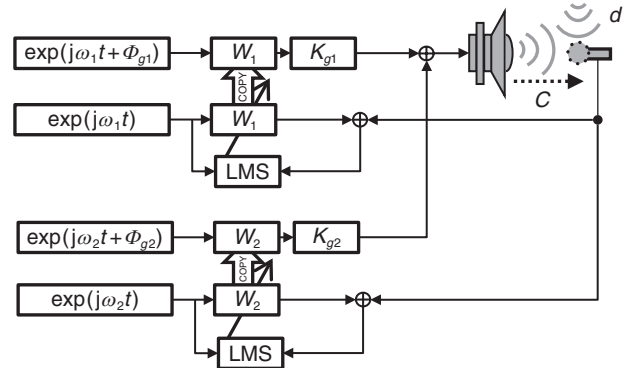


Fig. 6 Block diagram of parallel SAN feedback control

Because the sum of the feedback-type ANC controller characteristics produced by the two SAN filters is the overall controller characteristic in this method, the overall characteristic is simple to calculate. Controllers were designed to reduce the center frequencies of the 45 Hz and 125 Hz frequency bands by 4 dB each, and their frequency response characteristics were calculated. Figure 7 shows the characteristic for the 45 Hz-band controller only, the characteristic for the 125 Hz-band controller only, and the characteristic when the two controllers are connected in parallel.

Figure 7 shows that there is a difference between the frequency response characteristics obtained from the controllers in isolation and the characteristic for the controllers connected in parallel. This is because the characteristic of the 45 Hz-band controller at 125 Hz is added to the characteristic of the 125 Hz-band controller. Similarly, the 125 Hz-band controller changes the controller characteristic in the 45 Hz band. This indicated that a controller with the design frequency characteristic would not be realized, and that as a result the target level of noise reduction would not be achieved. A logic that would mitigate the effect of a controller for a specific frequency band on the characteristics of a controller for another frequency band was therefore necessary. Two methods of employing the characteristic of multiple SAN filters signal extractor to mitigate interference between controllers were proposed. Together with the parallel error connection type discussed above, this represented three control methods. The characteristics and effects of these three control methods were studied, and the results are shown below.

(1) Parallel error connection type: Two controllers based on SAN filters were connected in parallel. This is a simple configuration, because the overall controller

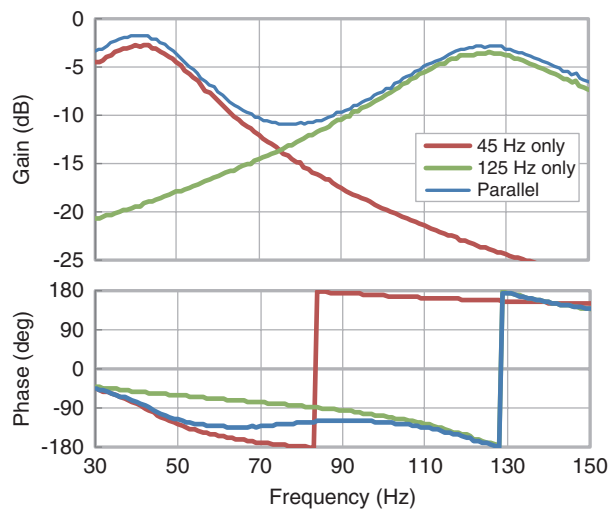


Fig. 7 Frequency response of parallel SAN feedback controllers

characteristic can be calculated as the sum of the characteristics of the two controllers.

- (2) Cascade error connection type: A cascade error connection type, in which the residual signal extracted from one SAN filter was employed as the input for the other SAN filter, was used. Because the results of signal extraction for one SAN filter were transmitted to the other filter, the potential for interference between the results of signal extraction between the filters was minimized, indicating that the effect of the characteristic of a controller for one frequency band on the characteristic of the controller for another frequency band would be mitigated.
- (3) Common error connection type: The method of integrating the results of signal extraction results for the two SAN filters was termed the common error connection type. There was a possibility of interference between the extraction results for the SAN filters, but prospects seemed good for mitigation of interference between the characteristics of the controllers for each frequency band.

Figure 8 shows a block diagram of the cascade error connection type, and Fig. 9 shows a block diagram of the common error connection type.

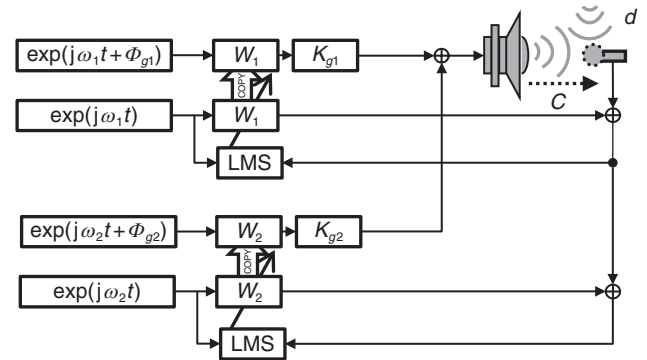


Fig. 8 Block diagram of cascade SAN feedback control

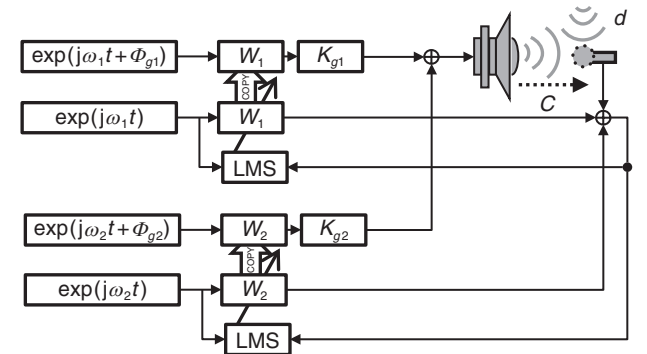


Fig. 9 Block diagram of common SAN feedback control

3. Verification of Controller Characteristics

3.1. Controller Simulation

With the target for the amount of change occurring as a result of the combination of the controllers for the two frequency bands set as within ± 0.1 dB, feedback-type ANC controllers were designed using the three connection methods discussed in Chapter 2, based on the same design values as indicated in Chapter 2, and their design values (amplitude characteristics) were calculated. Figure 10 shows the results.

As the results indicate, there is a divergence from design values for the controller characteristic in the case of the parallel error connection type and the cascade error connection type. However, in the case of the common error connection type, a frequency characteristic corresponding to the design values was obtained for both the 45 Hz and the 125 Hz frequency bands. While the design characteristic was realized in the 45 Hz band using the cascade error connection type, there was a divergence in the 125 Hz band. These results indicated that when combining multiple SAN filters, the connection of signal extractors using the common error connection type would help to ensure the realization of a controller characteristic true to design values.

3.2. Detailed Analysis of Common Error Connection Type

In order to verify the effectiveness of the common error connection type, the 45 Hz and 125 Hz controller characteristics were analyzed via simulation, with control gain K_{g1} and K_{g2} set to zero, as shown in Fig. 9. The results were compared with the controller characteristic when control was applied simultaneously to the 45 and the 125 Hz bands. Figure 11 shows the results.

Comparing the 45 Hz and the 125 Hz controller characteristics in the 125 Hz band, there is an attenuation of the amplitude characteristic of more than 40 dB and a difference of less than 1%. This means that the divergence

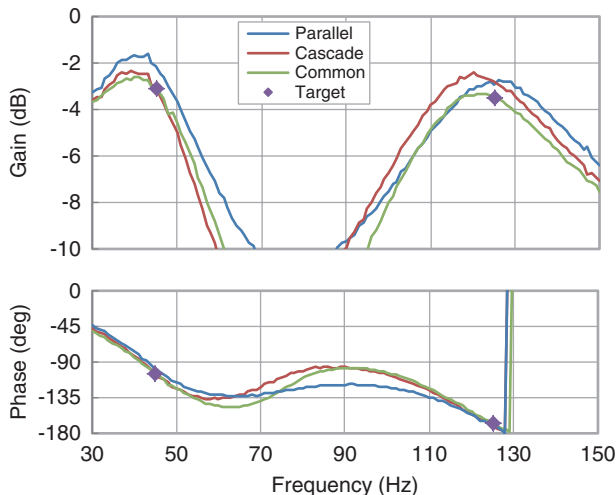


Fig. 10 Frequency response of three connection types

from design values for the controller characteristic has been controlled to within ± 0.1 dB. In the case of the parallel error connection type, attenuation was around 20 dB and there was a divergence of around 10% when the controller characteristics were added. In addition to mitigating the mutual effect of controller characteristics in different frequency bands, the common error connection type has the same effect as simply adding the controller characteristics, and it is therefore considered possible to realize a controller characteristic corresponding to the design values.

3.3. Study of Feasibility of System using Conventional Methods

The SAN filters were replaced with Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filters, both digital filter types in standard use, in order to test the feasibility of realizing the system with alternative filters. The least squares method, weighted for the controller characteristic for the common error connection type from 20 Hz to 200 Hz, was used to find the coefficients. Figure 12 shows the results. Even when an 800-tap FIR

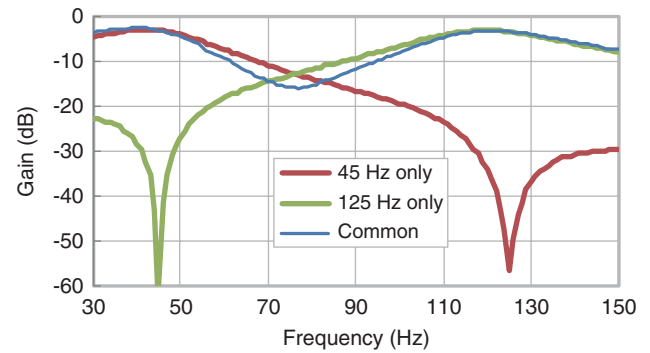


Fig. 11 Frequency response of decomposed common error-type SAN feedback controller

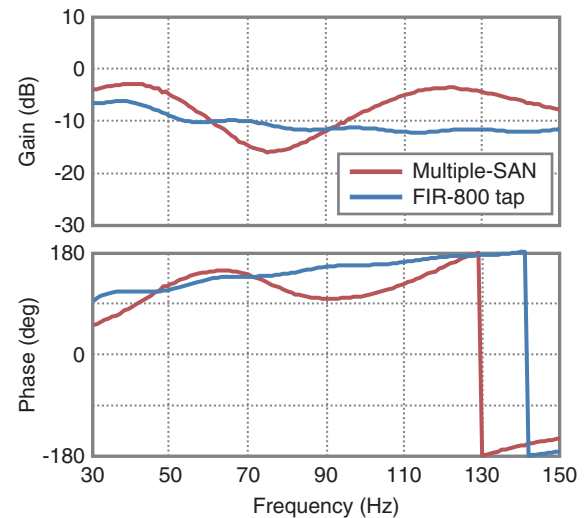


Fig. 12 Frequency response of multiple SAN filters and FIR filter

filter was employed, the characteristic obtained was as shown in the graph, and when an IIR was employed, it was not possible to obtain stable filter coefficients. The method of combining two SAN filters as discussed in this paper makes it possible to obtain a controller characteristic that realizes design values with minimal computation, and can be considered superior to conventional methods.

4. Control Performance

Control performance when the developed method was employed in a vehicle was studied. Feedback controllers were designed based on the acoustic characteristic shown in Fig. 3, with the targets for noise reduction set at -4.5 dB in the 45 Hz band and -3 dB in the 125 Hz band. Figure 13 shows the open loop function determined by simulation. The results show that it was possible to ensure a gain margin, indicating that the controller is stable. Figure 14 shows the sensitivity function. The target noise-reduction characteristic was realized in both the 45 Hz and the 125 Hz bands. The controller realized by the control design was applied in an actual vehicle, and control performance was studied. Figure 15 shows the results of noise measurements

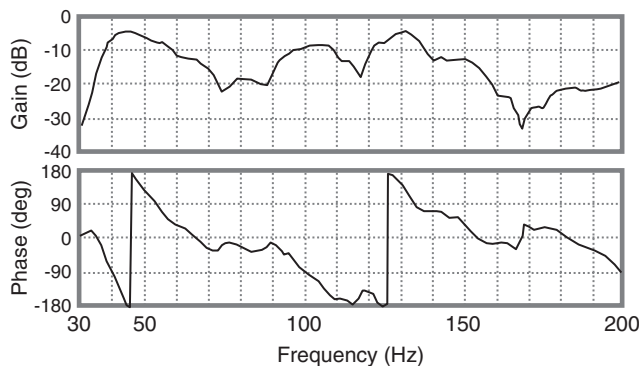


Fig. 13 Open loop function of common error-type SAN feedback controller

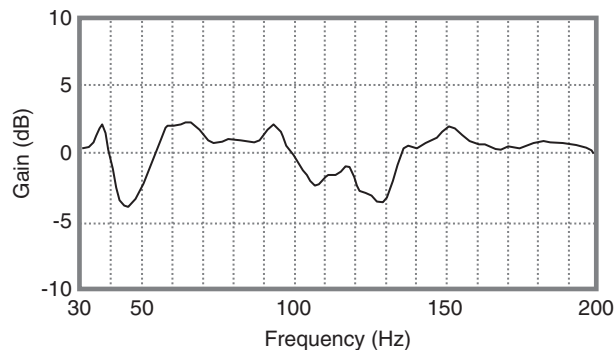


Fig. 14 Sensitivity function of common error-type SAN feedback controller

taken while driving at 60 km/h over a rough concrete surface and Fig. 16 shows measurements taken while driving at 40 km/h over a rough asphalt surface. The results demonstrate that the proposed method simultaneously reduces noise in the 45 Hz and 125 Hz narrow frequency bands, and realizes control performance equivalent to the sensitivity function.

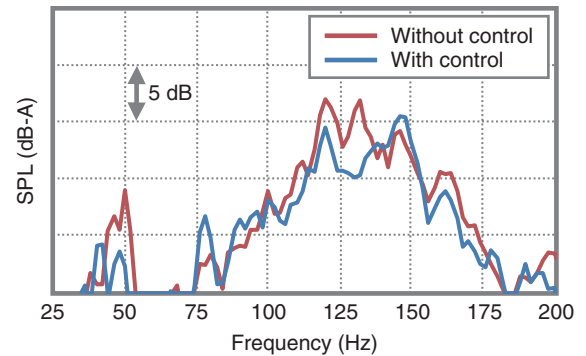


Fig. 15 Control performance 1 of common error-type SAN feedback controller on rough concrete surface

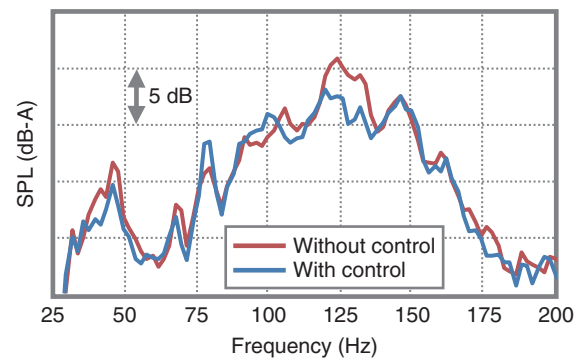


Fig. 16 Control performance 2 of common error-type SAN feedback controller on rough asphalt surface

5. Conclusion

A feedback ANC technology employing SAN filters that is able to simultaneously reduce noise in multiple narrow frequency bands has been developed. It is simple to adjust the controller characteristic for the frequency characteristics and acoustic characteristics of noise in different vehicles, and it is possible to stably obtain the target control characteristic. This paper has discussed results obtained by combining two SAN filters, but it would be possible to reduce noise in three or more narrow frequency bands by combining three or more SAN filters using the common error connection type.

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