Active Noise Control Experiments for an Acoustic-Structural Coupled Enclosure using Structural-Based Virtual Sensors

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ABSTRACT

This work was focused on the implementation of an active noise control strategy for an acoustic-structural coupled enclosure using structural-based virtual sensors. A virtual sensing system was developed to estimate the broadband sound pressure at virtual interior locations in the enclosure based on structural vibration measurement of its flexible structure, instead of using acoustic sensors. Experiments on a panel-cavity test rig were performed and an active control system using the FX-LMS algorithm was used to minimize the noise at a virtual location based on accelerometer measurements. Experiment results showed that the broadband noise level at the virtual location was suppressed even when the actual system dynamics was perturbed from the original one, demonstrating the robustness of active noise control system.

Keywords: virtual sensors, active noise control, structural-acoustic coupling, structural sensing
I-INCE Classification of Subjects Number(s): 38.2

1. INTRODUCTION

There has been the need to control excessive interior noise in an enclosure or a cavity for various engineering applications. To achieve this, an active noise control strategy can be utilized together with acoustic sensors that measure the interior sound pressure. In this case, the acoustic sensors act as error sensors that generally need to be placed at target locations for noise control. However, it may not be practical to place acoustic sensors physically at target locations. As an alternative, acoustic sensors can be placed 'virtually' at the target locations, using the virtual sensing method. In this method, the physical sensors can be placed at some distance away from the target locations. A number of virtual sensing methods, such as (1-10), have been proposed that demonstrate the feasibility of using virtual sensors for active noise control. Elliot and David (1) proposed the use of virtual microphone method for estimating the sound pressure away from the physical microphone location. The remote microphone method was used by Popovich (2) and Roure & Albarrazin (3) using a set of transfer functions for the sound pressure prediction. There is also the virtual sensing method that uses multiple microphones based on a polynomial extrapolation of acoustic signals, which does not require *a priori* system identification (5). Another method uses Kalman filter-based virtual sensors (7,10) to estimate the sound pressure at virtual locations. Petersen *et al*. (7) use physical acoustic sensors for estimating the interior sound pressure, while Halim *et al.* (10) utilize physical structural sensors for sound pressure estimation in an acoustic-structural coupled enclosure. For vibro-acoustic systems, the use of structural sensors can be beneficial since such sensors are generally non-bulky (e.g. compact piezoelectric sensors can be used) and they can be placed away from the interior of enclosure. The work by Halim *et al.* (10,11) is focused on developing a vibro-acoustic virtual sensing method for active noise control but it is yet to be applied experimentally. Therefore, this work will further investigate the design of vibro-acoustic virtual sensor for active noise control based on experimental analysis.

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2. EXPERIMENTS ON AN ACOUSTIC-STRUCTURAL COUPLED ENCLOSURE

A test rig was built at the Hong Kong Polytechnic University for investigating the proposed virtual sensing and noise control performances. A rectangular coupled panel-cavity test rig is depicted in Figure 1 with the X-Y-Z coordinate system. A rectangular aluminium panel of thickness 3mm was placed on the X-Y plane, and it’s X- and Y- dimensions were 380mm and 510mm, respectively. Grooves were cut out along the panel sides and the panel’s edges were clamped to the cavity to approximate simply-supported boundary conditions of the panel. The Z-dimension of the cavity could be changed to either 630mm or 640mm, allowing the system dynamics to be perturbed to test the virtual sensing robustness. Two loudspeakers were used as primary and secondary acoustic disturbances, whose locations are shown in Figure 1. In order to measure the panel vibration and interior noise, an accelerometer and a microphone were utilized. A B&K 4374 accelerometer was attached to the Aluminium panel at (*x*,*y*)=(165mm, 249mm), while a ½” B&K 4942 microphone were located inside the cavity at (*x*,*y*,*z*)=(315mm, 235mm, 365mm). This microphone location was used as the virtual sensor location, and the virtual sensing accuracy was evaluated by comparing the sound pressure estimation with the actual sound pressure measurements from the physical microphone.

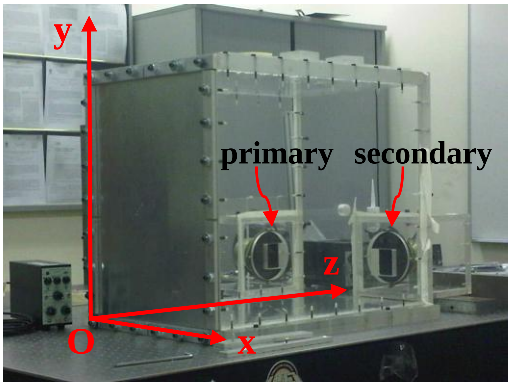
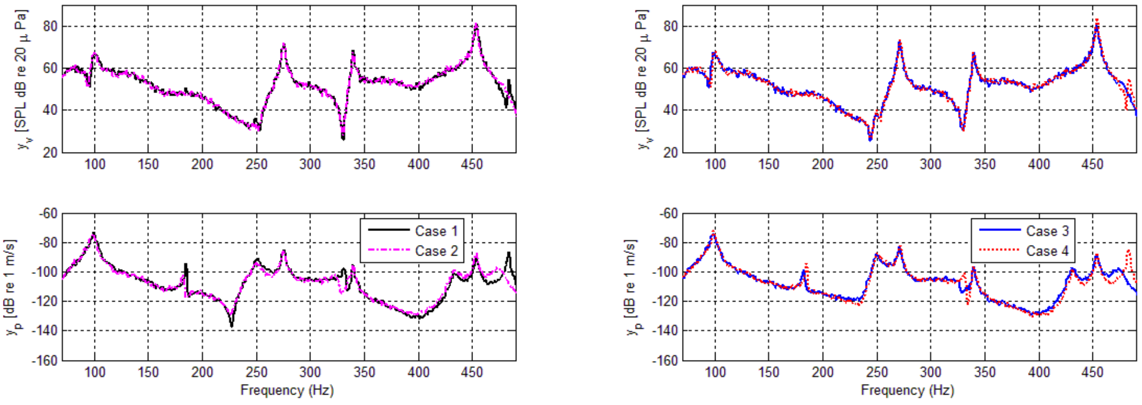


Figure 1 – Test rig: an acoustic-structural coupled enclosure.

To test the robustness of virtual sensing and active control system, several configurations of test rig were investigated. Figure 2 shows the results of structural and acoustic measurements from the test rig for 4 different cases. Cases 1 and 2 considered the panel-cavity system with the acoustic cavity (X,Y,Z) dimensions of (380mm, 510mm, 630mm). For case 2, however, the upper clamps of panel were partly removed to modify the boundary conditions of the panel, so to perturb the dynamics of panel-cavity system. In addition, cases 3 and 4 have a slightly larger cavity (X,Y,Z) dimensions of (380mm, 510mm, 640mm). Similar to case 2, case 3 considers the case where the upper clamps of panel were partly removed.



(a) (b)

Figure 2 – Sound pressure, y_v, and velocity, y_p, frequency responses for (a) cases 1-2 and (b) cases 3-4.

3. ROBUST VIRTUAL SENSING DESIGN

Having obtained structural and acoustic measurements from the test rig, a practical design of virtual sensor filter is considered in this section. A robust virtual sensor filter was proposed by Halim *et al.* (10) for acoustic-structural coupled systems. The general configuration of the virtual sensor filter is described in Figure 3 with possible structural and acoustic disturbances sources entering into the system. The task is to design a robust virtual sensor filter, F, to estimate the sound pressure at virtual locations, y_v , using measurements from structural sensors, y_p , which can be corrupted by measurement noise, v_p.

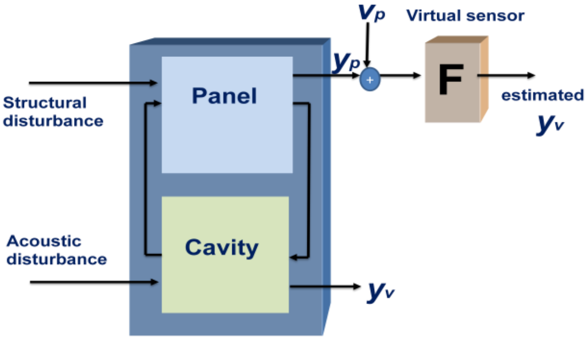


Figure 3 – The vibroacoustic virtual sensor (10).

Consider a vibroacoustic system that can be modeled as a linear time-invariant state space model:

$$\dot{\sigma}(t) = A\sigma(t) + B_d d(t) + B_u u(t) \quad (1)$$

$$y_p(t) = C_p \sigma(t) + v_p(t) \quad (2)$$

$$y_v(t) = C_v \sigma(t) \quad (3)$$

where $A, B_d, B_u, C_p, C_v, \sigma, d, u$ respectively describes the state matrix; input matrices for disturbance and control inputs; output matrices for structural and acoustic measurements; state vector; structural/acoustic disturbance input vector; and the control input vector.

The task now is to consider how a virtual sensor filter can be designed so that it will be sufficiently robust in the case of certain variations in system dynamics. In other words, when there are changes in dynamics of a vibro-acoustic system, the virtual sensor filter are still able to estimate the sound pressure at virtual locations with reasonable accuracies. As a consequence, the implemented active noise control system will still be able to minimize the interior noise level sufficiently. To address these important issues, the potential dynamic variation of vibro-acoustic system needs to be considered during the virtual sensor design. An architecture for a robust virtual sensor was proposed by Halim *et al* (10):

$$F(\omega) = \sum_{j=1}^{L} \theta_j F_j(\omega) \quad (4)$$

where ω is the frequency of interest, $\theta \in \Theta$ with $\Theta = \{\theta \in \mathbb{R}^L, \sum_{i=1}^{L} \theta_i = 1, \theta_i \geq 0\}$ and L is a positive integer number. The robust virtual sensor filter is a convex combination of multiple Kalman filters, and θ_i is the relative contribution of each Kalman filter to the robust virtual sensor filter. The practical implementation of such a design is explored in this work, considering 4 different cases of vibro-acoustic system.

As previously discussed, there are 4 cases that are considered for the virtual sensor design. The state space models for 4 cases were obtained using the Subspace System Identification method. It is decided to use cases 1 and 3 as the representative systems for developing the virtual sensor filter. For each case, a Kalman filter is designed using the robust virtual sensor method in (10). Let’s describe virtual sensor filters #1 and #2 as Kalman filters developed for cases 1 and 3, respectively. The robust virtual sensor is then developed by a convex combination of virtual sensor filters #1 and #2 as in Eq. (4) with θ_1 and $\theta_2 = 1 - \theta_1$ to be optimized.

For this optimization, the primary objective is to achieve robust sensing for all 4 cases of vibro-acoustic system. To achieve this, a constrained minimax optimization was performed to minimize the worst variance of the estimation error, $e_v = y_v - \hat{y}_v$, where $\hat{y}_v$ is the estimated acoustic pressure by the virtual sensor filter. Here, the variance is normalized with respect to the variance of the actual acoustic pressure at virtual location, y_v. A random noise was introduced to the enclosure, and a band-pass filter 60-500 Hz was used, so to focus the sensing and control only for this frequency region. These measurements were done for all 4 cases using either virtual sensors #1 or #2. Figure 4 shows the normalized error variance for varying θ_1. A constrained minimax optimization was then performed, and the obtained optimal solutions for θ_1 and θ_2 were 0.74 and 0.26 respectively. Based on these results, a robust virtual sensor filter was developed as a convex combination of two Kalman filters. As can be seen from the optimization results, the robust virtual sensor filter is contributed more by the virtual sensor #1, compared to virtual sensor #2.

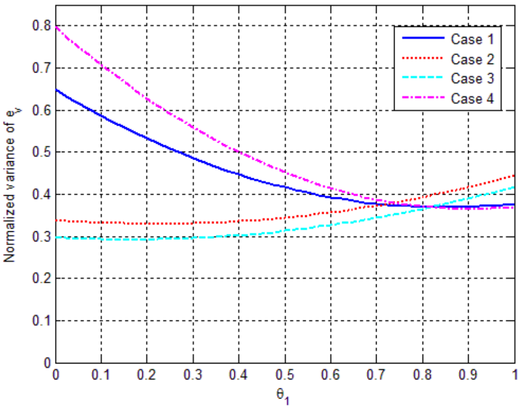


Figure 4 – Normalized variance of estimation error vs θ_1.

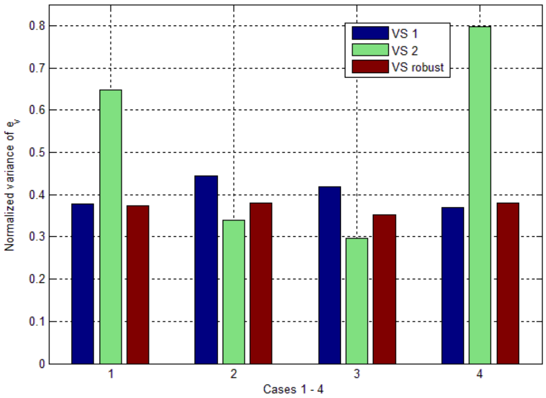


Figure 5 – Estimation accuracy of 3 different virtual sensors for cases 1-4: virtual sensor # 1 (VS1), virtual sensor # 2 (VS2) and the robust virtual sensor (VS robust).

Considering the estimation results, 3 virtual sensor filters are implemented and their accuracies for estimating the sound pressure at the virtual location are investigated. These are shown in Figure 6, which shows the virtual sensing performances for those virtual sensor filters, implemented for 4 cases. It can be seen that the sensing performance of the robust virtual sensor is consistent over those 4 cases. The virtual sensor #1 has also a reasonably good sensing performance. However, the sensing performance for virtual sensor #2 is significantly worse than the other two virtual sensors, particularly for case 4. This can be seen from Figure 6, where the estimation sound pressure is compared to the actual sound pressure for case 4. It is observed that the majority of virtual sensor filters are able to estimate the important resonances. There are inaccuracies at regions in between of resonances but this will not significantly impact on active control performance as it will be shown later. However, it is important to note that virtual sensor #2 has a poor estimation of resonance at around 490 Hz, as also reflected in Figure 5.

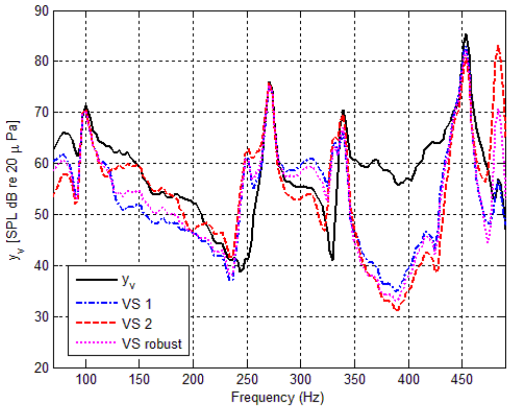
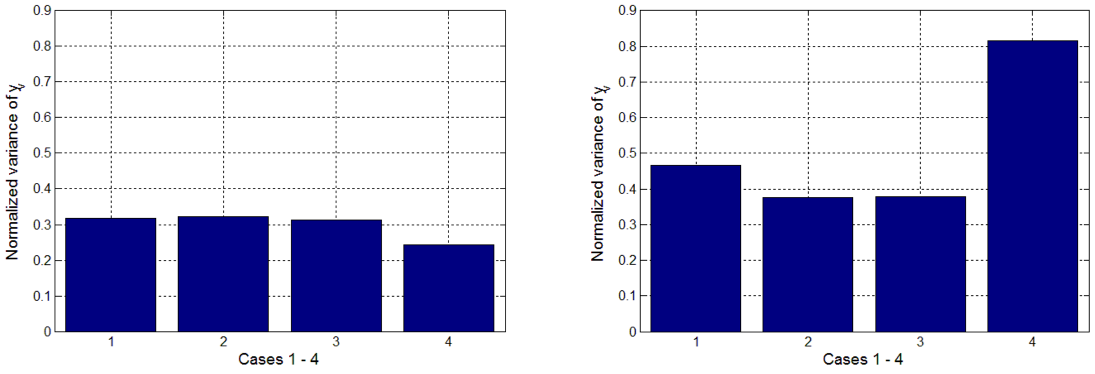


Figure 6 – Sound pressure frequency responses for various virtual sensors for case 4.

4. ACTIVE NOISE CONTROL EXPERIMENTS

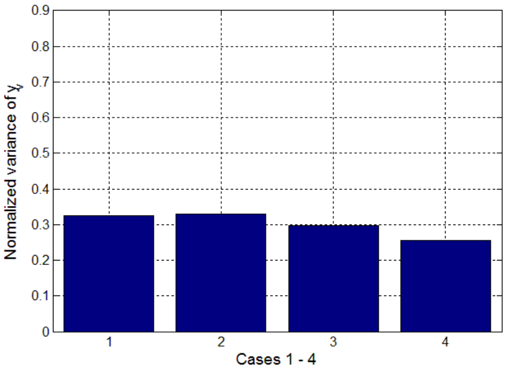
After the virtual sensors were designed, active noise control experiments were performed by using the Filtered-X LMS (FX-LMS) adaptive feedforward control algorithm (12). As shown in Figure 1, one of loudspeakers was used as the primary disturbance, while the other was used as the secondary disturbance to minimize the interior noise at the virtual sensor location. For a fair comparison of control performances, the secondary path system used in FX-LMS algorithm was all based on the averaged secondary path model for cases 1 and 3. Figure 7 depicts the control performance of 3 virtual sensor filters. It is observed that virtual sensor #2 has the worst noise control performance. This can be expected based on the previous discussion on its virtual sensing accuracy. Figure 8 demonstrates the control performance using virtual sensor #2, with an increase of noise level at 460-500 Hz.

On the other hand, the other 2 active noise control systems that were respectively based on virtual sensor #1 and robust virtual sensor, showed good noise control performances for all 4 cases. Although there was not much difference between the broadband control performances of those two controllers, it was observed in experiments that the controller using the robust virtual sensor has a better performance in reducing the resonance peaks.



(a)

(b)



(c)

Figure 7 – Noise control performances for cases 1-4 using (a) virtual sensor #1, (b) virtual sensor #2, and (c) the robust virtual sensor.

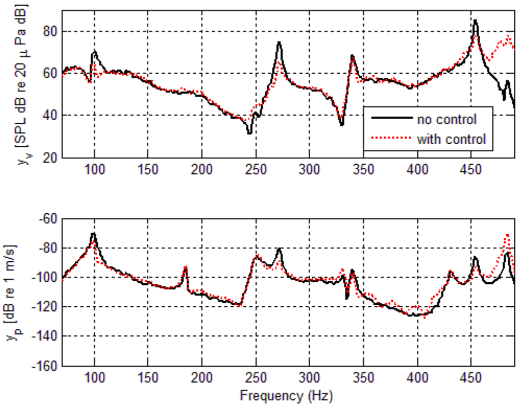
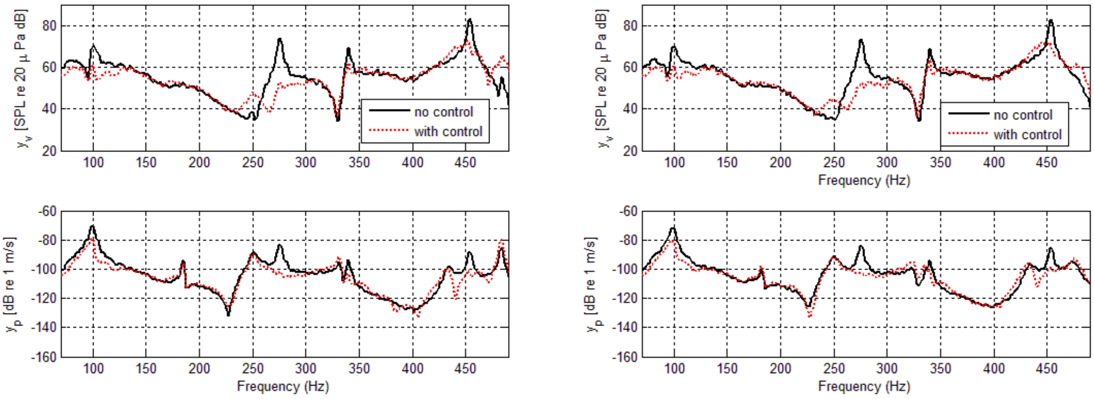
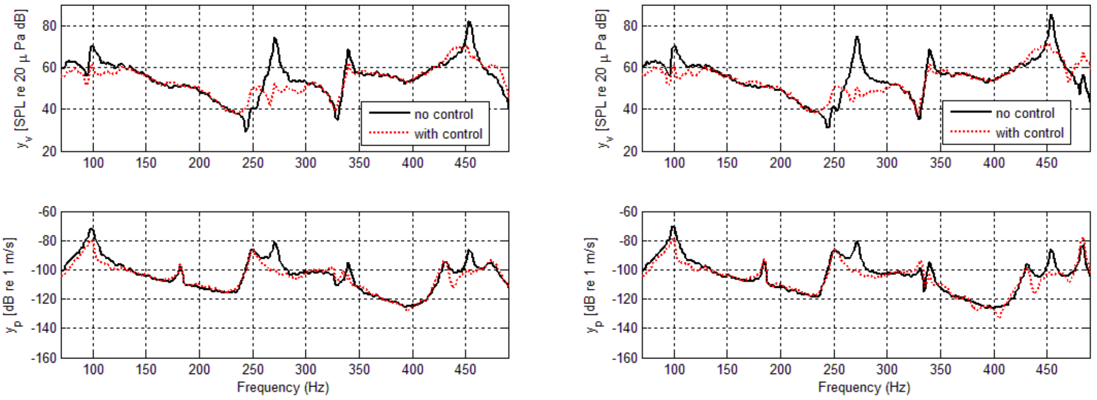


Figure 8 – Active control results for case 4 using virtual sensor #2.

Figure 9 shows the control performances for all cases using the robust virtual sensor. The implemented active noise control has been able to suppress the noise level particularly around the dominant resonances.



(a) (b)



(c) (d)

Figure 9 – Active control results using the robust virtual sensor:
(a) case 1, (b) case 2, (c) case 3, (d) case 4.

5. CONCLUSIONS

The experimental implementation of an active noise control strategy using structural-based virtual sensors has been presented. A robust virtual sensor filter was developed to deal with possible dynamic changes in a vibro-acoustic system, to ensure that a good noise control performance could still be achieved. The virtual sensor filter was designed as a convex combination of multiple Kalman filters that take into account potential variations in system dynamics. Experiments showed that the robust virtual sensor could estimate the interior sound pressure satisfactorily particularly at important resonance responses. It is shown that the proposed active control system was able to control the broadband interior sound pressure at a virtual location successfully even when the system dynamics have been perturbed. The results demonstrated the robustness of the virtual sensing and active control system. Therefore, the proposed robust virtual sensors can be used for various vibro-acoustic control applications, particularly the ones whose system dynamics is expected to change during control operations.

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