Feedback Control of an Active Sound Insulation Unit*

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This paper describes designs of structures and control systems of an active sound insulation unit consisting of active cells which are individually controlled as a single input single output system. Two types of Active Sound Insulation Cell (ASIC) using lightweight card-type speakers were manufactured for trial. It became clear that ASIC can reduce the transmitted noise whose sound field inside the cell is uniform. That means that the size of ASIC should be less than quarter wavelength of controlled sound and secondary noise sources should be properly arranged. The feedback control system for ANC was systematically designed by H-infinity control theory, and the sound attenuating performance was verified by the simulation.

Key Words: Measurement and Control, Active Wave Control, Acoustic, Active Noise Control, Feedback Control, Sound Insulation, H-Infinity Control

1. Introduction

Active noise control of large space needs a multiple channel control system. And it is supposed to be too difficult to be applied to the real space because of its complexity and expensive cost. Then it is considered to be more realistic to control acoustic boundary by setting simple and individually controlled acoustic units side by side at the boundary. For example, Active Acoustic Treatment (AAT) was proposed for absorbing sound at walls and Active Soft Edge (ASE) was developed for attenuating sound refraction at noise barriers by the authors^{(1)–(3)}.

On the other hand, light and high performance sound insulation wall is needed especially for vehicle body. And some active noise control system is expected to be effective for increasing sound transmission loss of panel at low frequency region without adding mass. Several researches were already reported, and effective results were obtained^{(4)–(7)}. But these were not aimed to be light and simple. Recently, researches of the active insulation system using the lightweight actuator are also advanced⁽⁸⁾.

The purpose of this research is to develop distributed control system which consists of many individually controlled light units for increasing sound insulation of panel.

In this paper, two types of unit which is called Active Sound Insulation Cell (ASIC) were proposed and manufactured for trial. They used light card-type speakers. And their performances of sound insulation were evaluated by simple experiments using a reverberation chamber. It became clear that ASIC can reduce the transmitted noise whose sound field inside the cell is uniform. That means the size of ASIC should be less than quarter wavelength of controlled sound. The sound attenuation control experiment using Filtered-x-LMS algorithm was conducted to ASIC, and the about 10 dB sound attenuation effect was acquired by the frequency band 400 Hz or less.

However, a reference signal cannot be acquired when a cell is actually used. The controller needed to be made into the feedback system only using an error signal. The feedback controller for ANC was systematically designed by H-infinity control theory, and the stable sound attenuating performance of about 4 dB of maximum was obtained below 500 Hz by the simulation.

2. Basic Concept of Active Sound Insulation Unit

Schematic drawing of the typical examples of active sound insulation systems using ASIC is shown in Fig. 1. These examples have double walls whose inner space is divided to many cells. Uniform sound field exists in each cell below the target frequency, and sound pressure level is actively controlled to zero. There exist light card-type speakers, an error microphone and a controller inside the cell. Speakers are controlled to minimize the output of the error microphone, according to incident sound. Each cell is simply controlled individually as a single input single output system. Feedback control is generally adopted

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because the information of incident sound cannot be obtained. Technical issues to realize these kinds of ASIC are as follows:

- (1) Make clear the relation between controllable frequency and cell size.
- (2) Optimize the position of speakers and an error microphone.
- (3) Optimize the controller.
- (4) Reduce cross-talk between neighboring cells.
- (5) Reduce solid-borne noise.
- (6) Optimize the material of cells.

In this paper, the first three items were studied.

3. Manufactured ASIC and Test Procedure

3.1 Outlines of manufactured ASIC

Two types of ASIC were manufactured and tested for trial. Both types of ASIC used card-type speakers because of reducing weight. One is Type-A in which card-type speakers are set along a side wall parallel to the sound path as shown in Fig. 1. The other is Type-B in which card-type

Fig. 1 Two types of active sound insulation unit

Fig. 2 Active sound insulation cell (Type-A)

speakers are set perpendicular to the sound path as shown in Fig. 1.

The size of a manufactured ASIC is 240 mm square and the air-space between double walls is 70 mm. The frames are made of wood whose thickness is 5 mm. Double walls are made of aluminum plate whose thickness is 0.5 mm. Light card-type speakers (Panasonic WM-R57A) are used as the secondary source. Type-A uses 4 speakers set with 15 mm back space and actuated by same signal, which is shown in Fig. 2. And 9 minute microphones are set in the cell to measure the sound field in the cell as shown in Fig. 2. One of them is used as an error microphone. In Type-B, 16 speakers are set and actuated by same signal as shown in Fig. 3.

3.2 Test apparatus

Test apparatus is shown in Fig. 4. In order to realize random sound incident condition, a reverberation chamber was constructed which was 800 mm wide and 1135 mm high. A manufactured ASIC was attached to the chamber window. A speaker set in the chamber was used as a primary source. And a set of card-type speakers in the ASIC was actuated as a secondary source. Monitoring microphones were set at 50 mm and 500 mm apart from the ASIC (m_1 and m_2) to evaluate the sound attenuating performance.

3.3 Acoustic characteristics of active cell

Based on our concept, ASIC should be controlled as a single input single output system. That means that the sound field inside an ASIC should be uniform (same gain and same phase). Then transfer functions between every two microphones' outputs inside the cell were measured in both cases of the primary source excitation and the secondary source excitation.

3.4 Prediction of sound attenuating performance

Sound attenuating performance of ASIC was predicted at the monitoring positions m_1 and m_2 based on

Fig. 5 Transfer functions from e_9 to e_i (at primary source excitation: Type-A)

Fig. 6 Transfer functions from e_9 to e_i (at secondary source excitation: Type-A)

4.2 Sound attenuating performance prediction

Sound attenuating performance was predicted according to the above method. Sound power spectra at m_1 with and without control are shown in Fig. 7. Peak spectra from 170 Hz to 200 Hz and around 370 Hz are attenuated by the active control. But other spectra cannot be reduced. The result clearly shows that the sound attenuating performance was acquired in the frequency band whose inside of the cell is uniform sound field. It was confirmed to be necessary to generate uniform sound field inside the cell by the secondary source.

5. Test Results of Type-B

5.1 Sound field in the cell

In order to study how we can realize uniform sound field inside the cell by the secondary source, Type-B ASIC

Fig. 7 Sound attenuating performance of the active control (simulation: Type-A)

Fig. 8 Transfer functions from e_1 to e_i (at secondary source excitation: Type-B)

was tried to be manufactured and tested. In this case a speaker plate constructed by 16 card type speakers was set in the cell perpendicularly to the sound path. Figure 8 shows transfer functions between microphones' outputs in the cell when the secondary source is operating.

5.2 Sound attenuating performance prediction and experiment

Figure 9 shows the predicted sound attenuating performance of the Type-B ASIC. It is found that sound attenuating frequency region become wider than Type-A.

Then, the sound attenuating control experiments are performed to the cell of Type-B using the Filtered-x-LMS control system. The experimental setup shown in Fig. 10 is controlled by Filtered-x-LMS algorithm which used the noise generator signal r and the error microphone signal e_5 . The Sampling frequency is 2 kHz and the tap length is 512. Figure 9 shows the experimental results when setting a monitor point to m_1 . Notice is about 10 dB sound attenuating performance below 400 Hz, and the control result as prediction. However, the frequency band without sound attenuation exists. As the reason, it is possible that the

Fig. 9 Sound attenuating performance of the active control (Type-B)

Fig. 10 Experimental setup for ANC

tap length of a FIR filter cannot express the acoustic characteristics of the reverberation chamber. In the following paragraph, Type-B is used.

6. Feedback Controller Design for ASIC

6.1 Structure

In feedback control, only an error microphone is referred. Figure 11 is the block diagram of the feedback control system. Where P is a plant and C is a controller. Signal d is incident sound and e is an error. Signal r is desired sound attenuation and is set to 0. The controller has forced to control the point of the error microphone using the signal detected with the error microphone. Therefore, even when any incidence sound is input, the feedback system must attenuate sound without diverging.

6.2 Controller design via tandem compensators

The design of Controller C was realized by connecting plural phase compensators in series to plant P. Controller C designed is set to C_1 . The notes by the design of the open-loop transfer function are as follows:

- (1) The gain margin for stability must exist.

Fig. 11 Block diagram of the feedback control system

Fig. 12 Plant P, controller C_1 and open-loop transfer function PC_1

Fig. 13 Simulation results by open-loop method

- (2) In the frequency band of sound attenuation, the gain is above 0 dB.

- (3) On a high frequency side, fully drop the gain.

Figure 12 is bode diagrams of a plant P, a designed controller C_1 and the open-loop transfer function PC_1 . The result of the sound attenuating simulation using this controller C_1 is Fig. 13. The transfer function from the noise signal d to the error signal e is shown in that figure. The primary sound source d was made from the white noise which passed the 100 to 500 Hz band path filter. Since the gain is above 0 dB between 150 Hz and 550 Hz, sound attenuating performance is realizable.

6.3 Controller design via H-infinity control theory

The controller C_1 is designed for the only plant P. However, the actual plant P is changed by temperature change or a manufacture error of a cell. Perturbation of the plant may make a closed-loop system unstable, then it may diverge. For practical use, the controller must guarantee stability also to such perturbation of the plant. On the other hand, we want to design a controller from the specification of the desired sound attenuation. Then, we applied H-infinity control theory.

Fig. 14 Block diagram for H-infinity control

Fig. 15 Multiplicative uncertainty and weighting function W_1

The specification of a sound attenuation and a stability margin can be given as maximum of H-infinity norms of the closed-loop system. And the controller which fulfills those conditions is systematically found by H-infinity control theory. Figure 14 is the block diagram for H-infinity control. P is a nominal plant and Δ is uncertainty expressed with $\|\Delta\|_\infty \leq 1$.

Two weighting functions W_1 and W_2 are determining the maximum of multiplicative perturbation and specifying sound attenuation respectively. And C_2 is a found controller. The closed-loop transfer functions T and S are defined as follows:

$$T = \frac{PC_2}{1 + PC_2} \quad (7)$$

$$S = \frac{1}{1 + PC_2} = 1 - T \quad (8)$$

The design conditions of a controller are guaranteeing robust stability in case a plant has uncertainty, and that the error signal e becomes smaller than the signal d of a primary sound source, and are expressed with inequality (9) and (10), respectively:

$$\|W_1 T\|_\infty < 1 \quad (9)$$

$$\|W_2 S\|_\infty < 1 \quad (10)$$

The weighting functions W_1 and W_2 are decided as follows, respectively.

First, the plant containing multiplicative uncertainty is expressed with:

$$\tilde{P} = (1 + \Delta W_1)P \quad (11)$$

The supremum of the uncertainty is limited by inequality (12).

$$\left| \frac{\tilde{P}(j\omega)}{P(j\omega)} - 1 \right| < W_1(j\omega), \quad \forall \omega \quad (12)$$

Deciding W_1 means deciding the supremum of the closed-loop transfer function T . W_1 is decided as shown in Fig. 15.

Fig. 16 Weighting functions W_1 and W_2 and closed-loop transfer functions S and T

Fig. 17 Experimental results by H-infinity control

Next, W_2 is selected to attenuate sound between 30 Hz and 80 Hz as shown in Fig. 16. Taking care is that inequality (8) and (10) conditions exist. The controller C_2 is found above those conditions using MATLAB.

Shown in Fig. 16 are bode diagrams of the closed-loop transfer functions S and T . Notice that S and T become as specified mostly. Then the simulation using the controller C_2 were conducted in 10 kHz of sampling frequency. The simulation result shown in Fig. 17 has the sound attenuating performance of about 4 dB of maximum in frequency band below 100 Hz.

7. Conclusions

An active sound insulation system which has distributed and individually controlled Active Sound Insulation Cells (ASIC) was studied. The secondary source in ASIC was constructed by card-type speakers for weight consumption. Obtained results are as follows:

(1) Uniform sound field in the cell are roughly obtained below the frequency whose wavelength is 4 times of the cell dimension when primary source is operating.

(2) It was proved that the transmitted sound was attenuated at the above frequency region if uniform sound field was constructed by the secondary source.

(3) Type-B has better sound attenuating performance than Type-A. However, some better arrangement of the secondary source needs to be developed.

(4) The ANC experiment result by Filtered-x-LMS algorithm shows that about 10 dB of the sound attenuation performing was obtained below 400 Hz.

(5) The feedback controller for ANC was systematically designed by H-infinity control theory, and the stable sound attenuating performance of about 4 dB of maximum was obtained below 100 Hz by the simulation.

The future works are creation of a more uniform sound field, improvement of the design technique of the weighting functions for enlarging sound attenuating performance more, and development of the hardware in which sound attenuation can be realized in a larger frequency band.

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