Proceedings of the 1998 IEEE
International Conference on Control Applications
Trieste, Italy 1-4 September 1998

FA03

Active Noise Control System for Automobiles based on Adaptive and Robust Control

Shuichi Adachi

Dept. Electrical, Electronic Eng.
Utsunomiya University
2753 Ishii, Utsunomiya
Tochigi 321-8585, Japan
Phone : +81 28 689 6125
Fax : +81 28 689 6125
Email:adachis@utsunomiya-u.ac.jp

Hisashi Sano

Tochigi R&D Center
HONDA R&D Co., Ltd.
4630 Shimotakanezawa, Haga-gun
Tochigi 321-3321, Japan
Phone : +81 28 677 7090
Fax : +81 28 677 7000
Email:hisashi_sano@n.t.rd.honda.co.jp

Abstract

An active noise control (ANC) problem, especially for active control of road noise inside automobiles is presented. First, a model for an acoustic field, which includes loudspeaker and microphone characteristics, is constructed using the system identification theory. Second, the control law of a 2DOF-ANC (two-degree-of-freedom ANC) system is designed based on the identified model. Lastly, the control performance of the 2DOF-ANC system is examined through computer simulations using actual vehicle data measured in the experiment which simulates road noise within the cabin.

1. Introduction

With respects to the vibration control system, active control strategies have attracted much attention in comparison with passive control strategies. In particular, ANC (active noise control)[1] is a challenging area for both acoustic and control engineers. In the automobile industry, vehicle weight reduction has become increasingly important from the fuel consumption point of view, however, this increases noises in the automobile. Therefore, ANC is considered to be a promising means of noise reduction[2].

Two problems, modeling of the acoustic field by the system identification theory[3] and the control systems design for ANC based on the identified model are discussed.

First, a model for an acoustic field which includes loudspeaker and microphone characteristics is constructed using system identification theory. In particular, 4SID (subspace-based state-space system identification) method is adopted in order to build an IIR (infinite impulse response) model for the acoustic field. The IIR model is used as a nominal model for designing a feedback controller and it can reduce the number of arithmetic operations in feedforward control. The 4SID method can determine the order of the IIR model based on singular values of the Hankel matrix. The 4SID method has a few drawbacks, for example, it operates in a off-line manner and it requires a great deal of computations. However, modeling of the acoustic field for ANC is usually conducted before ANC is implemented, so the computational burden is minimal.

Then, the control law of a 2DOF-ANC (two-degree-of-freedom ANC) system[4]~[6] is designed based on the identified model. The FF (feedforward) part of the 2DOF-ANC is a conventional filtered-x LMS adaptive control and the FB (feedback) part is based on an internal model control (IMC)[7] which is known as a robust control design method especially for dead-time systems.

Finally, effectiveness of the proposed control system design procedure is examined through identification and control experiments. First, a system identification experiment by random excitation is conducted to model the acoustic field. It will be shown that the identified IIR model is of low order and has a considerably similar gain characteristic to that of the conventional FIR (finite impulse response) modeling by LMS (least mean square) algorithm. Then, the control performance of the 2DOF-ANC system, that is designed based on the identified model, is examined through computer simulations using actual vehicle data measured in the experiment which simulates cabin road noise.

2. Active noise control problem

In this paper, the single-input, single-output, single-error (SISOSE) system shown in Fig.1 is considered.

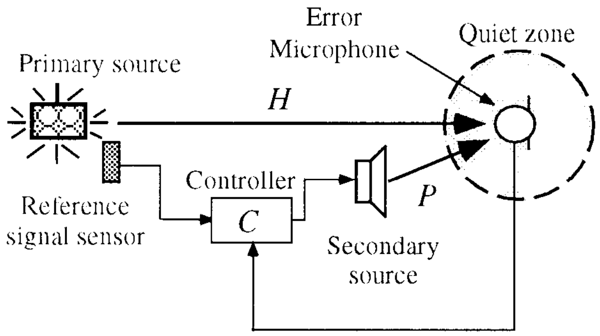


Figure 1: Principle of ANC for SISOSE system

where H and P are the transfer functions from the noise source to the error sensor (microphone), and from the secondary source (loudspeaker) to the error sensor, respectively. C represents the transfer function of the controller, which calculates the control signal based on the reference and error signals.

Two problems, the system identification and the control system design problems, are discussed in this paper. The former involves how to identify the plant P based on *a priori* information and the measured input-output data, and the latter concerns how to design the controller, C.

3. Modeling of acoustic field

In this section, modeling of the plant P, *i.e.*, the acoustic field, is discussed. As a model of the acoustic field, the FIR model has been widely used, because the FIR model can be easily identified from measured input-output data and is always stable. However, the FIR model has two problems as a result of it requiring many parameters. One is the increase in the number of arithmetic operations when it is desired to construct the conventional FF-ANC system based on the adaptive filtering theory, such as the filtered-x LMS algorithm[8]. The other is the difficulty of designing the FB-ANC system based on the modern or so-called post-modern control theory such as the robust control theory. Therefore, there is an urgency to establish a new modeling method, utilizing an IIR model, for the acoustic field in order to construct an accurate and practical ANC system.

First, the nominal model, P_{nom}, is calculated by the 4SID method. Next, a detail model, P_{detail}, is identified by the conventional LMS algorithm. It must be noted that the nominal model and the detail model are described by the IIR model and FIR model, respectively. Finally, an additive model uncertainty is evaluated based on the nominal and detail models.

Nominal model
The IIR model is adopted as a nominal model for designing the FB controller based on IMC. As an IIR modeling method, the SHARF (simplified hyperstable adaptive recursive filter) method was proposed[9]. It ensures the stability of the IIR model, however, the order of the IIR model is determined heuristically. To clear this point, it is proposed that the 4SID method is applied to identify the IIR model in this paper.

The 4SID method has attracted much attention in the past decade because it has a great number of advantages. For example, it can easily extend to the MIMO (multi-input multi-output) system identification problem and has no nonlinear optimization procedure[10]. Moreover, the 4SID method allows us to quantitatively determine the order of the IIR model based on singular values of the Hankel matrix[11]. The 4SID method has a few disadvantages, *e.g.*, it requires a heavy computational burden and it can not operate in an on-line manner. However, the modeling of the acoustic field needs not be conducted on-line, the computational complexity of the 4SID method is not significant.

Although many algorithms for the 4SID method have been proposed, the Multivariable Output-Error State Space (MOESP) algorithm[12] proposed by Verhaegen, *et al* is utilized in order to identify P_{nom}.

Detail model
A detail model, P_{detail}, which is described by a higher order FIR model, is identified by the LMS algorithm.

Model uncertainty
It is assumed that the true plant P can be described by an additive perturbation,

$$\Pi_a = \{P : |P(j\omega) - P_{nom}(j\omega)| \leq W_a(j\omega)\} \qquad (1)$$

where $W_a(j\omega)$ is a frequency weighting function. Because the true plant P is not available, $W_a(j\omega)$ is evaluated based on the nominal and the detail models, as follows,

$$|P_{detail}(j\omega) - P_{nom}(j\omega)| \leq W_a(j\omega). \qquad (2)$$

System identification experiment
System identification experiment was conducted using the apparatus shown in Fig.2. The experiment was intended for the rear passenger ANC. The loudspeaker and microphone were located in the rear tray and rear seat headrest, respectively. The distance of the acoustic field from the loudspeaker to the microphone was 0.2 (m). The identification input was a pseudo-random signal, the power spectral

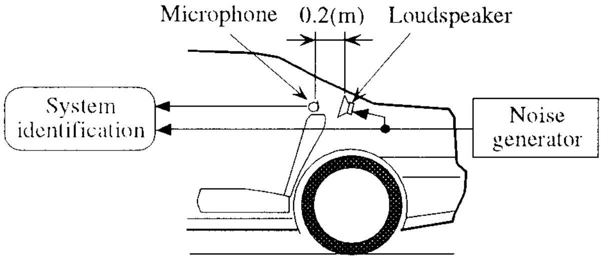
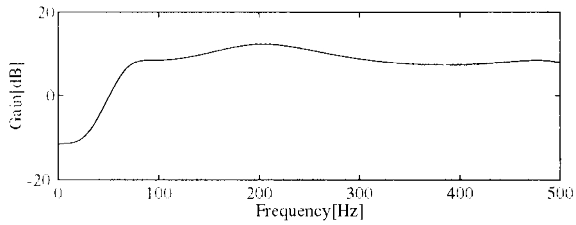
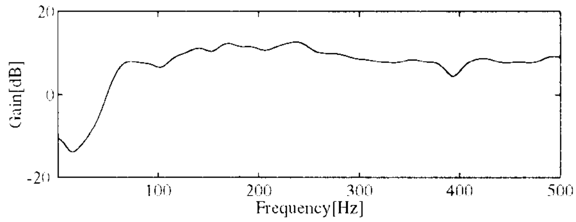


Figure 2: System identification of the acoustic field in the cabin



(a) Nominal IIR model by the 4SID method



(b) Detail FIR model by the LMS method

Figure 3: Identified gain characteristics of the acoustic field

density of which was flat below 1 (kHz). The input-output data for system identification was measured at a sampling rate of 1,280 (Hz). A nominal model which is the 6th-order IIR model was identified by the 4SID method and the identified gain characteristic is shown in Fig.3(a). A detail model which is the 58th-order FIR model was obtained by the LMS algorithm, shown in Fig.3(b). It is clear that the gain characteristics of the IIR model is considerably similar to that of the FIR model.

Based on the identified P_{nom} and P_{detail}, the weighting function of the additive uncertainty, $W_a(j\omega)$, is determined as follows.

$$W_a(s) = \frac{0.79(s+3.85)}{s+80}\frac{s^2+185.6s+320^2}{s^2+420s+350^2} \qquad (3)$$

The gain characteristic of $W_a(s)$ is shown in Fig.4.

4. 2DOF-ANC system based on adaptive and robust control

The ANC system is designed based on the identified

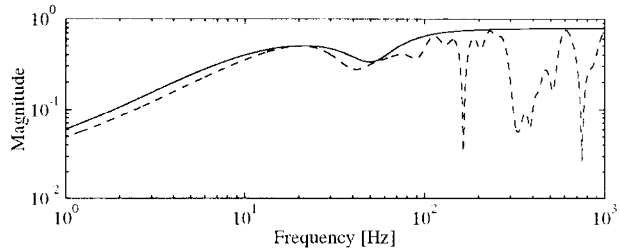


Figure 4: Frequency weighting function (solid line : $W_a(j\omega)$, dashed line : $P_{detail}(j\omega) - P_{nom}(j\omega)$)

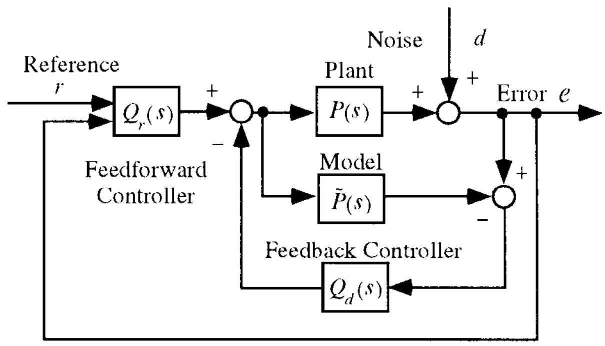


Figure 5: 2DOF-ANC system

model.

Configuration of 2DOF-ANC system

The 2DOF-ANC system[4]~[6] shown in Fig.5 was briefly reviewed, where $P(s)$, $\tilde{P}(s)$, $Q_d(s)$ and $Q_r(s)$ are the plant transfer function of acousitic field from the secondary source to the error sensor, a model of $P(s)$, the FB controller, and FF controller, respectively. It is noted that the FB and FF controllers can be designed independently.

The 2DOF-ANC system adopts an adaptive control strategy based on the well-known filtered-x LMS algorithm for the FF part, and a robust control strategy based on IMC for the FB part. Because the transfer function from the suspension signal to the error microphone depends on the velocity of the vehicle and the road surface, it is necessary for the FF part to be based on adaptive control. On the other hand, for the FB control, the plant P changes only with the number of passengers and deterioration of the loudspeaker and microphone. It is necessary for the FB controller to be designed such that it does not cause howling (instability). Thus, the key point is the design of the FB controller.

FB controller based on IMC

FB-ANC is designed by Morari's IMC design procedure[7] as follows.

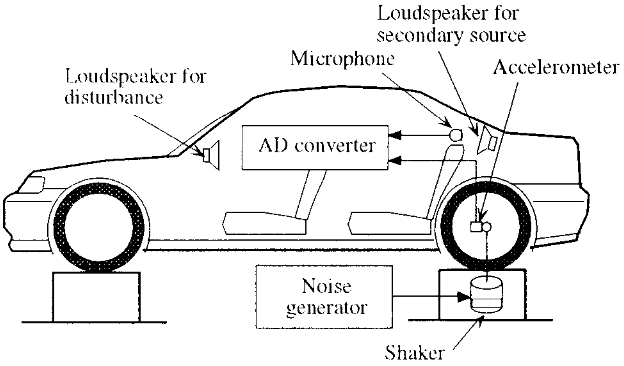


Figure 6: Data acquisition experiment simulating road noise in the cabin

Step 1 : Nominal performance
First, the nominal case, $\tilde{P}(s) = P(s)$, is considered. Evaluating the error e in $\mathcal{H}_2$ norm,

$$\min_{Q_d(s)} \|e\|_2^2 = \frac{l}{c} \tag{4}$$

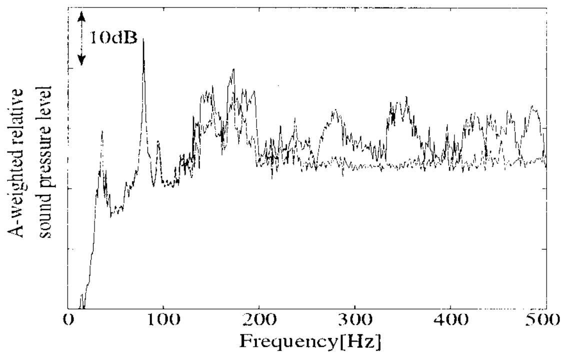
is obtained when the noise is a step function, *i.e.* $d(s) = 1/s$, where c is the speed of the sound and l is the distance from the loudspeaker to the microphone[5]. Eq.(4) indicates that FB-ANC is efficient only if the distance from the loudspeaker to the microphone is short.
Step 2 : Robust stability
It is assumed that the plant family Π_a can be described in terms of an additive uncertainty given by eq.(1). Then the IMC filter is selected as

$$F(s) = \frac{1}{\lambda s + 1} \tag{5}$$

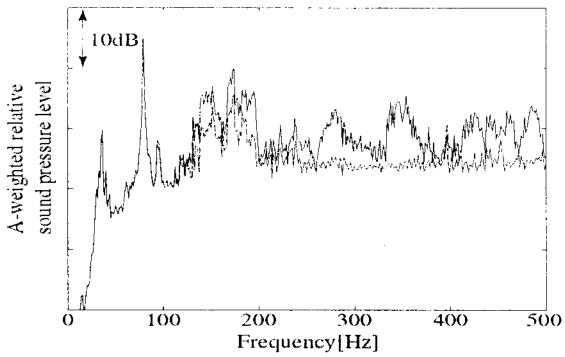
and λ is adjusted so that the robust stability condition is satisfied.

Active noise control experiment
In order to examine the effectiveness of the identified nominal IIR model in the previous session 3, the residual sound pressure level of the FF-ANC system, based on the identified IIR and FIR models, were calculated using actual vehicle data. A basic diagram of the experiments is shown in Fig.6. The results by the 58th-order FIR model and the 6th-order IIR model are shown in Fig.7. These figures show that the IIR model gives the same reduction in sound pressure as the FIR model. However, the number of parameters in the IIR model is about 1/5 of that for the FIR model.

Next, the FB-ANC system was designed based on the identified nominal IIR model. The controller was designed in a continuous-time system, and transformed



(a) Nominal IIR model



(b) Detail FIR model

Figure 7: Sound pressure level obtained by FF-ANC (solid line:without control, dashed line:with control)

a discrete-time system using a bilinear transformation. In this case, the distance between the loudspeaker and the microphone was 0.2 (m). The weighting function given by eq.(3) was used. The IMC filter was designed such that

$$F(s) = \frac{1}{0.0173s + 1}. \tag{6}$$

Fig.8 shows the sensitivity function which is the transfer function from the noise to the error. From this figure, it can be seen that between 50 and 150 (Hz) attenuation occurs, and other frequency ranges amplification occurs. The existence of the amplification ranges can be explained by the fact that the plant considered here has unstable zeros, which inevitably cause the water-bed effect[13]. It is important that the attenuation band is predicted in advance using the sensitivity function without carrying out experiments. The sound pressure level of the FB-ANC is shown in Fig.9(a). The figure shows that it is difficult to reduce road noise using only the FB controller.

Finally, the 2DOF-ANC system was constructed based on the FF and FB controllers. The sound pressure level was shown in Fig.9(b). The figure shows that the 2DOF-ANC system attenuates the sound

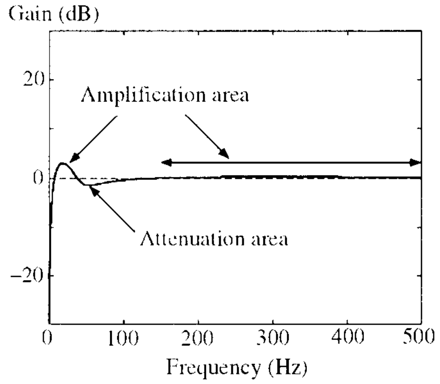


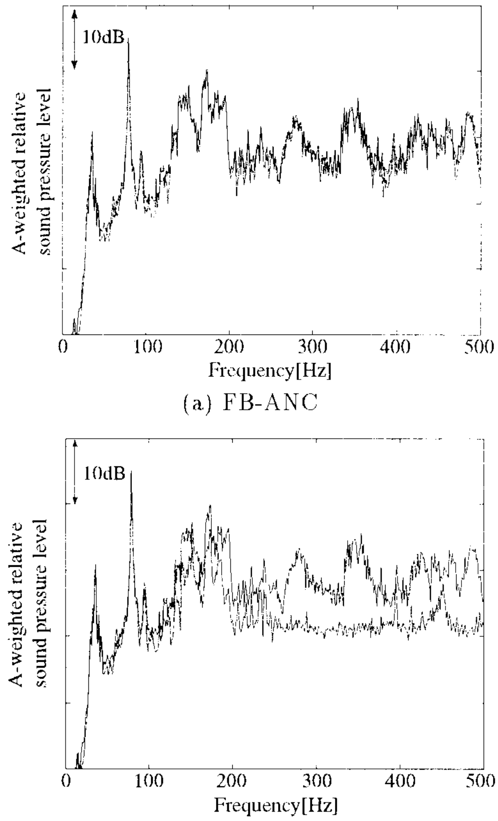
Figure 8: Sensitivity function

pressure over wider frequency range more than either the FF-ANC or FB-ANC system used independently.

5. Conclusion

In this paper, the 2DOF-ANC system has been designed based on the identified model of the acoustic field. The model consists of a nominal part and a detail part. The former is an IIR model which is identified by the 4SID method, and the latter is an FIR model which is identified by the LMS method. The effectiveness of the proposed design procedure was demonstrated through computer simulations using actual vehicle data.

Acknowledgement The authors would like to thank Y.Yoshida, T.Sannoudou and Y.Yoneya for their help with the computer experiments.



(a) FB-ANC

(b) 2DOF-ANC

Figure 9: Sound pressure level

References

[1] P.A.Nelson and S.J.Eliott, "Active Control of Sound," Academic Press, 1992.

[2] H.Sano, S.Adachi and H.Kasuya, "Application of a least squares lattice algorithm for an automobile," ASME J. DSMC, Vol.119, No.2, pp.318–320, 1997.

[3] L.Ljung, "System Identification : Theory for the User," Prentice-Hall, 1987.

[4] S.Adachi and H.Sano, "Application of two-degree-of-freedom type active noise control using IMC to road noise inside automobiles", CDC'96, pp.2794-2795, Japan, 1996.

[5] S.Adachi and H.Sano, "Two-degree-of-freedom active noise control based on internal model control", ECC'97, Brussels, 1997.

[6] H.Sano and S.Adachi, "Two-degree-of-freedom active noise control of road noise inside automibiles", ACTIVE97, Budapest, pp.543–556, 1997.

[7] M.Morari and E.Zafiriou, "Robust Process Control," Prentice Hall, 1989.

[8] B.Widrow and S.D.Sterns, "Adaptive Signal Processing", Prentice-Hall, 1985.

[9] M.G.Larimore, *et al.* "SHARF – An algorithm for adaptive IIR digital filters," IEEE Trans., ASSP-28, No.4, pp.428–440, 1980.

[10] M.Viberg, "Subspace-based Methods for the Identification of Linear Time-Invariant Systems," Automatica, Vol.31, No.12, pp.1835–1851, 1995.

[11] S.Y.Kung, "A new identification and model reduction algorithm via singular value decomposition," 12th Asilomar Conference on Circuits, Systems, and Computers, pp.705–714, 1978.

[12] M.Verhaegen and P.Dewilde, "Subspace model identification. Part I: The output-error state space model identification class of algorithms," Int. J. Control, Vol.56, pp.1187–1210, 1992.

[13] Doyle J.C., *et al.* "Feedback Control Theory", Macmillan Publishing Co., 1992.

[14] S.J.Elliott and T.J.Sutton, "Feedforward and feedback methods for active control", Proc. Institute of Acoustics, Vol.16, No.2, pp.255–273, 1994.