DEVELOPMENT OF DYNAMIC LOUDSPEAKERS MODIFIED AS INCIDENT PRESSURE SOURCES FOR NOISE REDUCTION IN A DOUBLE PANEL STRUCTURE

Jen-Hsuan Ho

Department of Electrical Engineering, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands

Arthur Berkhoff

TNO Technical Sciences, Acoustics and Sonar Acoustics, P.O. Box 96864, 2509 JG Den Haag, The Netherlands

Department of Electrical Engineering, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands

e-mail: j.ho@utwente.nl

This paper presents a modified loudspeaker source for decentralized feedback cavity control in a double panel structure to reduce the noise transmission. The double panel structure consists of two panels with air in between and offers the advantages of low weight, low sound transmission at high frequencies, and thermal insulation. The main issues of the double panel structure are the resonance of the cavity and the high noise transmission at low frequencies. Many papers have discussed applying active structural acoustic control to the panels or active noise control to the cavity. In our previous study, we considered the resonance of the panels and the cavity simultaneously and numerically compared various decentralized structural and cavity feedback control strategies basing on identical control stability margins. Cavity control by loudspeakers, which are modified to operate as incident pressure sources, was found to provide the largest noise reduction. The incident pressure source loudspeaker can be realized by using a dynamic loudspeaker, a microphone, and a velocity sensor with a feedforward controller. In this paper, experimental results of a one dimensional realization with a feedforward controller are presented.

1. Introduction

A double panel structure, which consists of two panels with air in the gap, offers the advantages of low sound transmission at high frequencies, low weight, and low heat transmission. Therefore, this structure is often applied to the aerospace and automotive industries. However, both the two panels and the cavity cause the resonance, which limits the noise reduction performance. To improve the noise reduction of the double panel structure, many control methods have been discussed [1-3]. In our previous work, various structural and cavity control strategies were applied to the structure to reduce the amount of noise transmitted. Cavity control by incident pressure sources provides the largest noise reduction [4]. As an extension of our previous work, the present paper shows the realization of this incident pressure source by using a dynamic loudspeaker, a microphone, and a particle velocity sensor with feedforward control. In order to minimize the reflecting pressure from the boundaries, a wave separation technique is applied to our work [5]. To improve the convergence rate and stability, regularized modified filtered-error algorithm (RMFe) is applied to our feedforward control system [6, 7]. The result shows, with the adaptive feedforward RMFe control, the average broadband reflecting pressure reduction in a duct is 26.2 dB.

This paper has three main sections. Section 2 describes the pressure source development, the wave separation method, and the experiment set-up. Section 3 shows the adaptive feedforward RMFe algorithm and the real-time control result. Section 4 gives the conclusions.

2. Development of a pressure source

2.1 Configuration

The incident pressure source indicates there is no reflecting pressure from the incident boundary. In other words, the reflecting pressure from the solid surface should be minimized. Therefore, we use the reflecting pressure instead of the total pressure as our error signal. The reflecting pressure can be derived by measuring the pressure and the velocity. Figure 1 shows our system configuration. A dynamic loudspeaker generates the primary source; another dynamic loudspeaker, which is placed between the primary source and the solid surface, gives the secondary source; one pressure sensor and one gradient pressure sensor, which functions as a particle velocity sensor, are placed at the same position in the duct to measure the error signal. The incident pressure source is realized by minimizing the reflecting pressure with a feedforward controller.

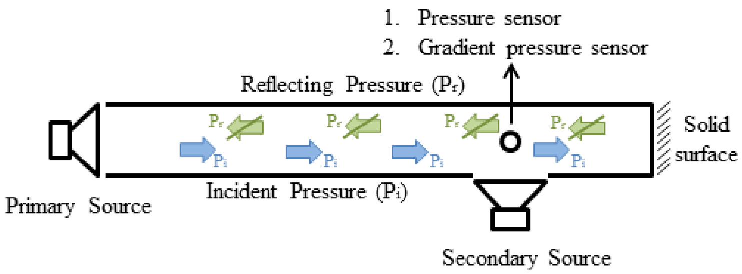


Figure 1. Configuration control system.

2.2 In-duct wave separation

For plane wave propagation, the momentum equation is written as

$$\rho\frac{\partial v}{\partial t}+\frac{\partial p}{\partial x}=0, \tag{1}$$

in which ρ [kg m^{-3}] is the density of the air; p [Pa] is the pressure; v [m s^{-1}] is the particle velocity; t [s] is the time and x indicates the wave propagate on x-axis. The particle velocity v_i [m s^{-1}] corresponding to the incident wave p_i [Pa] can be written as

$$v_i=\frac{p_i}{\rho c}. \tag{2}$$

where c is the sound speed [m s^{-1}]. On the other hand, v_r [m s^{-1}], the particle velocity corresponding to the reflecting wave p_r [Pa] is

$$v_r=\frac{p_r}{\rho c}, \tag{3}$$

The total particle velocity and total pressure can be written as

$$v = v_i + v_r = \frac{p_i}{\rho c} - \frac{p_r}{\rho c}; \tag{4}$$

$$p = p_i + p_r. \tag{5}$$

Then the incident pressure and the reflecting pressure can be expressed as

$$p_i = \frac{1}{2}(p + \rho c v); \tag{6}$$

$$p_r = \frac{1}{2}(p - \rho c v). \tag{7}$$

Equations 6 and 7 show that we can obtain the incident pressure and the reflecting pressure by measuring the pressure and the particle velocity.

2.3 Experiment set-up

The experimental set-up is shown in Fig. 2. A 2.5-meter-long duct is used; the radius of the duct cross section is 7.5 cm. The left end of the duct is the primary source generated by a dynamic loudspeaker, and the right end of the duct is a sealed solid surface. We use another dynamic loudspeaker as the secondary source, which is placed 2.06 meters away from the primary source. One pressure microphone and one gradient pressure microphone, which functions as the velocity sensor, are placed in the duct at the same position.

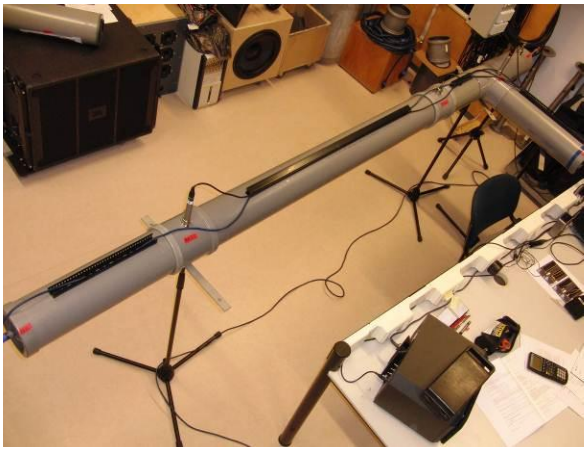


Figure 2. Experiment set-up for real-time control.

3. Adaptive feedforward control

3.1 Adaptive feedforward control method

In this paper, the regularized modified filtered-error algorithm (RMFe) is applied to the real-time feedforward control implementation. This adaptive algorithm eliminated the inherent delay in the adaptive path by using an inner-outer factorization of the transfer path between the actuator and the error sensor. Double control filters combined with a regularization technique, which can preserve the factorization properties, are used for compensating the delay. Compared to the standard filtered-reference and filtered-error algorithm, RMFe has good convergence properties. A detailed RMFe algorithm description can be found in [6, 7]. A block diagram of the adaptive single-channel RMFe scheme, where the dashed line indicates the controller, is shown in Fig. 3. P and G are the transfer functions between the primary source and secondary source to the error sensor. W is the control filter and D represents a delay. The augmented plant $\overline{G}$ consists of G and a regularization function G_{reg} to avoid a saturated control signal. To improve the convergence and to ensure the stability, an all-pass function $\overline{G}_i$ and minimum phase function $\overline{G}_o$ are used to perform a so-called inner-outer factorization, where $\overline{G} = \overline{G}_i \overline{G}_o$, $\overline{G}_o^T(q^{-1})\overline{G}_o(q) = I$ with q the unit delay, and $\overline{G}_i^* = \overline{G}_o^T(q^{-1})$. Internal model control (IMC) can be realized by subtracting the contribution of the secondary source on the reference signal, where the transfer function is G_{rp} and the reference signal is x_{ref} [8, 9].

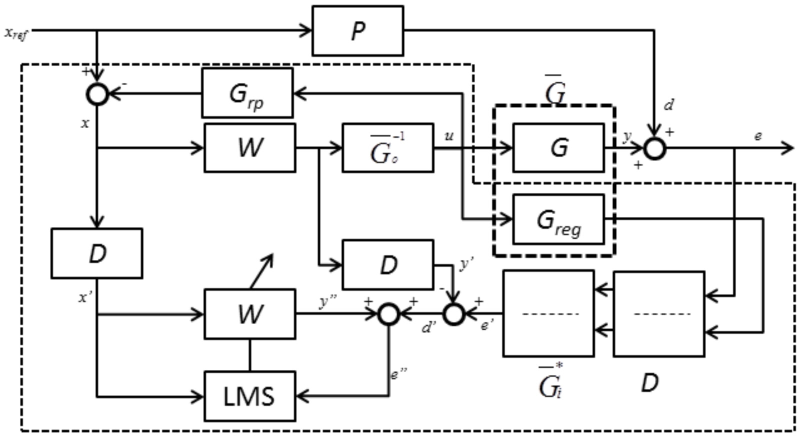


Figure 3. Regularized modified filtered-error adaptive control scheme with IMC.

$$W_i(n+1) = W_i(n) - \alpha e''(n) x'^T(n-i) \tag{8}$$

Equation 8 is the update rule for the controller coefficients, where W_i is the ith filter, the sample number is denoted by n. e'' is the auxiliary error signal, α is the convergence coefficient and x' is the delayed reference signal.

3.2 Real-time feedforward control

In this section, two sensor-actuator configurations are presented. Configuration 1 shows that the error sensors are placed in front of the second source, at sensor position 1. Configuration 2 shows that the error sensors are placed between the primary source and the secondary source, at sensor position 2. These two positions are shown in Fig. 4.

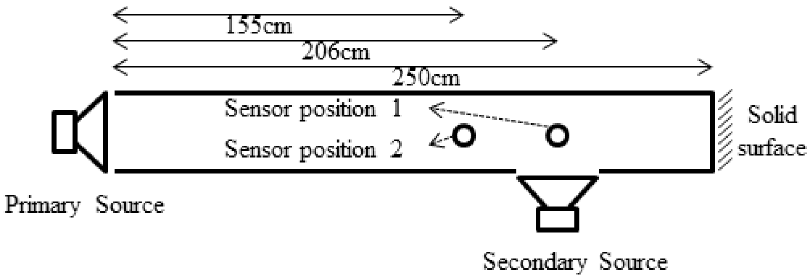


Figure 4. Sensor positions.

Figure 5 presents the reduction of the reflecting pressure, which is the error signal, with configuration 1 control. The results shows the RMFe feedforward control can effectively reduce the reflecting pressure with an average 26.2 dB reduction, assuming that the error sensor provides an exact measure of the reflected pressure. The total pressures measured at positions 1 and 2 are shown in Figs. 6(a) and 6(b). The resonance in the duct is removed by reducing the reflecting wave.

Moreover, although the error sensor is placed at position 1, the improvement can also be seen at position 2.

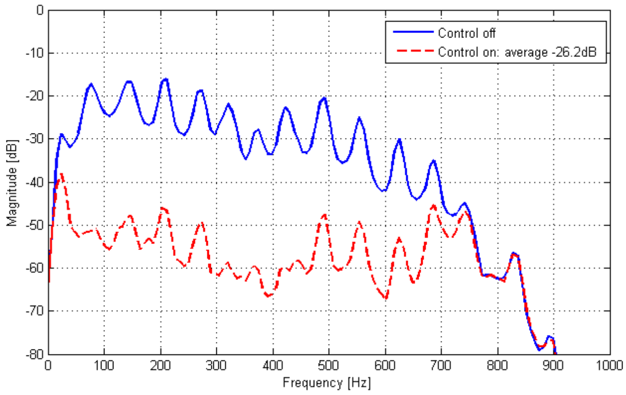
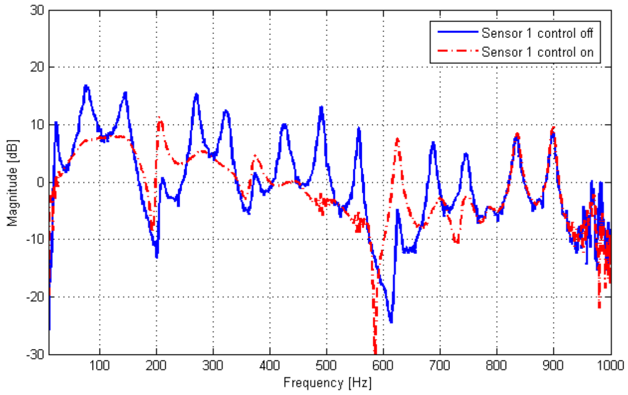
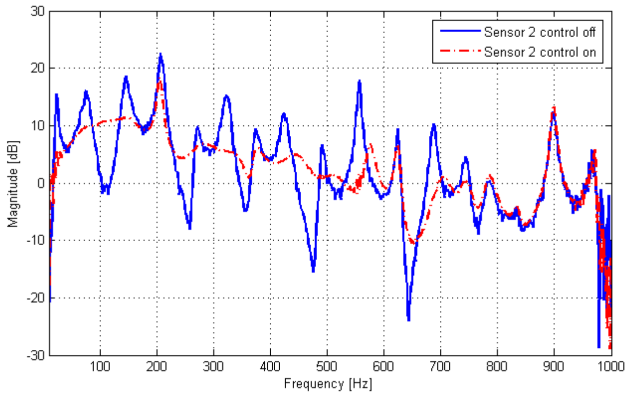


Figure 5. Reflecting pressure response: with real-time feedforward configuration 1 control.



(a)



(b)

Figure 6. Total pressure response: with real-time feedforward configuration 1 control. (a) sensor position 1; (b) sensor position 2.

Figure 7 presents the reduction of the reflecting pressure with configuration 2 control. This configuration gives an average 25.4 dB reduction. The total pressure measured at position 1 and 2 are shown in Figs. 8(a) and 8(b). The duct resonance is effectively removed at position 2, as shown in Fig. 8(b). However, the control system cannot control the resonance behind the error sensor, for instance at position 1, as shown in Fig. 8(a). The result shows, with the RMFe feedforward control, both configurations can effectively remove the resonance between the primary source and the error sensors and realize an incident pressure source.

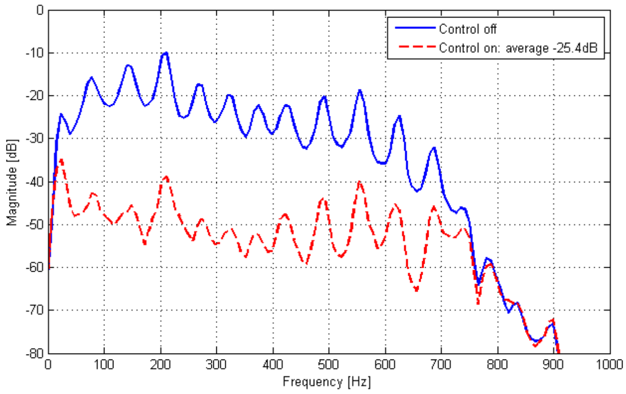
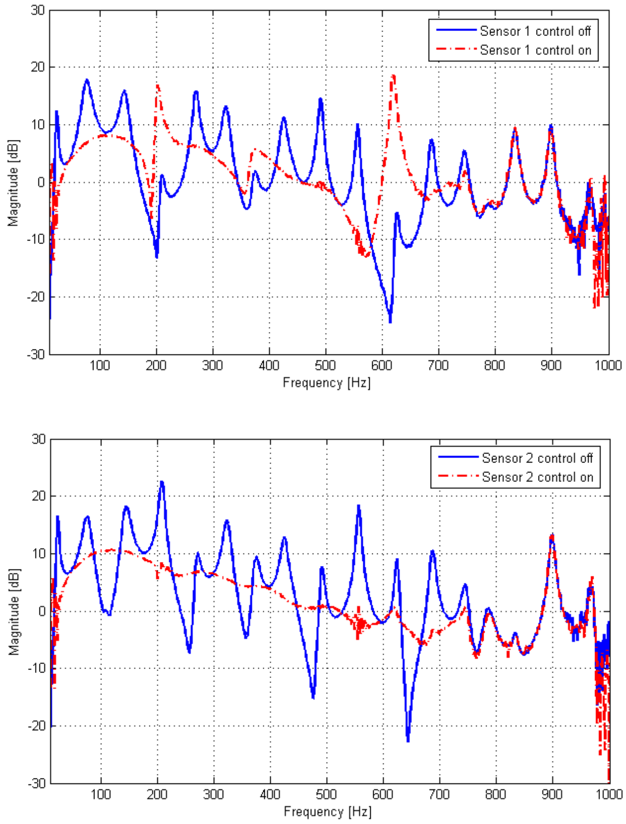


Figure 7. Reflecting pressure response: with real-time feedforward configuration 2 control.



(a)

(b)

Figure 8. Total pressure response: with real-time feedforward configuration 2 control.
(a) sensor position 1; (b) sensor position 2.

4. Conclusions

The one dimensional real-time realization of the pressure source loudspeaker with feedforward control is presented in this paper. The reflecting pressure reduced on average by 26.2 dB and the pressure resonance in the duct can be effectively removed. Our work shows the incident pressure source loudspeaker can be realized by using a dynamic loudspeaker, a microphone, and a velocity sensor with a feedforward controller. And a non-reflecting boundary condition can be realised by minimizing the reflecting pressure from the solid surface. Therefore, the transmitted noise in a double panel structure can be effectively reduced by applying this modified pressure source loudspeaker.

Acknowledgments

This work was funded by STW (De Stichting voor de Technische Wetenschappen, The Foundation for Technical Sciences), project No.10602 IMPEDANCE (Integrated Modules for Power Efficient Distributed Active Noise Cancelling Electronics). The authors would like to express their appreciation to Sjoerd van Ophem, Henny Kuipers, and Geert Jan Laanstra of the Signals and Systems Group, Faculty of EEMCS, University of Twente for the excellent support.

REFERENCES

[1] Alujevic, N., P. Gardonio, and K.D. Frampton, Smart Double Panel for the Sound Radiation Control: Blended Velocity Feedback. *American Institute of Aeronautics and Astronautics Journal*, 2011. **49**(6): p. 1123-1134.

[2] Mao, Q. and S. Pietrzko, Experimental study for control of sound transmission through double glazed window using optimally tuned Helmholtz resonators. *Applied Acoustics*, 2010. **71**(1): p. 32-38.

[3] Pietrzko, S.J. and Q. Mao, New results in active and passive control of sound transmission through double wall structures. *Aerospace Science and Technology*, 2008. **12**: p. 42-53.

[4] Ho, J.H. and A. Berkhoff, Comparisons between various cavity and panel noise reduction control methods in double-panel structures. *The Journal of the Acoustical Society of America*, 2012. **131**(4): p. 3501-3501.

[5] Zhu, H., R. Rajamani, and K.A. Stelson, Active control of acoustic reflection, absorption, and transmission using thin panel speakers. *The Journal of the Acoustical Society of America*, 2003. **113**(2): p. 852-870.

[6] Berkhoff, A.P. and G. Nijsse, A rapidly converging filtered-error algorithm for multichannel active noise control. *International Journal of Adaptive Control and Signal Processing*, 2007. **21**(7): p. 556-569.

[7] Wesselink, J.M. and A.P. Berkhoff, Fast affine projections and the regularized modified filtered-error algorithm in multichannel active noise control. *The Journal of the Acoustical Society of America*, 2008. **124**(2): p. 949-960.

[8] Morari, M., *Robust process control*, 1989. Englewood Cliffs, NJ Prentice Hall.

[9] Elliott, S., *Signal Processing for Active Control*, 2001. London: Academic Press.