

Active Control System for Low Frequency Road Noise Combined with an Audio System

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ABSTRACT

An active control system for low frequency road noise in automobiles combined with an audio system was developed as a commercial application for the first time in the world. The system was installed in a station wagon. The purpose of this paper is to provide an outline of the system and describe the newly developed cost reduction technology used therein. A major factor in the successful application of active noise control technology to a commercial product is reduced system cost. The methods used to reduce costs include utilization of feedback control, implementation by analogue circuits, and common use of audio system speakers. This system reduces low frequency road noise in the front seat by about 10 dB and improves the audio system listening experience while driving.

1. Introduction

Recent years have brought increased emphasis on vehicle weight reduction in order to achieve further fuel economy in automobiles. However, countermeasures for reducing noise in automobiles result in an increase in weight. Active noise control (ANC) technology reduces noise by adding anti-phase noise to potentially solve these contradictory issues. Significant research in ANC application to automobiles has been taking place. However, ANC has not achieved widespread application because of its unfavorable cost performance^{(1), (2)}.

In order to improve cost performance, we concentrated on the cost of the ANC system. As a result, an active control system for low frequency interior road noise (drumming) combined with an audio system was developed and installed in a mass-production station wagon. Although it is limited to the lower frequency ranges, this is the world's first ANC system for road noise and the first combined ANC and car audio system.

The specific methods used to reduce the cost include utilization of feedback control (FB), implementation of analogue circuits, and the common use of car audio speakers. This paper briefly surveys the history of ANC technology, provides an overview of the mass-production system and discusses the newly developed ANC.

2. ANC Technology in Automobiles: A Brief History and Methods for Solving Practical Application Issues

This section briefly reviews the history of ANC technology in automobiles from the perspective of research and development (R&D) and control methods. It also discusses approaches to the solution of issues for practical application of this technology.

2.1. The State of R&D on ANC

ANC R&D became active from the 1980s, in conjunction with the rapid development of hardware such as digital signal processors (DSP). Active R&D on automotive applications for ANC began in the latter half of the 1980s⁽³⁾.

Examples of this technology applied to periodic noise include applications for engine booming noises in the cabin⁽⁴⁾, ⁽⁵⁾, mufflers, and intake ducts⁽⁶⁾, ⁽⁷⁾. A paper on practical applications for engine booming noise in the cabin has already been published⁽⁸⁾. Although not related to automobiles, there is an example of practical application of ANC for periodic noise in Shinkansen train cars. Here, an ANC system reduces noise near passenger ears⁽⁹⁾.

A typical example of random noise is generated inside automobiles by input from the road surface while the vehicle is moving. There has been active research on road noise⁽¹⁰⁾⁻

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⁽¹²⁾, but due to unfavorable cost performance, many issues related to practical application still remain.

2.2. Control Methods

The control method mainly used in the ANC field is adaptive feedforward (FF) control. This method is characterized by the use of an error signal for adaptive signal processing and a reference signal for feedforward control. FF control is extremely effective with ANC for engine induced booming noise. Here, the ignition pulse can be used as a reference signal. However, road noise is caused by a variety of input sources. This results in a large number of reference signals. Thus, the high cost of sensors and controllers capable of handling the enormous amount of adaptive signal processing become an issue. In addition, the question of where to place the numerous reference signal sensors is also an issue.

On the other hand, FB control is also available as a control method. However, in ANC applications, the use of FB control has been limited to headphones, where the speakers and microphones are very close together, and to duct ANC utilizing the tight coupled monopole (TCM) method⁽¹³⁾. The controllers used in these applications are only very rarely designed from a control engineering perspective, and the lack of knowledge about just how these controllers are designed can present issues. In this paper, designing a controller from a control engineering perspective means modeling the control object using various control theories (classic control theory, modern control theory, and post-modern control theory as represented typically by robust control theory) and designing a controller using the model obtained.

The only reported research⁽¹³⁾ on FB-ANC in automobiles appears to be on the use of adaptive signal processing for wind throb noise, which can be heard, for example, when the sunroof is open. There are no previous examples of ANC application to a three-dimensional closed sound field such as an automobile interior using controllers designed using control engineering methods. The status of practical application of ANC technology is summarized in Table 1.

Table 1 Examples of practical use of ANC

Acoustic condition	Feedforward control	Feedback control
1-dimension	• Headphone • Duct of air-conditioner • Refrigerator	Headphone
3-dimension in closed space	• Engine booming noise in a car • Motor booming noise in a train	Nothing

2.3. Approaches to Solving Issues in Practical Application

One of the factors that determine the value of a technology is cost performance. In other words, practical application of ANC can be achieved either by reducing cost or by significantly improving performance. Since the strength of ANC lies in its noise reduction capabilities below about 500 Hz, the use of ANC to achieve quietness that extends to higher frequency ranges would be very problematic. Even if this were achieved, the cost would be unrealistic. Therefore, the authors have directed their efforts toward cost reduction.

First, the research is focused on control of drumming, the low frequency component of road noise. The use of passive techniques to reduce drumming entails vibration control by such means as reinforcement of the car body frame⁽¹⁵⁾. This involves increasing weight. The development objective is, therefore, to use ANC technology to realize cost and weight constraints on par with passive countermeasures. The next section will present an overview of the system and the specific methods used to reduce costs.

3. Overview of Mass-Production System and Cost-Reduction Methods

3.1. System Overview

The acoustic first-order mode shown in Fig.1, and is calculated by eigen value analysis. It shows that a drumming noise tends to be generated at around 40 Hz in the front seat of a station wagon. This is due to the sound field determined by the cabin configuration. The yellow and red portions in the figure show the loop while the green and blue portions show the node.

The drumming noise of around 40 Hz heard in the front seat is the noise to be controlled. Development was initially directed toward cost reduction of the adaptive FF control. However, even with the focus narrowed to drumming, ANC implementation using adaptive FF control required multiple reference signal sensors, error sensors, and a digital controller employing a DSP. Elimination of noise at around 40 Hz further presupposed the use of woofer speakers. The resulting total cost showed that practical application would be difficult because system cost would be much higher than passive countermeasure technology.

This development project utilizes a number of different methods to achieve reduced cost. The control method of the system adopted for mass production is shown in Fig.2. The configuration of the system as installed in a car is shown

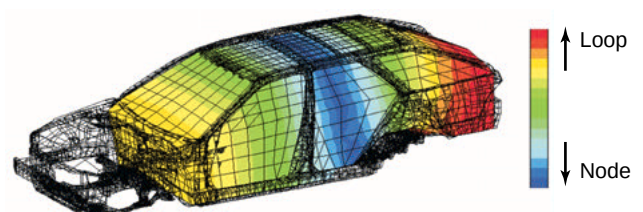


Fig.1 An acoustic mode of a station wagon at 40Hz

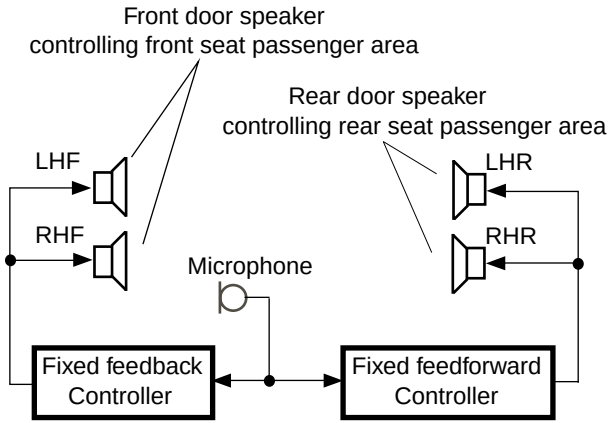


Fig.2 Control strategy in the car

in Fig.3. The control method will be outlined using these figures. Further details of the control technology developed will be provided in section 4.

The electronic control unit (ECU) is placed under the driver's seat. Results of the 40Hz sound field analysis in Fig.1 show that the area from the floor to the roof in the front passenger area is generally in phase. It is clear, therefore, that placing the microphone under the driver's seat would allow reduction of the drumming noise for the front seats. Consequently, the microphone is installed on the ECU circuit board. The fixed FB controller and the front door speakers are then used to reduce drumming in the front seats. Moreover, fixed FF control and the rear door speakers are used to control the resulting amplification in noise in the rear seats. In other words, the microphone installed under the driver's seat is used by FB control as an error microphone (error sensor) and by FF control as a reference signal microphone (reference signal sensor).

The results of sound field analysis also show that there is virtually no phase difference between left and right. Therefore, the FB controller for the front seats simultaneously drives the left and right front door speakers. The FF controller for the rear seats also drives the rear door speakers simultaneously.

The next topic is approaches and methods for cost reduction.

3.2. Approaches and Methods for Cost Reduction

Cost reduction is carried out for the key components for control: sensors, controllers, and actuators (speakers). The cost reduction methods implemented for this system can be summarized as follows:

- (1) Cost reduction methods for sensors and controllers
 - Use of FB control to reduce noise in the front seats and FF control to limit the increase of noise in the rear seats
 - Adoption of fixed control rather than adaptive control
 - Implementation of analogue circuits
 - Use of a microphone as a sensor and mounting this microphone on a circuit board
- (2) Cost reduction methods for speakers
 - Common use of standard car audio system speakers

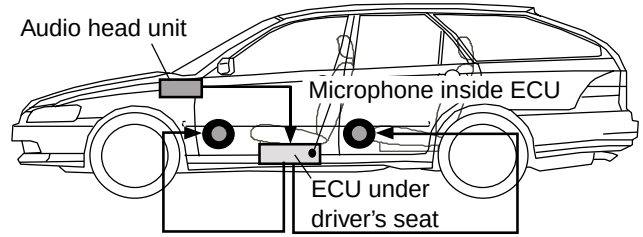


Fig.3 System installation configuration

- Insertion of a limiter circuit to limit output level when sound pressure is excessive

These cost reduction methods are explained below.

3.2.1. Cost Reduction for Sensors and Controllers

We adopted FB control as the front seat control method in order to significantly reduce the number of sensors. FB control allows significant reduction of the number of sensors because it does not require reference signals and only uses an error sensor. Since FB-ANC is a form of sound field control, it uses microphones as error sensors (error detection sensors). Microphones are less expensive than acceleration and force sensors. However, much less research has been performed on FB-ANC than on FF-ANC. There are two reasons for this, as follows:

- (1) The non-collocation of a speaker and a microphone means that the control object (the plant) becomes a non-minimum phase system. This makes it difficult to reduce noise over a broad range of frequencies, and further, it involves an inevitable waterbed effect^{(16), (17)}, whereby sounds at frequencies above the noise reduction range are increased.
- (2) Since a sound field of a three-dimensional closed space such as a car cabin has reverberation, the plant is complex. This increases the difficulty of modeling the plant and designing a controller.

Despite these conditions, research to investigate the possibilities of FB-ANC has been carried out by the authors⁽¹⁸⁾⁻⁽²²⁾ and the Ohki team⁽²³⁾. It was determined that by restricting the control range, the noise amplification range caused by the waterbed effect can also be limited. Thus, FB-ANC proves to be effective and consequently, the authors adopted FB control for reduction of drumming in the front seats⁽²⁴⁾.

Both the FB and FF controllers are implemented using analogue circuits. Currently, analogue circuits still have a significant cost advantage over digital circuits. In addition to this cost advantage, analogue controllers are continuous time controllers so they are not affected by the sampling delay found in digital controllers nor by the delays of anti-aliasing filters, reconstruction filters, and other such analogue circuits. Therefore, analogue controllers have the advantage that FB speed control is extremely fast.

On the other hand, since the voltage of the microphone signal is very low, the wire from the microphone to the ECU must be shielded when the microphone is installed remotely. However, shielded wire is more expensive than ordinary wire. Therefore, in this development, the sound field analysis

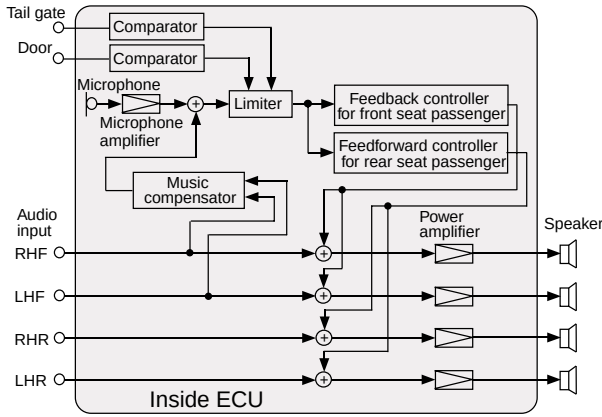


Fig.4 The system configuration in ECU

shown in Fig.1 is performed, demonstrating that placement of a microphone under the driver's seat would allow reduction of drumming in the front seat area. The microphone is mounted on the ECU circuit board under the driver's seat to eliminate the need for a microphone wire, to reduce microphone-related costs, including the cost of wiring, and additionally to improve the controller's robustness with regard to electrical noise.

3.2.2. Cost Reduction for Speakers

Implementing noise reduction at around 40 Hz on all types of road surfaces requires speakers with high-performance woofer characteristics. This is disadvantageous in terms of cost. However, standard car audio system speakers (standard speakers) are now provided with good performance in order to improve audio system quality. Further, these speakers are capable of reproducing sounds in the vicinity of 40 Hz. Noise reduction tests by ANC are conducted with this in mind. The results show that although noise reduction is difficult for standard speakers when driving on surfaces that generate large inputs, such as a Belgian road or a road with large bumps, standard speakers function well on roads that tend to generate a bothersome drumming noise. In this development project, the limiter function described below is introduced to an ANC circuit. This enables the ANC to share standard audio system speakers.

Fig.4 shows the system configuration of the ECU. The limiter circuit is inserted after microphone output. When sound pressure measured by the microphone exceeds a preset specified value, the circuit significantly limits the amplitude of that signal, so that ANC operation is minimal. As a result, when the car is driving over an extremely rough surface, when the audio system volume is high, or when the microphone input is at very high pressure, the limiter circuit both prevents speaker distortion and improves speaker durability.

3.3. Benefits for the Car Audio System

Since this system utilizes FB control, it is necessary to include a music compensation circuit as described next. If this circuit is not included the system will reduce not only

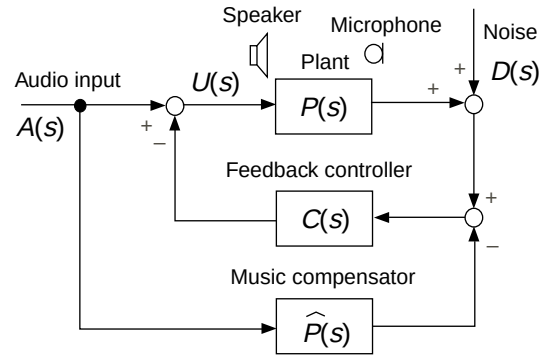


Fig.5 A music compensator

the noise at around 40 Hz but also the components of music in that frequency range as well. To prevent this from occurring, the music compensator shown in Figs.4 and 5 is added. This circuit identifies the transfer characteristics of the acoustic transfer system between the speakers and the microphone in advance. It then subtracts the music component generated by the audio head unit from the microphone output signal. In this way, the system operates without canceling out the music. The basic principle is feedforward control in order not to erase the music signal. This is equivalent to the internal model control (IMC)⁽²⁵⁾ in control engineering and the echo canceller in telecommunications⁽²⁶⁾.

In Fig.5, $P(s)$ is the plant. It represents the transfer function of the acoustic path between the front door speakers and the microphone. The $\hat{P}(s)$ estimating transfer function of $P(s)$ is now sought. If $P(s) = \hat{P}(s)$, then

$$U(s) = A(s) - \frac{C(s)}{1 + P(s)C(s)} D(s) \quad (1)$$

It is apparent that the audio signal $A(s)$ is not influenced by the controller characteristic $C(s)$.

The music compensator and ANC effect generate the following benefits for the car audio system:

- Clarity of bass sounds
- Improved music listening quality provided by the masking effect

These benefits add value for the user as well as reducing drumming noise.

3.4. Replacing the Audio Head Unit

A number of different audio head units are offered as options for vehicles that apply this system. Therefore, the ANC system must be able to operate with any of these units. A power amplifier is consequently added in the ECU, as shown in Fig.4, in order to make it possible for the user to exchange audio head units. Unfortunately, this feature leads to increased ANC costs. Cost reduction can be sought in vehicles that are not likely to have the audio system exchanged, such as high-end cars, by sharing the internal power amplifier in the audio head unit.

3.5. Howling Prevention

The use of FB control means that howling can occur when the control system becomes unstable. Major factors influencing stability are the plant transfer characteristics. Here, since the plant is the transfer characteristics from the speakers to the microphone, the plant transfer characteristics are most severely affected when the doors and tailgate are open. This system has sufficient enough stability that howling will not occur even when a door or tailgate is open. In order to avoid any risk, however, the limiter shown in Fig.4 operates when a door or tailgate is open.

4. New ANC Technology

This section describes the ANC technology developed for the drumming reduction system. This includes the adaptive FF control system that was examined during the initial development effort, the fixed FB control system, the fixed FF control system that was designed to control noise amplification in the rear seat, the ANC performance in the actual vehicle and an observation of FB control.

4.1. Adaptive FF Control System

During initial development, the system was constructed with adaptive FF control. The algorithm used for adaptive signal processing is the filtered-reference LMS algorithm⁽³⁾,⁽⁹⁾ commonly used for FF-ANC. The developed system is characterized by the use of a microphone rather than an accelerometer as the reference signal sensor. Conventional ANC for road noise using adaptive FF control uses an accelerometer that detects vibration acceleration in the suspension or body. This is used as the reference signal sensor⁽⁶⁾,⁽¹⁰⁾⁻⁽¹²⁾. However, the use of an accelerometer involves the following issues:

- (1) Accelerometers are extremely expensive compared to microphones.
- (2) Installing accelerometers in the suspension is more expensive than installing them in the cabin as the environment in the suspension is more severe than that of a cabin.

In order to resolve these issues, a method was devised to install a microphone inside the cabin and use it as the reference signal sensor. However, using a microphone as the reference signal sensor may cause howling. This is because the canceling sound from the speakers detected by the reference microphone generates acoustic FB. The developed system prevents this by adopting a howling canceller (based on the same principle as the IMC described above).

The application of a microphone as the reference signal sensor allows a major cost reduction over the use of an accelerometer. However, this system requires the use of a digital controller employing DSP in order to handle multiple microphones and adaptive signal processing. This makes the cost still much higher than passive technology. Therefore, unfortunately, it has not been matured for use in mass-produced vehicles.

Still, this method enables good control even when the reference signal microphone and the error microphone are close together. This result provides a powerful impetus to

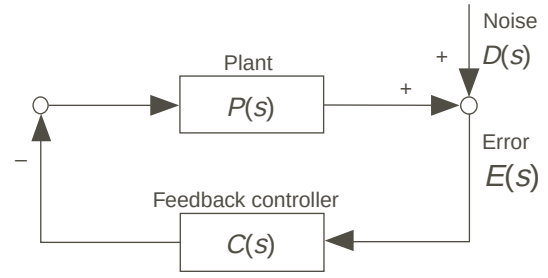


Fig.6 Block diagram of feedback ANC

accelerate development of the FB control system, described in the following subsection.

4.2. Fixed FB Control System

In regard to FB control within the field of ANC, there is little precedent for designing controllers based on control engineering methodology. Therefore, the authors have sought to design control systems on the basis of modeling. This subsection describes the method used to model the plant, and the method used to design a controller based on the model thus obtained.

4.2.1. Design Specifications for the Control System

Fig.6 shows a block diagram of the FB-ANC. It is apparent, from the perspective of control engineering, that FB-ANC is equivalent to disturbance rejection control. Seen in this way, it is a simple matter to apply various theories systematized by control engineering.

The first and most important point for the control specifications is to stabilize the closed loop system. In other words, it is necessary to assure control performance with the condition that feedback will not cause howling.

Next, the performance specifications are described as follows: The aim of control is for the FB controller $C(s)$ to reduce the disturbance, noise $D(s)$, added to the output of the plant $P(s)$ (here, the input to the microphone). The transfer function $S(s)$ from $D(s)$ to error $E(s)$ shown in Fig.6 is called the sensitivity function, and it is expressed as

$$S(s) = \frac{1}{1 + P(s)C(s)} \quad (2)$$

Consequently, it will be possible to reduce noise if $|S(j\omega)|$ can be kept lower than 1. If a model of $P(s)$ is obtained, then $S(s)$ can be derived as soon as $C(s)$ has been designed. Therefore, it is possible to predict noise reduction performance in advance of implementation.

Based on the above, the FB-ANC design specifications are summarized as follows:

- (1) Stabilization of the closed-loop system
- (2) Reduction of the sensitivity function for the frequency range of the noise to be controlled

4.2.2. Fixed FB Control Design Based on Classic Control Theory

The point of this method is that the controller is designed so that the gain of the open-loop transfer function

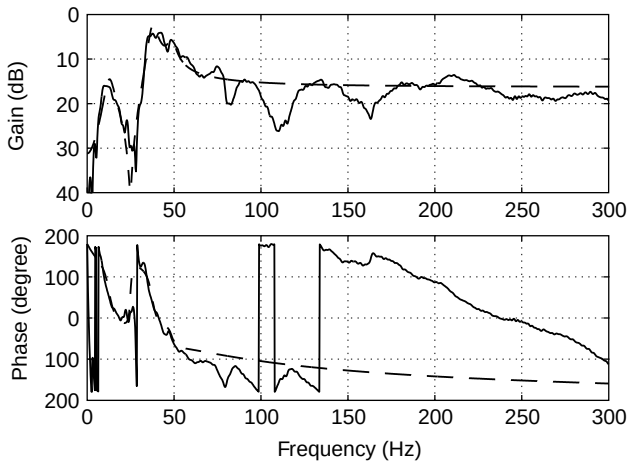


Fig.7 An identified frequency response function of the plant (solid line) and a reduced order model of the plant (dashed line)

$L(j\omega) = P(j\omega)C(j\omega)$ for the frequency range of the sounds targeted for control is set to be greater than 1 and the phase is set at zero. This approach is similar to the design method for loop shaping using a Bode plot in classic control theory. For example, when $|L(j\omega_1)| = 1$ and $\angle L(j\omega_1) = 0^\circ$ in the frequency ω_1 to be controlled, then the sensitivity function becomes

$$|S(j\omega_1)| = \left| \frac{1}{1 + L(j\omega_1)} \right| = \frac{1}{2} . \quad (3)$$

This means a potential 6 dB reduction of noise.

As preparation for application of this design method, the frequency response function (FRF)⁽²⁷⁾, which is the non-parametric model of the plant, is obtained by using a sine sweep signal. The Bode plot is shown in Fig.7.

The reason a sine sweep signal is used is to assure a signal-to-noise ratio that accounts for the low-frequency characteristics of the speakers.

Next, the open loop transfer function is shaped by adjusting the controller parameters so that the gain in the frequency range of the targeted noise is greater than one and the phase difference is zero, while the gain rolls off in the high frequency range. Although this design method involves some trial and error in setting the parameters, it is effective for the control of narrow band noise such as drumming. In addition, since a low order controller can be designed by this method, the method is not only advantageous in terms of cost, but further it has the significant advantage of allowing easy on-site adjustment when implemented by an analogue circuit.

The noise reduction performance will be discussed in subsection 4.4.

By comparing this design method and the results thereby obtained with the H_∞ control method and the results thus obtained as described in the next subsection, it is clear that this method is superior. Therefore, this design method was selected for mass-production application.

4.2.3. Fixed FB Controller Design by H_∞ Control

The advantages of using H_∞ control⁽²⁸⁾ for FB-ANC are that noise reduction performance is defined in the frequency domain by the sensitivity function and the robustness to uncertainty of the plant can be taken into account.

It is necessary first to obtain a parametric model of the plant. Obtaining a low order model not only makes controller design easier, but it also contributes to the designing of a reduced order controller, which is also important in terms of cost reduction. The FRF obtained in the previous subsection is used to model the plant using the following procedure:

- (1) Calculating a parametric model using an FRF whose frequency characteristic is close to the FRF in the frequency range targeted for control⁽²⁹⁾.
- (2) Consider the parametric model obtained in (1) to be the nominal plant $P(s)$ for the purpose of designing a controller, and utilize the difference between the gain of the original FRF in (1) and that of the nominal plant FRF as the plant uncertainty.

The method in (1) is a method known for calculating the transfer function from the FRF by the least square method. A low order parametric model is obtained using this method, and the FRF in the obtained parametric model is shown in Fig.7. It is apparent from this figure that the frequency characteristics of the nominal plant is close to that of the plant in the frequency range targeted for control.

The design specifications for FB-ANC with respect to nominal performance is expressed as

$$\|W_s(s)S(s)\|_\infty < 1 , \quad (4)$$

where $W_s(s)$ is the weighting function of control performance. The robust stability condition for the plant uncertainty is expressed by

$$\|W_T(s)T(s)\|_\infty < 1 , \quad (5)$$

where $W_T(s)$ is the weighting function covering plant uncertainty, and $T(s)$ is the complementary sensitivity function expressed by

$$T(s) = \frac{P(s)C(s)}{1 + P(s)C(s)} . \quad (6)$$

Then, $C(s)$ is calculated by solving the mixed sensitivity problem^{(28), (31)}.

Fig.8 shows $1/W_s(s)$. As shown, the weighting function is defined to reduce noise only in the 40 Hz region. The $S(s)$ calculated using the $C(s)$ is also shown in Fig.8. Based on these results, it is predicted that noise around 40 Hz is reduced by about 10 dB. This has been confirmed by results obtained from implementation in an actual digital circuit, which had roughly equivalent performance. However, the controller is of a high order and on-site adjustment is difficult when the controller is implemented by an analogue circuit.

Also, the weighting function setting still involves trial and error in H_∞ control. However, methods for obtaining a low order controller have been developed⁽³²⁾, and if it becomes possible to implement these in digital circuits at a low cost, then it can be expected to simplify on-site adjustment. Therefore, this avenue will continue to be explored in the future.

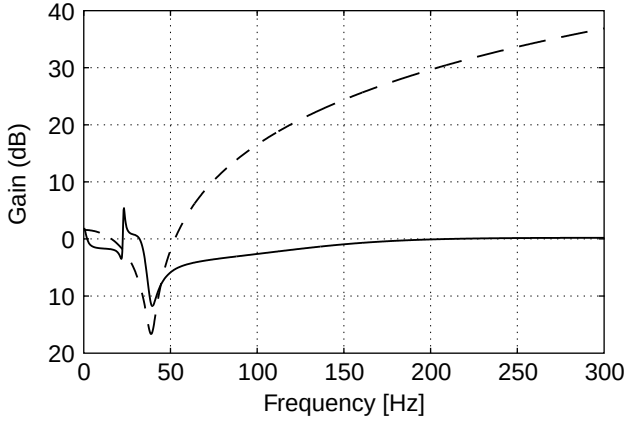


Fig.8 Sensitivity function (solid line) and $1/W_s(z)$ (dashed line)

4.3. Design of the Fixed FF Control System

The method used to design the fixed FB controllers discussed in subsections 4.2 and 4.3 has the problem that when the drumming at about 40 Hz is reduced in the front seats, the noise at the same frequency in the rear seat area is amplified by about 3 dB. This problem must be solved.

The method devised here is to use the output from the microphone utilized in FB control as a reference signal to suppress the amplified noise in the rear seat by FF control. As shown in Fig.9, error microphones are placed in the center of both the front and rear seats while FB control is applied to the front seat. Adaptive FF control is then used to suppress the amplification in the rear seat so that it would not adversely influence the front seats. This adaptive FF control is carried out using digital control. In Fig.9, $Q_1(z)$ and $Q_2(z)$ are the pulse transfer functions from the rear door speakers to the rear seat error microphone and from the rear door speakers to the front seat error microphone, respectively. $\hat{Q}_1(z)$ and $\hat{Q}_2(z)$ express the related estimated pulse transfer functions. The filtered-reference LMS algorithm is used as the adaptive signal processing algorithm. The value defined by the adaptive controller is then used as a fixed FF controller. This makes it unnecessary to use microphones in the rear seats for error sensors in adaptive FF control.

The discrete time controller (digital filter) obtained using adaptive FF control has the characteristics of a 40Hz bandpass filter. Therefore, an analogue filter with very close characteristics to the digital filter was designed and implemented.

It is conceivable that FB control could also be used here to suppress the amplification that occurs in the rear seat. However, it is difficult to design a multiple input multiple output (MIMO) controller. On the other hand, it is extremely simple to apply adaptive FF control to an MIMO system, and the issue of noise amplification in the rear seat is solved using the method described above.

4.4. Noise Reduction in an Actual Vehicle

The controllers derived as described above for use in front seat noise reduction and rear seat noise suppression

- Dashed line parts are only used in development stage.
- The filtered-reference LMS algorithm is utilized.
- After the adaptation, a feedforward controller is fixed.

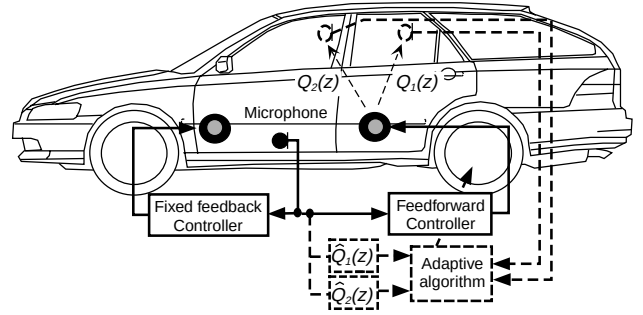


Fig.9 Rear seat control for suppressing amplification

are implemented in analogue circuits. Figs.10 and 11 show the drumming noise reduction performance achieved in the front and rear seats in a car driven at 50 km/h over a rough road surface. These figures show that drumming in the front seat is reduced about 10 dB, and the amplification of noise in the rear seat is suppressed to the level it is at before noise control is used.

4.5. Observations of FB Control

It used to be thought that ANC utilizing FB control was difficult to achieve when the distances between the speakers and the microphones were increased. It is natural to expect FB control to become difficult in terms of stability when there is a phase lag in the transfer function due to a distance delay. However, the present FB-ANC system achieved its success due to consideration given to the following three points:

- (1) Since the speaker has the characteristics of a high pass filter, the phase leads at frequencies below the resonance frequency of the speaker.
- (2) When the noise is at about 40 Hz, the phase lag will be slight, reaching only about 42° , even when there is a distance delay equivalent to 1 m.
- (3) The range of frequencies to be controlled is limited.

Point (1) is realized when physical modeling of the plant is performed^{(20), (21)}. As shown in Fig.7, phase lag in the plant is small because of (1) and (2) even when there is a distance delay. The small size of the phase lag is advantageous for controller design.

Another consideration is that not only does the persistent attempt to broaden the range of frequencies to as great a degree as possible make controller design difficult, it also results in amplification due to the waterbed effect in the same area as noise reduction. On the other hand, the noise in a narrow range of frequencies caused by resonance frequently becomes a concern in actual vehicle development. Therefore, it was decided to limit control to the phenomena within a narrow range of frequencies, as in point (3). Not only does this simplify controller design, but it also makes it possible to keep the range of frequencies amplified by the waterbed effect to a minimum.

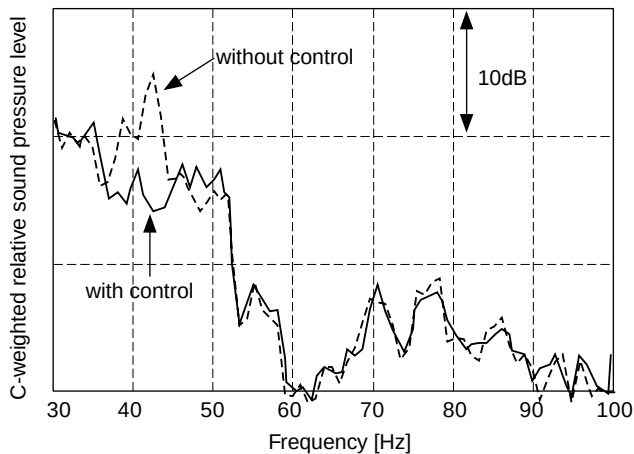


Fig.10 Sound pressure level at front passenger

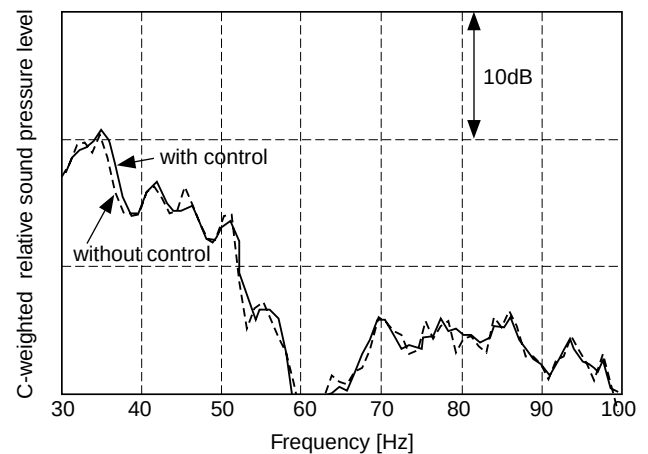


Fig.11 Sound pressure level at rear passenger

5. Conclusions

A product was developed that combines an ANC system that reduces drumming and a car audio system. This product was installed on a mass production model station wagon. This is the world's first ANC system targeting low frequency road noise and the world's first combined car audio and ANC system. Mass production is made possible by cost reduction. The technologies developed with the goal of cost reduction are summarized as follows:

- (1) FB-ANC for the closed sound field within the space of a car cabin
- (2) Implementation by analogue circuits
- (3) Achieving shared use with car audio system speakers by introducing a limiter circuit to prevent speaker distortion
- (4) Music compensator to prevent the canceling out of music
- (5) Fixed FB controllers designed from a control engineering perspective and fixed FF controllers using adaptive FF control

This development project, carried out in the digital age, leads to a renewed recognition of the positive qualities of analogue circuits. The authors intend to conduct a constant comparison of analogue and digital systems as they proceed into the next development project.

In conclusion, a review of the past decade or so of ANC technology development shows that ANC has been largely misunderstood to be a technology that provides revolutionary noise reduction methods to cancel all kinds of noises. Therefore, the system cost is high for the noise reduction obtained by ANC. This seems likely to prevent the automobile industry from pursuing this technology into the active application stage for many years. However, when we consider that it will be necessary to further reduce vehicle weight in the future, it appears that the importance of ANC as a noise control technology will continue to increase. It is hoped that this effort in practical application will serve to stimulate further work on the commercial applications of ANC not only in the automobile industry but also in other fields involved in acoustic engineering.

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