

Integrated Active Noise Control System for Low-frequency Noise in Automobiles

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ABSTRACT

Honda has developed two Active Noise Control (ANC) technologies, and has employed them as standard in a large number of vehicles. One of these technologies is a drumming reduction technology that employs feedback control, and the other is an engine booming noise control technology that employs feed forward control, which uses the engine speed signal as a reference signal. These technologies have previously not been combined to produce an integrated system due to issues of mutual interference between the control systems and stability in the feedback control. The research discussed in this paper created a new drumming control technology that resolved these issues, and developed an integrated ANC system. The new ANC system developed in the research has been employed in a number of vehicles.

1. Introduction

Today, awareness of the need to protect the global environment is intensifying demands for increased automotive environmental performance and fuel efficiency. Together with technologies to achieve weight savings, numerous technologies to increase fuel efficiency are being applied in automotive powertrains. At the same time, demands are also intensifying for increased noise and vibration performance, which represents a factor in the commercial competitiveness of the vehicle. However, because measures to combat noise and vibration, in particular low-frequency phenomena, entail increased weight, in many cases they are in an antagonistic relationship with the aforementioned demand for increased fuel efficiency. These measures are antagonistic because many of the technologies used to increase fuel efficiency use the low-engine-speed range with a greater frequency than is normally the case. Because of this, these technologies often increase intake and exhaust noise and engine vibration in the low-frequency range. In many cases, the passive technologies that have traditionally been adopted to counteract this increase in noise and vibration, such as increasing the noise-attenuating volume of the intake and exhaust or attaching stiff members or damping members to the vehicle body, and measures such as the use of dynamic dampers to reduce vibration in specific frequency ranges, result in increased vehicle weight. This necessitates the development of technologies to counteract noise and vibration in the low-frequency range that entail minimal

weight increase. Honda worked towards the development of two types of ANC technology that would balance fuel efficiency with noise and vibration performance. The developed technologies have been employed as standard in a large number of Honda vehicles. One of these technologies reduces drumming⁽¹⁾, a type of low-frequency road noise; the other reduces booming noise in the engine⁽²⁾⁻⁽⁴⁾. Figure 1 shows the in-cabin sound spectrum for a vehicle driven over an undulating road at a fixed speed of 50 km/h. Drumming and booming noise are produced simultaneously in the cabin. This situation demands the development of a control technology able to control these two phenomena simultaneously. In addition, the integration of the control systems would be desirable in order to minimize system costs. However, when ANC systems are

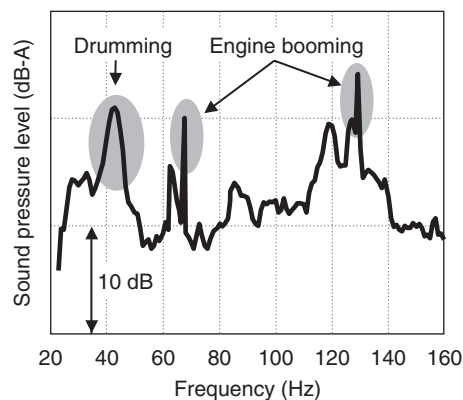


Fig. 1 Frequency characteristic for drumming and engine booming noise

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integrated, differences in their methods of control result in interference between the control devices and stability issues, and it has therefore not been possible to create an integrated system to date. This paper presents an overview of a new ANC technology for drumming and an integrated ANC technology produced by fusing this technology with a booming noise control technology, developed to resolve these technological issues.

2. Overview of Existing Technologies

2.1. ANC for Drumming

2.1.1. Characteristics of drumming

Figure 2 shows an acoustic eigenmode obtained by eigenvalue analysis of an in-cabin sound field modeled using the finite element method. When the vehicle is being driven, input from the road surface is transmitted to the body via the suspension, and drumming is produced by the excitation of the eigenmode. This phenomenon occurs at a frequency at which the length of the cabin is one-half the length of the sound waves, which is approximately 40 Hz in passenger vehicles. Figure 3 shows a sound pressure spectrum near the front seats when the vehicle is driving on a rough road surface. As this figure shows, drumming is a phenomenon that occurs in a narrow frequency band, occurring in a frequency width of around 8 to 10 Hz.

2.1.2. Existing drumming ANC system

Figure 4 shows the configuration of the drumming ANC system. As the diagram shows, the control unit (termed “ECU” below) is positioned underneath the driver’s seat.

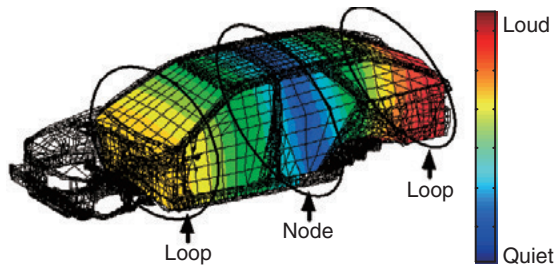


Fig. 2 Acoustic modes of station wagon

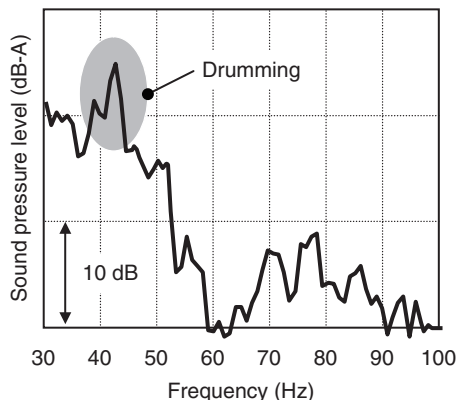


Fig. 3 Frequency characteristic for drumming

The system employs a feedback control method in which a control signal is output based on the sound in the cabin. The ECU is made up of a drumming control filter that comprises a number of analogue circuits, a speaker-drive amplifier, and a microphone. The in-cabin sound signal detected by the microphone is converted to a control signal to cancel out the drumming by passing through the drumming filter. This signal is amplified by the amplifier, and emitted into the cabin via the speakers.

2.1.3. Control technology of existing drumming ANC

Figure 5 shows a block diagram of feedback control (termed “FB control” below) for drumming control, using a microphone signal and control filter, and speakers that are shared with the audio system. The FB-ANC corresponds to external disturbance suppression control in control engineering. This is to say that the purpose of the control is, when an external disturbance (noise d) is added to the sound field of the cabin (the plant, C), which is the transfer function from the speakers to the microphone, to reduce this noise by means of the controller, G . If the signal remaining after control has been applied is termed e , e/d gives S , the sensitivity function. An S value of 1 or less indicates that noise can be reduced. S is expressed by Eq. (1). In order to reduce S , the controller, G , is adjusted to make the gain of the open loop function at the control target frequency ω [given by $L(j\omega)=C(j\omega)G(j\omega)$] as high as possible and its phase 0° . For example, when $|L(j\omega)|=1$ and $\angle L(j\omega)=0^\circ$, Eq. (1) gives an S value of 1/2, and noise can be reduced by 6 dB.

$$S = \frac{1}{1 + C \cdot G} \quad (1)$$

Because the microphone signal includes all frequency components, in addition to being adjusted to make the

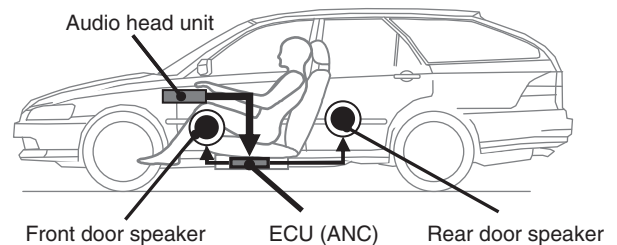


Fig. 4 On-board system configuration of drumming ANC

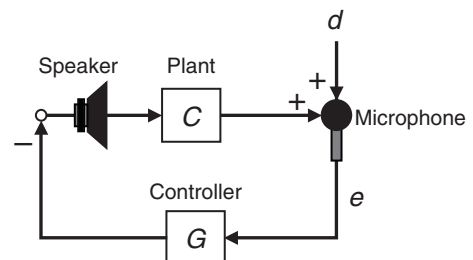


Fig. 5 Block diagram of feedback ANC

gain of the open loop function L in the control target frequency band as high as possible and its phase to 0° , the controller, G , is adjusted to reduce the high-frequency range, i.e., to display low pass characteristics, for the sake of stability. Figure 6 shows an example of the results of shaping the open loop function. Because the gain level is approximately 6 dB in the target frequency band (close to 40 Hz), a reduction in drumming of approximately 10 dB can be expected from Eq. (1); at the same time because the phase margin is approximately 90° and the gain margin is approximately 12 dB, it can be seen that stability has been achieved.

2.2. ANC for Engine Booming Noise

2.2.1. Characteristics of engine booming noise

Figure 7 shows cabin noise when the vehicle is accelerating. In this figure, the noise level is highest where the color is most intense. The area of high noise at the center of the figure shows engine booming noise. As this figure indicates, the engine booming noise component is synchronous with engine speed and occurs at high frequencies, and at the same time is a single-frequency phenomenon. That is, because booming noise has a noise waveform close to a sine wave, the canceling sound generated to reduce the noise has a waveform close to a sine wave of opposite phase.

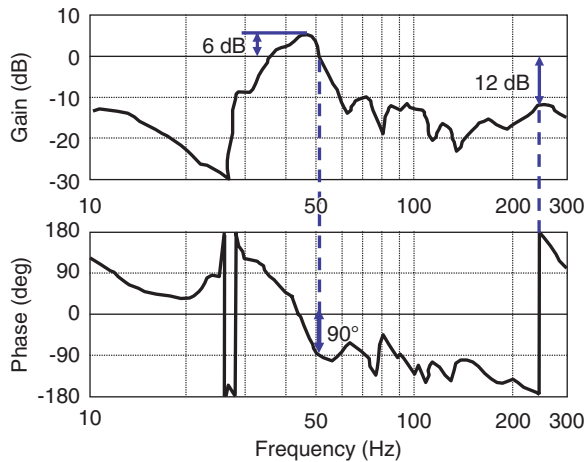


Fig. 6 Bode plot of open loop transfer function

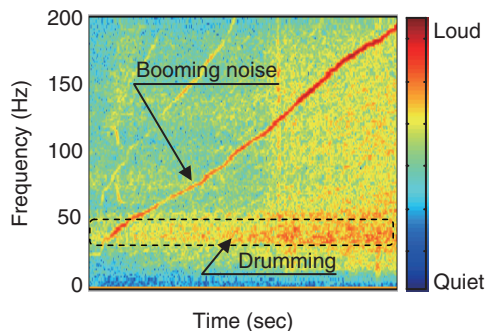


Fig. 7 Contour map of noise inside cabin

2.2.2. Overview of engine booming noise ANC system

Figure 8 shows the composition of the system. This system is made up of an ECU, microphone units positioned on the ceiling at the front and rear of the cabin, an audio unit fitted with an input terminal for the control sound signal from the ECU, and speakers shared with the audio system. The microphone unit positioned on the ceiling at the front of the cabin also has a voice recognition function for hands-free telephone or navigation system use. The system uses a feed-forward control method, in which the engine speed signal is used as a reference signal. In other words, the signals input to the ECU are the engine speed pulse signal (number of engine pulses: NEP) from the ENG-ECU that controls the combustion state of the engine, and the signals from the microphones that detect in-cabin noise. The output signal is a control signal that drives the speakers via the amplifier that is shared with the audio system.

2.2.3. Engine booming noise control technology

Because engine booming noise is a single-frequency phenomenon, it can be expressed on a complex plane, as shown in Fig. 9. As this figure indicates, using the reference signals corresponding to the real and imaginary axes (signals RX and RY), the canceling sound signal can be produced using the amplitude of signal RX , A , and the amplitude of signal RY , B . This method expands single-frequency adaptive notch (SAN)⁽⁵⁾ control, which internally generates orthogonal reference signals and adaptively operates adaptive notch filters A and B corresponding to the amplitudes of these signals, to filtered-x SAN, and is able to rapidly trace changes in engine speed as it reduces engine booming noise. In this method, the acoustic characteristic $\hat{c}$ (impulse response) is frequency decomposed as shown in

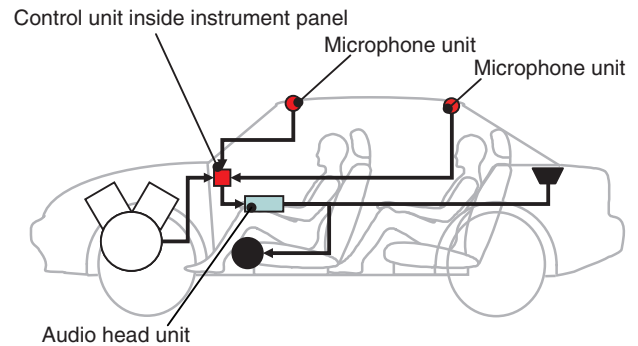


Fig. 8 On-board system configuration of engine booming ANC

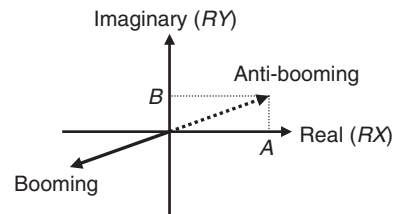


Fig. 9 Polar coordinates of booming noise

Eq. (2), and the frequencies are saved as $\hat{C}$ on a table for the control frequencies. The values corresponding to the control frequencies are read from the table and used in calculations. j represents an imaginary unit.

$$\hat{C}(f) = C_R(f) + j \cdot C_I(f) \quad (2)$$

The calculation of the filtered-x segment of the reference signal RX can be expressed as Eq. (3).

$$\hat{C}(f) \cdot RX = C_R(f) \cdot RX + C_I(f) \cdot RY \quad (3)$$

Because the signal RY is advanced 90° in phase in relation to RX , $j \cdot RX = RY$ is used in Eq. (3). Similarly, for the reference signal RY :

$$\hat{C}(f) \cdot RY = C_R(f) \cdot RY - C_I(f) \cdot RX \quad (4)$$

Figure 10 shows a block diagram of the engine noise booming control realized using Eqs. (3) and (4). The benefit of this method is that it can be realized using scalar operations alone, with no need for convolution (vector) operations, which involve a significant volume of computation. Because of this, the method can be realized using today's low-cost microcomputers.

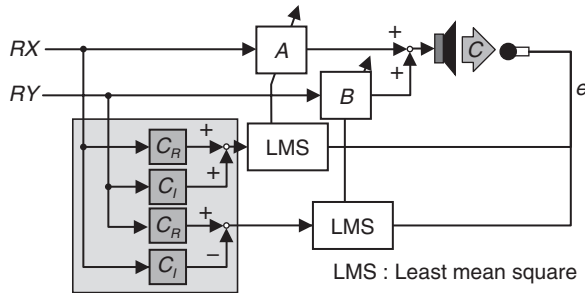


Fig. 10 Block diagram of frequency-filtered reference SAN algorithm

3. Integrated Control Technology for Low-frequency Noise

3.1. Issues in Integrating Two Control Technologies

The engine booming noise control technology employs digital data processing using low-cost microcomputers. Given this, it is possible to apply the technology to multiple vehicle types by rewriting the control parameters in the memory, and thus production costs can be kept low by sharing the hardware. By contrast, because the drumming control technology is realized using analogue circuits, the application of the technology to multiple vehicle types necessitates redesign of the circuit configuration for each model, which represents an impediment to the sharing of hardware. The project therefore decided to digitalize the drumming control technology to make it possible to modify

it solely by adjusting parameters, and at the same time to create a new technology by integrating this technology with the engine booming noise control technology.

3.1.1. Issues related to the digitalization of the drumming control technology

As indicated in the overview of existing technologies above, Honda's drumming control ANC employs feedback control. Feedback control can be expressed as a geometric series with the open loop transfer function $L (=CG)$ a series (Fig. 5). That is, while noise can be reduced in the frequency band in which the open loop function is close to 0° , noise increases in the frequency band in which the open loop is close to 180° . Because the speakers and the microphone cannot be positioned at the same point, the cabin sound field (the target of control) will necessarily display a phase lag, and despite the fact that the open loop function is adjusted to 0° in the drumming frequency band, there will necessarily be a frequency band in which the open loop function becomes 180° in the high-frequency range. This results in the "waterbed effect" shown in Fig. 11, in which bands in which there is a noise reduction effect and bands in which noise increases repeatedly alternate due to the occurrence of frequencies other than the control frequency. The waterbed effect is minimized and control is stabilized in feedback ANC by setting a control filter, using a band pass filter to control increases in noise, and a low pass filter to reduce the high-frequency range. The following describes issues associated with realizing this control filter using digital filters.

(1) Issues when using a finite impulse response (FIR) filter

In order for the engine booming noise ANC to rapidly trace changes in engine speed, the system samples frequencies that are very high in relation to the engine booming noise frequencies to be controlled. When an FIR filter is used to control low-frequency waves with long cycles while a high sampling frequency is maintained, the length of the filter increases (the number of elements in the filter coefficient increases). Because the inner products of the filter coefficient vector and the input signal vector are taken for each sample during filtering using an FIR filter, if the filter becomes long, the amount of computation

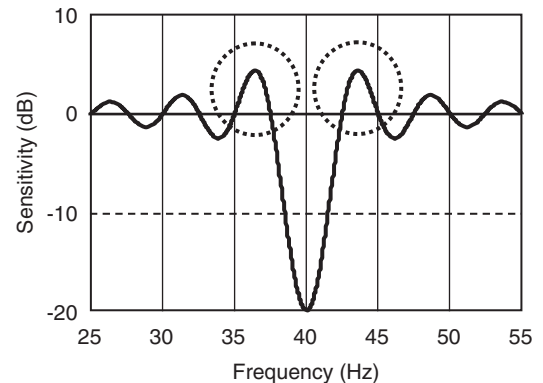


Fig. 11 Waterbed effect

increases. Given this, realization of this method using low-cost microcomputers represents a challenge.

(2) Issues when using an infinite impulse response (IIR) filter

When an IIR filter is used to adjust low-frequency waves while a high sampling frequency is maintained, the filter coefficient becomes low. Because of this, issues of calculation accuracy make it challenging to realize this method using low-cost microcomputers, which rely on fixed-point computation.

These digital filter-related issues made it challenging to simply digitalize the standard control filter used in drumming ANC.

3.1.2. Issue of interference between two control devices

(1) Waterbed effect on engine booming noise

The frequency of engine booming noise changes synchronously with changes in engine speed. Because of this, engine booming noise increases when the engine booming noise frequency overlaps with the frequency band in which noise increases due to the waterbed effect produced by drumming ANC.

(2) Changes in sound field characteristics from the perspective of the engine booming noise control device

Both drumming ANC and engine booming noise ANC store the transfer characteristic from the speakers to the microphone (to be precise, the input provided by the microcomputer output) and use it for control purposes. Given this, it is essential to consider changes in the transfer characteristic from the perspective of both control devices when integrating them.

These issues of interference between the control devices made it challenging to simply integrate the two existing ANC technologies.

3.2. New Drumming Control Technology

This section will discuss the digitalization of the drumming control technology. As indicated in Sub-section 3.1.1, when using feedback control, it is normal to employ a control filter created by combining a low pass filter and a band pass filter in order to help ensure stability in consideration of the water bed effect. This method presents issues from the perspective of integration with engine booming noise control. The project therefore did not choose to digitalize fixed filters, but instead proposed a new drumming control method, as shown in Fig. 12, in which drumming was extracted from the microphone signal, and the resulting signal was adjusted to fixed gain and phase characteristics and output. SAN control, which is also used in engine booming noise control, is used to extract drumming from the microphone signal. Drumming and engine booming noise differ in the width of their frequency bands. Specifically, while engine booming noise can be treated as a single-frequency signal, drumming is a phenomenon that occurs within a narrow frequency band

of around 8 to 10 Hz. The project therefore considered a method of expanding the SAN control frequency band. Equation (5) expresses the output signal for the SAN control block diagram shown in Fig. 13. Here, ϕ expresses the phase characteristic determined by the magnitude of the amplitudes at A and B in Fig. 13.

$$Out = \sqrt{A^2 + B^2} \cos(\omega \cdot t + \phi) \quad (5)$$

Equations (6) and (7) are the renewal equations for adaptive filters A and B .

$$A_{n+1} = A_n - \mu \cdot \cos(\omega t) \cdot e \quad (6)$$

$$B_{n+1} = B_n - \mu \cdot \sin(\omega t) \cdot e \quad (7)$$

Here, μ expresses the step size parameter. In Eq. (5), when A and B have fixed values, the output signal, Out , is a signal depending on the reference frequency, ω . However, when A and B are fluctuating at frequency ω_a , the output signal can be expressed by Eq. (10).

$$A = Q \cdot \cos(\omega_a t) \quad (8)$$

$$B = Q \cdot \sin(\omega_a t) \quad (9)$$

$$Out = Q \cdot \cos\{(\omega - \omega_a) \cdot t\} \quad (10)$$

From Eq. (10), the output signal, Out , is a signal of frequency $\omega - \omega_a$. That is, if A and B are fluctuating at 1 Hz, a signal that is shifted by 1 Hz in relation to the reference signal, ω , which causes the SAN to operate, can be output. When A and B rotate counterclockwise around the polar coordinates shown in Fig. 14, ω_a takes on a positive value, and when they rotate clockwise, it takes on a negative value. μ in Eqs. (6) and (7) is adjusted to make adaptive filters A and B fluctuate. Figure 16 shows the frequency characteristic of the output signal obtained from the signal

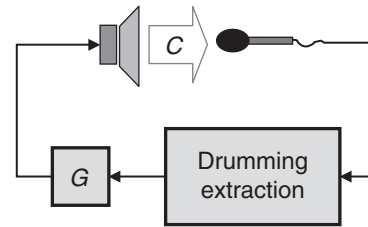


Fig. 12 Block diagram of drumming ANC

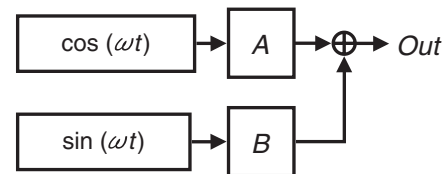


Fig. 13 Block diagram of SAN

processing simulation shown in Fig. 15. As Fig. 16 shows, the frequency width becomes narrower in proportion to the decrease in μ , and wider in proportion to the increase in μ . Figure 17 shows a block diagram of drumming ANC employing SAN control. ω in the figure corresponds to the central frequency of drumming. ϕ_d is the phase for control of drumming, and in the transfer characteristic from the speaker to the microphone, this corresponds to the phase that becomes 180° when the signal reaches the microphone. G_d is the gain for drumming control, and this is a parameter that is adjusted in response to the target degree of noise reduction. For example, following Eq. (1), a noise reduction of 6 dB can be expected if a G_d is selected to be 0 dB when multiplied by the transfer characteristic from the speakers to the microphone.

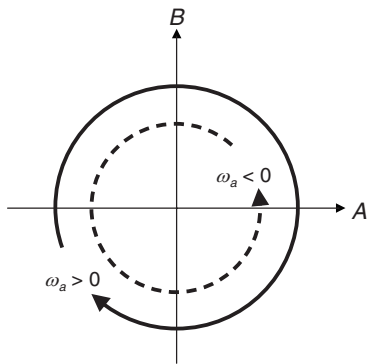


Fig. 14 Polar coordinates of gain coefficient

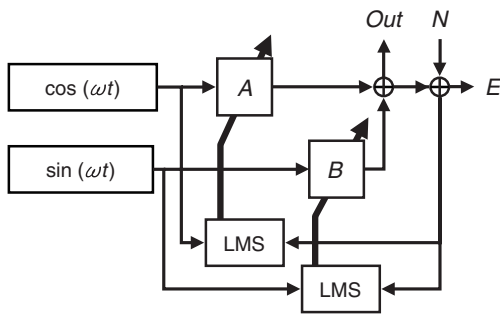


Fig. 15 Block diagram of signal extraction

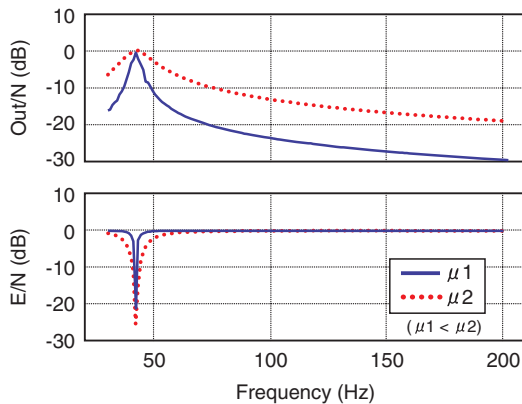


Fig. 16 Effect of signal extraction

3.3. Integration of Engine Booming Noise Control Technologies

3.3.1. Attempting to eliminate the increase in engine booming noise

The new drumming ANC employed a narrow frequency band pass filter for which a SAN filter was used. The phase difference was 0° at the central frequency, ω , but the phase varied significantly at frequencies above and below this. Because of this, the filter was affected by the waterbed effect. Engine booming noise increased when the frequency at which it occurred overlapped with the frequency band in which noise increased due to the waterbed effect. To attempt to prevent the waterbed effect, an SAN was employed to help eliminate the engine booming noise component when the signal from the microphone was processed. The effect of this measure can be expressed as E against noise N in Fig. 15, and corresponds to the graph shown at the bottom of Fig. 16.

3.3.2. Setting changes in $\hat{C}$ due to drumming ANC

The engine booming noise ANC and drumming ANC systems were integrated as shown in Fig. 18. Because the transfer function between output and input from the perspective of the control algorithm is stored as a control parameter ($\hat{C}$) in engine booming noise ANC, it was necessary to make settings with consideration of the effect of drumming ANC on $\hat{C}$.

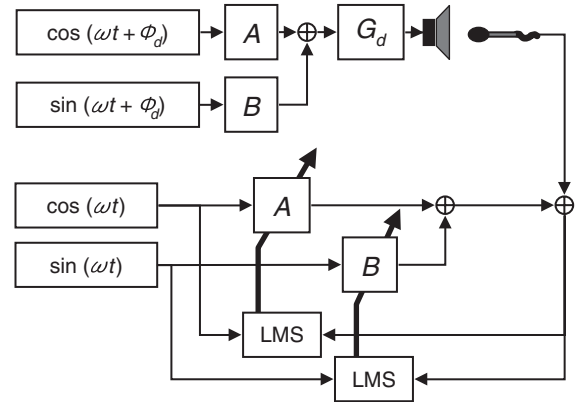


Fig. 17 Block diagram of drumming ANC using SAN

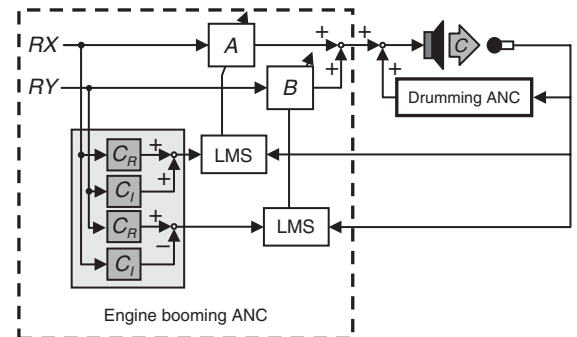


Fig. 18 Block diagram of integrated ANC

4. Integrated Control System for Low-frequency Noise

Figure 19 shows the configuration of the system. The engine booming noise ANC switches between operation and non-operation in response to engine speed. In addition, the system is configured to cease operation when a door is open, because the change in the distance between the speakers and the microphone changes the value of $\hat{C}$. Similarly, because the drumming ANC uses feedback control, the system is configured to cease operation when the vehicle is stopped in order to increase stability from the perspective of the market. It was further necessary to link operation of the system to the state of opening of the trunk in addition to the doors. The reason for this was that the opening of the trunk would change the central frequency of drumming due to the effect of a change in the sound field characteristic. Increasing the number of control signals in order to switch operating states in this way would make it necessary to increase the number of harnesses and change the size of the ECU couplers if system communications employed the analogue signals used to date (Fig. 8). This would make it challenging to share hardware between vehicle models. It was therefore decided that in the new system, vehicle data would be transmitted to the ECU from the control area network (CAN) via digital communications. Figure 20 shows the control block diagram for the newly developed integrated ANC system. In addition

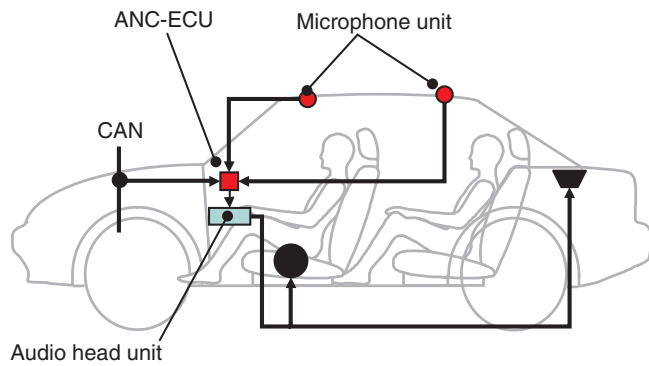


Fig. 19 On-board system configuration of integrated ANC

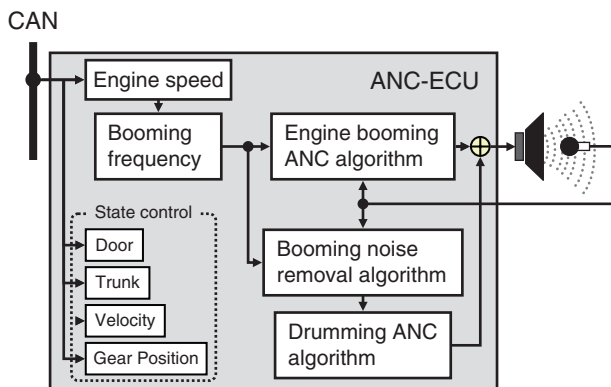


Fig. 20 Block diagram of on-board system for integrated ANC

to the control system shown here, the system also enhances the in-cabin acceleration noise control function⁽⁶⁾ that operates when the vehicle is accelerating, using vehicle state data including powertrain state and vehicle speed transmitted by the CAN, by adjusting the function for each gear stage, and incorporates a new function that reduces, as propeller shaft rotation order noise, the engine booming noise originating in imbalances in the rear differential in AWD and FR vehicles.

5. Effects of Application

5.1. Control Effect of New Drumming ANC

Figures 21 and 22 show the control effect of the new drumming ANC when the vehicle is driving on rough road surfaces. Figure 21 shows the time-average frequency spectrum for several seconds. The graph indicates a reduction of approximately 6 dB. Figure 22 shows the control effect on a time series signal for in-cabin noise produced by impulse input from the road surface when the vehicle crosses seams in the road such as might be encountered, for example, on a freeway. The graph indicates that the new drumming control technology is even able to reduce the drumming component in in-cabin noise produced by impulse input, indicating the realization of adequate performance in tracing changes in engine speed.

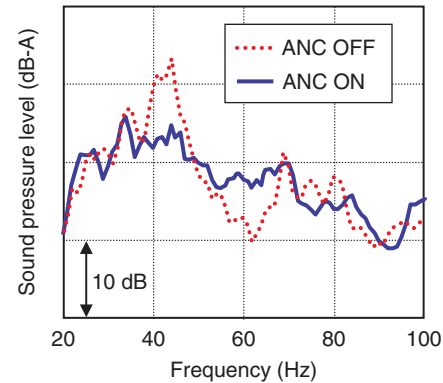


Fig. 21 Drumming reduction effect of developed drumming ANC

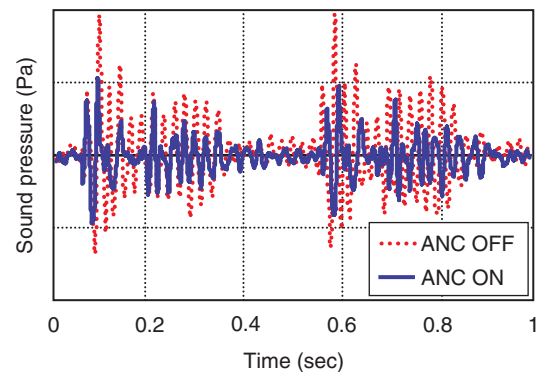


Fig. 22 Noise reduction effect of developed drumming ANC when receiving impulse input from road surface

5.2. Control Effect of Integrated ANC System

Figure 23 shows the control effect in relation to engine booming noise. As in the conventional system, the target order component can be reduced by around 10 dB. Figure 24 shows the control effect when the vehicle is driving on an undulating road surface at a vehicle speed of 50 km/h and an engine speed of 2300 rpm. The graph shows that the newly developed integrated ANC technology is able to simultaneously reduce drumming and engine booming noise, indicating the achievement of the desired functioning.

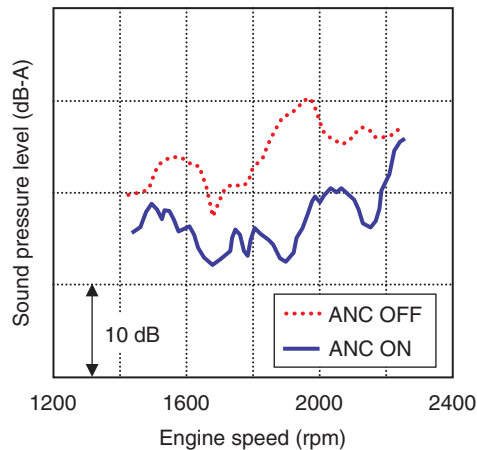


Fig. 23 Engine booming noise reduction effect of developed ANC

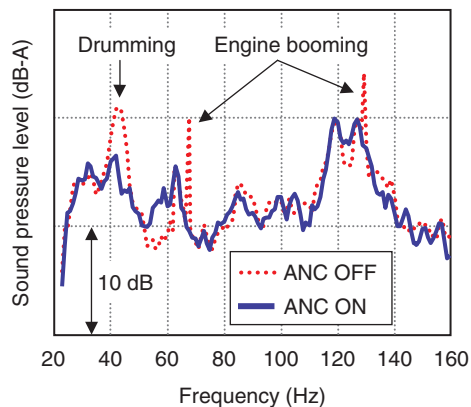


Fig. 24 Low-frequency noise reduction effect of developed integrated ANC

6. Conclusion

Using SAN control, which necessitates minimal calculation operations, a new drumming ANC technology employing digital feedback was developed. The use of a new technology that resolved the issue of interference between control devices in this new drumming ANC technology made it possible to integrate it with the existing engine booming noise control technology employing feed-forward control. By this means, it was possible to create an

ANC system able to simultaneously reduce drumming and engine booming noise. The new integrated ANC system discussed in this paper has been employed in new vehicle models. Because the system reduces low-frequency noise by emitting a canceling sound into the vehicle cabin rather than employing existing passive measures, it significantly boosts noise performance without increasing vehicle weight, and balances fuel efficiency with noise and vibration performance.

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