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ACTIVE NOISE CONTROL OF ONE-DIMENSIONAL DUCT USING H∞ CONTROL THEORY

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1. INTRODUCTION

The feedforward control method which uses a adaptive filter theory has attracted a great deal of attention recently for active noise control (1). However, a reference signal is required continuously. In many cases it is impossible to obtain a reference signal because the temperature of motor vehicle exhaust duct systems is very high, making is difficult to attach a microphone.
This has created the need to investigate the effectiveness of a feedback control method that does not require a reference signal. Such research has also recently attracted substantial attention (2)-(8).
A previous report (5)(6) investigated a one-dimensional duct system feedback active noise control that does not use a reference signal by using a loop frequency shaping generated by a phase lead/lag compensator using classic control theories, as well as trial and error. Consideration was given to the dynamic characteristics of speakers and microphones. The noise level was reduced by 7dB during the simulations and experiments for 5 resonance modes between the third and seventh resonance modes of the duct noise system. This confirmed the basic effectiveness of active noise control over a wide frequency range using feedback control (5). However, the design of the loop frequency shaping generated by a phase lead/lag compensator and the accompanying trial and error is complex.
Accordingly, the present research attempts to realize active noise control while maintaining control performance stability, even when the model has uncertainty or the noise object parameters fluctuate. This is accomplished by using the method described above to improve nominal performance. The loop frequency shaping is incorporated into the model-based active noise control using the H_∞ control theory as a robust control theory. In particular, the present report verifies the improved nominal performance using the H_∞ control theory(7). Finally, we propose two degree of freedom a active noise ccontrol with model matching(8).

2. FEEDBACK NOISE CONTROL DESIGN AND SIMULATION USING H_∞ CONTROL THEORY(7)

One-Dimensional Duct System and Secondary Speaker and Microphone positioning

Noise can be actively reduced by two methods.One involves the active reduce of noise within the duct using a secondary sound source. The other involves the active reduction of noise radiated in the space surrounding the duct using a secondary sound source. The present research uses a one-dimensional exhaust duct system active noise control under conditions corresponding to those of Hull et al. The experimental device used in this study is shown in Fig. 1. This device is a simplified large motor vehicle exhaust duct which is designed to reduce sound pressure at the outlet of the exhaust duct. In Fig. 1, the primary speaker (primary SP) is a noise source. This generated noise passes through the one-dimensional exhaust duct system, becomes resonic sound, and then is radiated to the exhaust duct exterior. Then, a microphone detects the sound pressure at the exhaust duct opening and a signal is relayed to the DSP. Inside the DSP (TMS320C40), a feedback compensator calculates the H_∞ control input from the resulting algorithm, and a secondary speaker (secondary speaker) control input signal is generated to produce noise control sound from a secondary sound source. In addition, a single harmonic sound and white noise was used in this experiment.

Feedback Active Noise Control System Design Specifications

Figure 1 demonstrates the purpose of feedback active noise control which is the reduction of the sound pressure at the outlet of the duct in the 500Hz frequency range. In particular, it reduces the voltage output of the microphone at point E in Fig. 1.

From the viewpoint of the control theory, Figure 1 is equivalent to the feedback control system shown in Fig. 2. The above-mentioned noise reduction problem can be considered as a feedback system output sensitivity reduction problem of the frequency range.

H_∞ Control Standard Problem

The H_∞ standard problem is shown in Fig. 3. First, the general plant is provided by the following equation.

$$\begin{bmatrix} z \\ e \end{bmatrix} = P(s)\begin{bmatrix} d \\ u \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix}\begin{bmatrix} d \\ u \end{bmatrix} \qquad (1)$$

Here, d is the external signal, z is the control value, u is the control input, and e is the observation output.

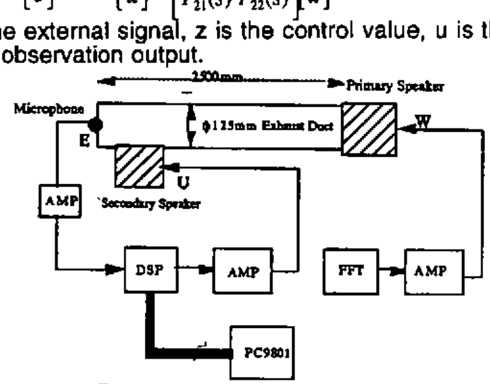

Fig. 1 Active noise control device

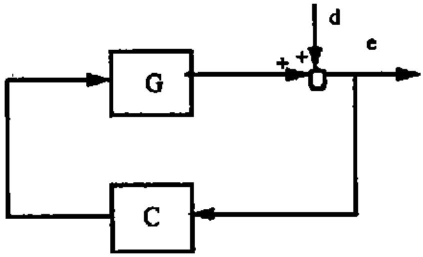

Fig. 2 Feedback control block diagram

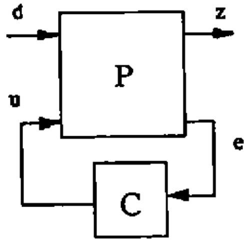

Fig. 3 H_∞ standard problem

The control law is given by the following equation:

$$u = C(s) \qquad (2)$$

In this control system, the transfer function T_{zd} from the external signal d to the control value z is provided by the following linear fractional tranformation.

$$T_{zd} = P_{11}(s) + P_{12}(s)C(s)[I - P_{22}(s)C(s)]^{-1}P_{21}(s) \qquad (3)$$

Here, the H_∞ standard problem is to find the stable controller to minimize $\|T_{zd}\|_\infty$. The stable controller obtained here is called the H_∞ controller.

Active Noise H_∞ Control System Design using the Mixed Sensitivity Problem

In the present research, the controller is realized by the DSP which creates a computation time delay. Accordingly, the following primary Pade approximation is used to approximate the computation delay during the modeling step.

$$e^{-\tau s} = \frac{2 - \tau s}{2 + \tau s} = G_2(s) \qquad (4)$$

This approximation is inserted into the model in order to design the controller with an expanded plant. The plant model produces curve fit for a model with actualized data up to 500Hz using 14th order rational functions.

On the other hand, the dynamic characteristics of the high frequency area above 500Hz is ignored (6). Modeling additive errors are shown in Fig. 4. Finally, the following control specifications were used.

$$\left\| \begin{array}{c} \frac{1}{\gamma} W_2(s) \frac{1}{1 + G(s)C(s)} \\ W_1(s) \frac{C(s)}{1 + G(s)C(s)} \end{array} \right\|_\infty < 1 \qquad (5)$$

The MATLAB Glover-Doyle algorithm was used to design the H_∞ compensator. Finally, the frequency characteristics of the designed controller are shown in Fig. 5. The results of the simulations using the designed controller are shown in Fig. 6. Figure 6 shows the frequency response from the primary speaker input to the microphone output with and without control.

Figure 6 shows that this closed loop system is nominally stable. Figure 6 shows that when the H_∞ compensator is used, noise is reduced in all resonance modes, particularly in modes 4 through 7 in which the noise was reduced by approximately 7dB.

3. EXPERIMENTS

Experimental Method

First, the continuous controller described in Section 2 is discretized by tustin transformation with the sampling time to 0.1ms, and then installed on the DSP. Next, experiments were performed.

The control experiment block diagram is shown in Fig. 1. The microphone signal was amplified in the pre-amplifier, and then passed through the A/D converter to the DSP (TMS320C40). The control output signal formed by the DSP was input to the power amplifier via the D/A converter, and then output to the secondary speaker. Two types of noise were input to the speaker for this experiment, white noise and single harmonic sound. Next, the results of each experiment are shown.

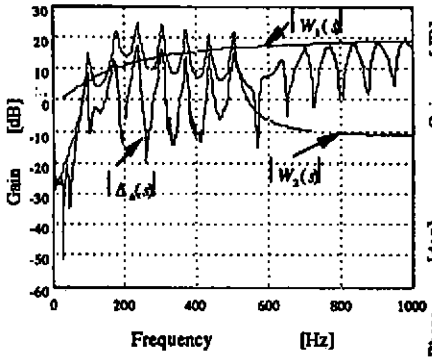

Fig. 4 Weighting functions and modeling addition error frequency characteristics

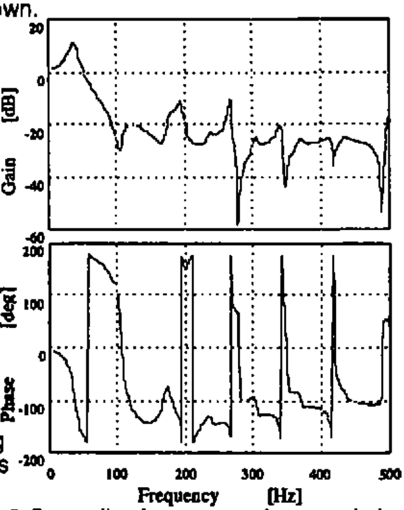

Fig. 5 Controller frequency characteristics

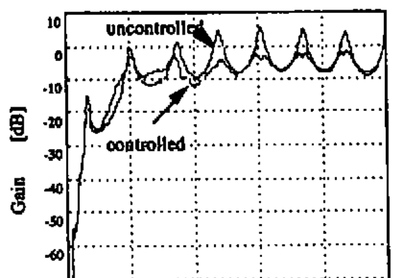

Fig. 6 Microphone position frequency response of simulation using H_∞ compensator

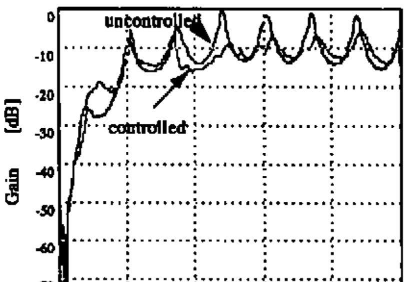

Fig. 7 Microphone position frequency response from experiment using H_∞ compensator

Experimental Results

Figure 7 shows the results of the experiment with white noise speaker input with and without control.

By comparing Fig. 6 with Fig. 7, little difference can be detected between the simulation and actual experimental data in the second resonance mode. Thus, the simulation and experimental results are very similar overall. The similarity between the simulation and experimental results verify the legitimacy of this model. In addition, the noise level was reduced by approximately 7dB in the duct sound system resonance modes 3 through 7, as with the simulation.

The above results show that the H_∞ control theory is an effective active control for both white noise and harmonic noise.

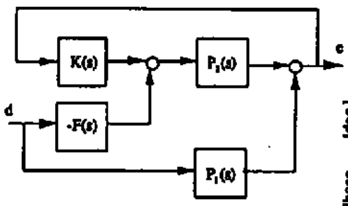

Fig.8 Block diagram with two-degree-of freedom active noise control system

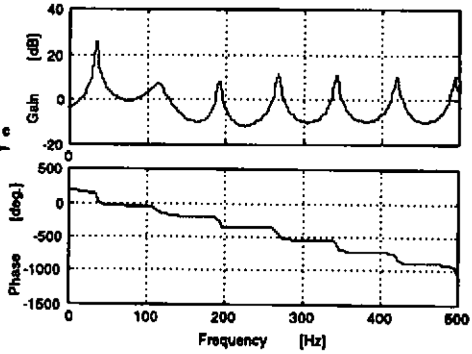

Fig.9 Frequency response of feedforward controller based on model matching

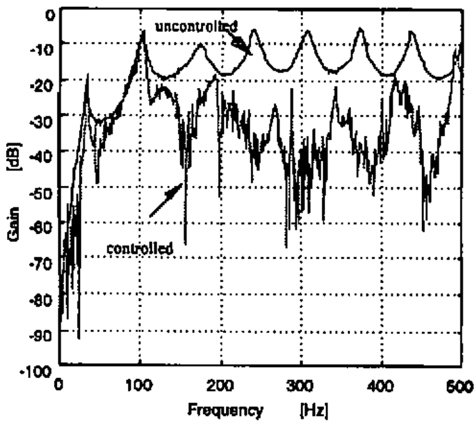

Fig.10 Experimental frequency response using two-degree-of freedom system at microphone location

4. TWO-DEGREE-OF FREEDOM ACTIVE NOISE CONTROL WITH MODEL MATCHING(8)

Figure 8 shows the block diagram for two degree of freedom active noise control system with model matching. $P_1(s)$ is the transfer function between the reference signal and the microphone and $P_2(s)$ is the transfer function between the secondary speaker and the microphone. $F(s)$ and $K(s)$ mean the feedforward and the feedback controllers. Figures 9 and 10 shows the feedforward controller using model matching theory and experiments. The noise reduction more than 15dB are obtained in the wide frequency range.

5. CONCLUSIONS

The present research presents the following conclusions based on results obtained by applying the H_∞ control theory to one-dimensional exhaust duct system active noise control.
(1) The computational time delay was derived to the model using the Pade approximation, and the active noise control system was formulated with the H_∞ control theory.
(2) The H_∞ compensator can be used to increase the damping ratio for most exhaust duct system resonance modes, thereby decreasing the resonance sound.
(3) Based on results of the one-dimensional exhaust duct system noise control simulations and experiments, the H_∞ compensator was determined to be superior to the phase lead/lag compensator.
(4) The loop frequency shaping method using frequencly weighting functions of the sensitivity function within the framework of the H_∞ control theory is easier to apply than phase lead/lag based on trial and error.
(5) It is very useful for active noise control to apply not only a feedback control withH_∞ control theory but also a feedforward control based on model matching.

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