Cavity Control and Panel Control Strategies in Double-Panel Structures for Transmitted Noise Reduction

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Abstract

Investigation and comparisons of the cavity control and the panel control in a double-panel structure are presented in this paper. The double-panel structure, which comprises two panels with air in the gap, provides the advantages of low sound-transmission at high frequency, low heat-transmission and low weight. Therefore, the double-panel structure is adopted in various applications such as aerospace and vehicle industry. However, the resonance of the air cavity and the high sound-transmission at low frequency limit its noise control performance. Furthermore, the resonant behaviors and the sound radiating modes of single panel structures are different from double-panel structures. As a consequence, the panel control strategy, which is widely applied in structural acoustic control, for single-panel structures needs to adapt to double-panel structures. In this paper, a structural-acoustic coupled model is developed to investigate and to compare various panel control and cavity control methods. A detailed investigation of the structure and the cavity resonance is shown. Both the numerical analysis and the real time control results show that the panel control should apply to these two panels simultaneously. Cavity control by loudspeakers modified to operate as pressure sources can provide remarkable noise reduction in the double-panel structures. Finally, the combination of feedforward panel control and feedback cavity control can further reduce the transmitted noise.

1. Introduction

The increasing need for a comfortable environment points to the importance of noise control technology. With the development of smart materials and computation power, noise control is no longer only using passive control but also involving in many active control methods in the last decades. Active noise control (ANC) has been developed for decades and has found successfully applying in small spaces with broadband noise [1, 2]. However, for a large control region, this 3D computation problem will become very complicated and inefficient. Instead of dealing with 3D wave propagating problem, active structure acoustic control (ASAC) directly control the vibrating structure to reduce its radiating sound. This method can make the computation problem from 3D to 2D [1, 3]. The control strategy and the algorithm also have been investigated and designed for various applications. For a large configuration, decentralized control can effectively reduce the computation amount of the controller [4-8]. Decentralized feedback control strategy has been noted for its remarkable performance for the broadband objective [9]. A combination of direct feedback control and adaptive feedforward control can improve the performance of the broadband active noise and vibration control [10]. The adding weight of the controller installation is another important issue [11]. The double panel with an air gap structure can provide the advantage of a low weight structure, is another common noise reduction method. Many control strategies have been discussed in the double panel structure [12-15].

In this paper, the comparison between various combinations of sensors-actuators, direct feedback control, and adaptive feedforward control are analyzed. A real time structural control has been done to prove the numerical conclusion; piezoelectric actuators can only effectively reduce the transmitted noise when they are attached to the dominant resonant panel [15]. This paper is composed of three sections. First, the multiple decentralized feedback and adaptive feedforward control theory are introduced. Second, the finite element method model and the experiment measurement methods are described. Finally, the control performances of various control strategy combinations are compared and discussed.

2. Multiple decentralized control

2.1 Feedback control

A direct feedback control loop was applied in our system. The error signal matrix $\mathbf{e}(j\omega)$ can be derived as $(\mathbf{I}+\mathbf{G}(j\omega)\mathbf{H}(j\omega))^{-1}\cdot\mathbf{d}(j\omega)$, where $\mathbf{G}(j\omega)$ is the plant transfer matrix, $\mathbf{d}(j\omega)$ is the noise source matrix and $\mathbf{H}(j\omega)$ is the control matrix. To present the interactions between multiple control units, the plant transfer matrix $\mathbf{G}(j\omega)$ is fully coupled as,

$$\mathbf{G}(j\omega)=\begin{bmatrix}\mathbf{G}_{11}(j\omega) & \cdots & \mathbf{G}_{1m}(j\omega)\\ \vdots & \ddots & \vdots\\ \mathbf{G}_{l1}(j\omega) & \cdots & \mathbf{G}_{lm}(j\omega)\end{bmatrix} \tag{1}$$

where $\mathbf{G}_{lm}(j\omega)$ is the transfer matrix from the m$^{\text{th}}$ actuator to the l$^{\text{th}}$ sensor.

In theory, the control stabilities can be unconditionally stable when the sensors and the actuators are collocated; otherwise the control gain is limited. By the Nyquist criterion, the MIMO decentralized control system is said to be stable when the plot of $\det[\mathbf{I}+\mathbf{G}(j\omega)\mathbf{H}(j\omega)]$ neither crosses nor encircle the origin (0, 0) [9]. Gain margin, phase margin and modulus margin are used to represent the perturbation endurance of the system in this paper.

2.2 Adaptive feedforward control

In the feedforward control part, the cost function is defined as the squared error signals plus the squared control signals with en effort weighting factor β (Eq. (2)). $\mathbf{e}^{\mathrm{H}}$ is the Hermitian matrix of $\mathbf{e}$. Steepest descent algorithm was used for the adaptive controller. Then, the control signal can be derived as Eq. (3). To guarantee the stability of the system, the real parts of the eigenvalues $\boldsymbol{\lambda}$ of the matrix $\hat{\mathbf{G}}^{\mathrm{H}}\mathbf{G}+\beta\mathbf{I}$ need to be positive. Otherwise, β can be set to $-\min\mathrm{Re}(\boldsymbol{\lambda})$ to make the system just stable [16]. However, feedforward control needs perfect knowledge of reference signal, therefore the control results may only apply for tonal noise.

$$J=\mathbf{e}^{\mathrm{H}}\mathbf{e}+\beta\mathbf{u}^{\mathrm{H}}\mathbf{u} \tag{2}$$

$$\mathbf{u}=-[\hat{\mathbf{G}}^{\mathrm{H}}\mathbf{G}+\beta\mathbf{I}]^{-1}\hat{\mathbf{G}}^{\mathrm{H}}\mathbf{d} \tag{3}$$

3. Model analysis and measurement

An accurately estimated finite element model was built [15]. Fig. 1 shows the configuration of the simulation model. The primary noise source was produced by an incident spherical pressure wave from the corner of the bottom side, which can produce an asymmetric incident noise wave. The double panel structure was modeled by two simply supported panels and a cavity with 35mm thickness. The lower panel (the incident panel) was 2mm thickness aluminium panel and the upper panel (the radiating panel) was 5.8mm thickness honeycomb panel. And hard-wall boundaries were set for these cavity side walls.

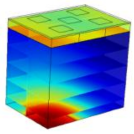

Figure 1: Acoustic-structure interaction model.

For the real time control, a double panel mounted on a rectangular box was set up for measurement (Fig. 2). A loudspeaker in the bottom of the rectangular box generated the primary noise source. This box was made with 40 mm thick walls of acrylic plates to prevent the sound from leaking through side walls. On each panel, there were both 5 velocity sensors and 5 piezoelectric patches on it. The kinetic energy of the radiating panel was measured by these 5 velocity sensors on the radiating panel. Further parameters and details refer to our previous papers [15, 17].

Figure 2: Experiment configuration.

4. Results discussion

4.1 Structural control with piezoelectric patches

Our previous numerical research showed that piezoelectric actuators can only effectively reduce the transmitted noise when they are attached to the dominant resonant panel [15]. Fig. 3 shows the kinetic energy of the radiating panel, which can represent the radiating sound pressure level of the panel in the far field at low frequencies. In this frequency range, both incident panel and radiating panel dominate the resonant energy. In order to reduce all the resonant peaks, 10 piezoelectric actuators were used to control these two panels. However, the interaction of these two panels reduces the system stabilities. The control gain is limited by the stability. The increasing complication of two independently controlled panels brings less stability; therefore the control performance of 10 piezoelectric actuators is also limited.

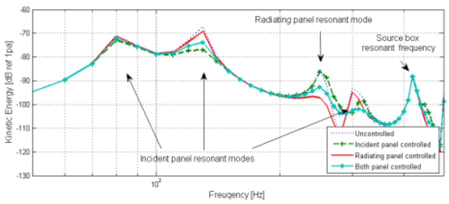

Figure 3: Piezoelectric actuators control performance.

In the real time control, 5 piezoelectric patches and 5 velocity sensors are attached to the radiating panel. Fig. 4 shows piezoelectric actuators can effective reduce all the resonant peaks except the source box resonant peak in the single panel structure. In the double panel structure, radiating-panel piezoelectric actuators can only reduce certain peaks (Fig. 5). The results of the real time control can prove the conclusions from the numerical analysis. Piezoelectric actuators can only effectively reduce the resonant peaks when they are attached to the dominant resonant panel.

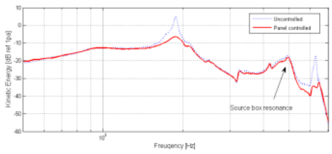

Figure 4: Single panel control result.

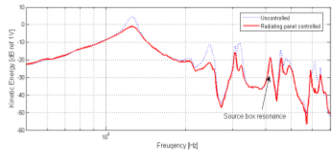

Figure 5: Double panel control result.

4.2 Actuators and Sensors comparison

Various sensor-actuator control strategies for direct feedback control in the double panel system had been analyzed. Three combinations are presented here. (1) 10 piezoelectric actuators and 10 velocity sensors (5 sets on each panel). (2) 6 loudspeakers modified to operate as pressure sources (loudspeaker with pressure source in the following description) and 6 microphones. (3) 6 loudspeakers with acceleration source and 6 microphones. Fig. 6 is the configuration of the 6 loudspeakers and 6 microphones. Fig. 7 shows the control performance comparison, which is based on equal control gain margin, phase margin, and modulus margin (Table 1). The loudspeakers with pressure source feedback control can create more noise reduction in this double panel structure.

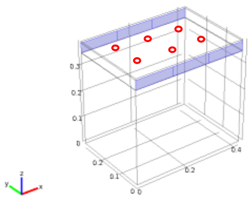

Figure 6: 6 Loudspeakers configuration.

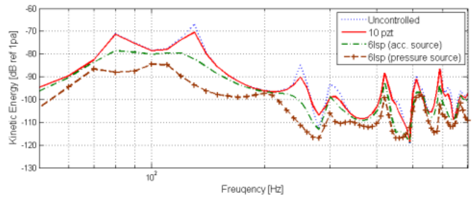

Figure 7: Control performance comparison.

Table 1: Stabilities and energy reduction.

Combinations	6 loudspeakers (acc. Source)	6 loudspeakers (pressure source)	10 pzt (inc. & rad. panels)
Control gain	0.001	0.77	265 (inc.); 150 (rad.)
Gain margin	Inf.	Inf.	Inf.
Phase margin	-76.2^{o}	-76.0 ^{o}	-76.1 ^{o}
Modulus margin	1.04	0.99	1.00
Total energy reduction* [dB]	**7.28**	**14**	**1.56**

* **(10*log$_{10}$(ΣKE_uncontrolled/ΣKE_controlled)**

4.3 Feedback and feedforward combination

Various actuators- sensors in feedforward control such as loudspeakers, piezoelectric patches on the radiating panel, and piezoelectric patches on both panels were chosen to be combined with various actuators-sensors in the feedback control such as loudspeakers, radiating-panel piezoelectric patches. With the noise reduction comparison between these combinations, we found piezoelectric patches on the radiating panel in the feedforward control combining pressure source loudspeakers in the feedback control can provide the largest improvement of the control effect. The combined control performance is shown in Fig. 8.

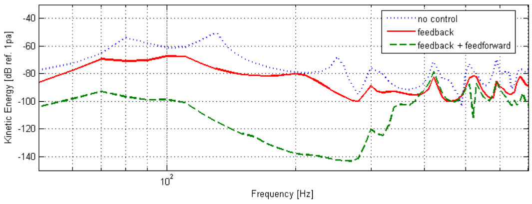

Figure 8: Combined control result.

5. Conclusions

Through the numerical analysis and the experiment measurement, this paper has shown that in the direct feedback control, piezoelectric actuators should be simultaneously applied to both the incident panel and the radiating panel in a double panel structure. However, the interactions between these two panels would reduce the control stability and limit the control performance. Loudspeakers modified to operate as pressure sources can provide more noise reduction than panel attached piezoelectric patches in feedback control loop.

The combination of direct feedback control and adaptive feedforward control can further reduce the transmitted noise. From the comparison between various combinations, it shows piezoelectric actuators on the radiating panel in the adaptive feedforward control combines with the loudspeakers modified to operate as pressure sources in the feedback control can reach the lowest noise transmission.

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References

1. Pan, J. and C. Bao (1998). "Analytical study of different approaches for active control of sound transmission through double walls." Journal of the Acoustical Society of America 103: 1916-1922.
2. Kaiser, O. E., S. J. Pietrzko, et al. (2003). "Feedback control of sound transmission through a double glazed window." Journal of Sound and Vibration 263: 775-795.
3. Carneal, J. P. and C. R. Fuller (2004). "An analytical and experimental investigation of active structural acoustic control of noise transmission through double panel systems." Journal of Sound and Vibration 272: 749-771.
4. Nelson, P. A. and S. J. Elliott (1992). Active Control of Sound. London, Academic Press.
5. Gardonio, P., E. Bianchi, et al. (2004). "Smart panel with multiple decentralized units for the control of sound transmission. Part I: theoretical predictions." Journal of Sound and Vibration 274: 163-192.
6. Gardonio, P., E. Bianchi, et al. (2004). "Smart panel with multiple decentralized units for the control of sound transmission. Part II: design of the decentralized control units." Journal of Sound and Vibration 274: 193-213.
7. Gardonio, P., E. Bianchi, et al. (2004). "Smart panel with multiple decentralized units for the control of sound transmission. Part III: control system implementation." Journal of Sound and Vibration 274: 215-232.
8. Berkhoff, A. P. and J. M. Wesselink (2009). Combined MIMO adaptive and decentralized

controllers for broadband active noise and vibration control. International Symposium on Active Control of Sound and Vibration, Ottawa, Canada, INCE.
9. Elliott, S. J., P. Gardonio, et al. (2002). "Active vibroacoustic control with multiple local feedback loops." Journal of the Acoustical Society of America 111: 908-915.
10. Wesselink, J. M. (2009). A rapid prototyping system for broadband multichannel active noise and vibration control. Ph.D Thesis, Univerisity of Twente.
11. Berkhoff, A. P. (2004). Weight reduction and transmission loss tradeoffs for active/passive panels with miniaturized electronics. International Symposium on Active Control of Sound and Vibration. Washington DC, USA, INCE: 1-12.
12. Mao, Q. and S. Pietrzko (2010). "Experimental study for control of sound transmission through double glazed window using optimally tuned Helmholtz resonators." Applied Acoustics 71(1): 32-38.
13. Alujevic, N., P. Gardonio, et al. (2008). "Smart double panel with decentralized active dampers for sound transmission control." AIAA Journal 46: 1463-1475.
14. Alujevic, N., P. Gardonio, et al. (2011). "Smart Double Panel for the Sound Radiation Control: Blended Velocity Feedback " AIAA Journal 49(6): 1123-1134.
15. Ho, J. H. and A. Berkhoff (2011). Panel Resonance Control and Cavity Control in Double-Panel Structures for Active Noise Reduction. 22nd International Conference on Adaptive Structures and Technologies, ICAST, Corfu, Greece.
16. Elliott, S. J. and C. C. Boucher (1994). "Interaction between multiple feedforward active control systems." Speech and Audio Processing, IEEE Transactions on 2(4): 521-530.
17. Ho, J. H., J. Kalverboer, et al. (2012). Comparisons between various cavity and panel noise reduction control in double-panel structures. THE ACOUSTICS 2012 HONG KONG conference and exhibition, Hong Kong, The Hong Kong Institute of Acoustics.