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ACTIVE CLUSTER CONTROL OF STRUCTURAL ACOUSTIC POWER USING SMART SENSORS

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ABSTRACT
This paper deals with the minimization of total acoustic power radiated from a vibrating distributed-parameter planar structure. This paper presents a novel control method utilizing both the smart sensors and cluster actuation, thereby enabling one to suppress the total acoustic power without causing observation/control spillover problems. First, the acoustic power matrix of a planar structure is shown to be expressed in a form of a block diagonal matrix by reordering the columns and rows of the matrix, and hence the suppression of the power mode defined in each block matrix leads to the suppression of the total acoustic power. Then, cluster control consisting of cluster filtering and cluster actuation is introduced, which permits one to control each cluster independently. Finally, the experiment is conducted, demonstrating the validity of the proposed method for suppressing the total acoustic power.

1 - INTRODUCTION
Minimization of the structural kinetic energy of a vibrating structure does not necessarily mean the minimization of the total acoustic power radiated from the structure. Sometimes the sound level increases while the vibration level decreases. Furthermore, the use of point sensors and actuators for controlling the structural vibration causes both the observation and control spillover problems leading to the instability of a control system.

To overcome the problems, this paper presents a novel control method utilizing both smart sensors [1] $\sim$ [4] and cluster actuation [5], thereby enabling the suppression of the total acoustic power without causing observation / control spillover problems. The smart sensor implemented with signal processing functions is realized by shaping PVDF film sensors with the aim to extract the acoustic power mode that is the common thread connecting directly the vibration field and acoustic field. Therefore, the suppression of the power mode leads to that of total acoustic power. The cluster actuation is a control strategy to activate the specific targeted cluster without inducing control spillover in the sense of cluster, its conceptual background being based upon cluster filtering; that is, all the structural vibration modes of a rectangular panel, for instance, may be filtered into four clusters − odd/odd modal cluster, odd/even modal cluster, even/odd modal cluster and even/even modal cluster. Among these, the odd/odd modal cluster is the greatest contributor to the total acoustic power. By introducing smart sensing and cluster control, the extraction and suppression of each cluster without causing spillover can be performed. This paper begins by discussing the acoustic power modes of a vibrating panel, presenting a method for suppressing the total acoustic power by suppressing the acoustic power mode. By employing the cluster control comprising both smart sensors and cluster actuation, the smart cluster feedback control system is constructed. Finally, the experiment is carried out, demonstrating the validity of the proposed method for suppressing the total acoustic power of a vibrating panel.

2 - ACOUSTIC POWER MODE
Consider some generic structure, subject to harmonic excitation by an unspecified primary forcing function. Then the total acoustic power radiated from the structure is written as

$$P_w = \mathbf{v}^H \mathbf{A} \mathbf{v} = \mathbf{v}^H \mathbf{Q} \mathbf{\Lambda} \mathbf{\Lambda}^{-1} \mathbf{v} = \mathbf{u}^H \Lambda \mathbf{u} \quad (1)$$

where $\mathbf{v}$ is the vector of complex modal velocity amplitudes, H is the matrix Hermitian, $\mathbf{A}$ is some real, symmetric, positive-definite acoustic matrix, $\mathbf{u}$ is the power modal amplitude vector, $\mathbf{Q}$ is the modal matrix and Λ is the diagonal matrix obtained by the orthonormal transformation

$$\mathbf{A} = \mathbf{Q} \Lambda \mathbf{Q}^{-1} \quad (2)$$

As can be seen from Eq. (1), $\mathbf{u}$ is given by

$$\mathbf{u}=\mathbf{Q}^{-1}\mathbf{v}=\mathbf{Q}^T\mathbf{v} \quad (3)$$

Accordingly, the velocity at $\mathbf{x}$ of a structure is expressed by

$$v(\mathbf{x}) = \Psi^T(\mathbf{x})\,\mathbf{v}=\Phi^T(\mathbf{x})\,\mathbf{u} \quad (4)$$

where Ψ and Φ are the vectors of the eigenfunction and power mode function, respectively. The relevance between these vectors are given by

$$\Phi(\mathbf{x}) = \mathbf{Q}^T \mathbf{\Psi}(\mathbf{x}) \quad (5)$$

The total acoustic power in Eq. (1) is, then, expressed as

$$P_w = \sum_{i=1}^{N_m} \lambda_i |u_i|^2 \quad (6)$$

where λ is the eigenvalue of $\mathbf{A}$, which is always positive and real due to the property of $\mathbf{A}$, and hence P_w is always suppressed when u_i, the power modal amplitude, is reduced. Furthermore, the acoustic power modes are combinations of like-index structural modes (odd/odd modes, odd/even modes, even/odd modes and even/even modes) which contribute independently to the acoustic radiation.

3 - CLUSTER CONTROL

The difficulty in controlling the vibration of a distributed-parameter structure lies in the infinite number of eigenfunctions (structural modes) present in a "real" system. The approach presented in this paper for tackling this problem is "cluster control" that consist of both "cluster filtering" and "cluster actuation". Cluster filtering places structural modes into a finite number of clusters, each cluster possessing some common property, while employing cluster actuation excites targeted clusters independently. Thus, by using both cluster filtering and actuation, cluster control avoids observation/control spillover in the sense of cluster. The end result means that groups of modes can be treated independently, and it becomes possible to preferentially direct control effort to the most bothersome clusters. This is an important result for structural acoustics, as the clusters containing volumetric modes can be preferentially dampened using a DVFB-like approach with guaranteed stability.

Unlike a conventional modal control approach using point sensors and point actuators for suppression of structural modes, cluster control aims to suppress the cluster of interest, leading to suppression of all structural modes belonging to the cluster.

With a view to giving further insight into the significance of cluster control, it is worthwhile using the specific example of controlling the odd/odd modal cluster. First, in order to construct the cluster control system, 4 sensors for cluster filtering and 4 actuators for cluster actuation are needed. Because of the shortage of paper, the development of formulas eliminated here, and the details will be shown in the presentation.

4 - EXPERIMENT

A steel test panel measuring 0.9 m x 1.8 m x 0.009 m was supported on knife edges fixed to the perimeter of the enclosure covered with absorbent material, an electro-dynamic shaker located at $\mathbf{r}$ = (0.2m, 0.21m) was installed to excite the plate, which was mounted on the bottom of the enclosure with anti-vibration rubber pads. In addition, four electro-dynamic shakers (control actuators) located at $\mathbf{r}_1$ = (0.15m, 0.16m), $\mathbf{r}_2$ = (0.75m, 0.16m), $\mathbf{r}_3$ = (0.15m, 0.166m), $\mathbf{r}_4$ = (0.75m, 0.166m) was driven by the feedback control signal from the smart sensor output. The disturbance force is measured by a force transducer installed between the shaker and panel.

The driving point accelerance is illustrated in Fig. 1 (a), which was obtained by the disturbance shaker driven by a broadband white noise with a frequency range between 10 and 500 Hz. As seen from the figure, there are twenty-two vibration modes from the (1,1) to the (4,1) mode.
Figs. 1 (b) $\sim$ (e) show the smart sensor outputs for the 1st power mode (odd/odd modal cluster), 2nd power mode (odd/even modal cluster), 3rd power mode (even/odd modal cluster) and 4th power mode (even/even modal cluster), respectively.

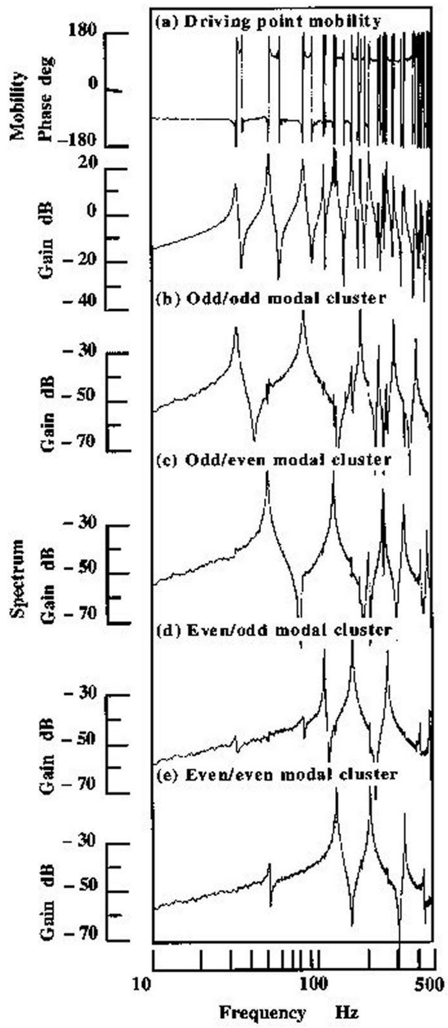

Figure 1: Driving point mobility and smart sensor outputs for each power mode.

Illustrated in Fig. 2 are the control effect for suppressing each smart sensor output by using the direct feedback control. As is seen from the figure, all the power modes are suppressed significantly without causing instability of the feedback control system.
Figure 3 depicts the spectrum of the acoustic power before and after control. In the frequency range from 32.5 to 34.5 Hz where the (1,1) mode exists, an acoustic power reduction of 22.1 dB has been achieved. Furthermore, in a broadband frequency range 23 $-$ 516 Hz the acoustic power level reduction of 10 dB was accomplished.

5 - CONCLUSIONS

A new control approach for suppressing the total acoustic power radiated from a planar structure using both distributed-parameter sensors and cluster actuation has been presented. It was found that the smart sensors based upon the shaped PVDF film may extract the targeted power mode. It was also found that the cluster actuation enables the independent excitation on the targeted cluster without causing control spillover in the sense of cluster. Experimental results demonstrate the validity of the proposed method for suppressing the total acoustic power radiated from a vibrating panel.

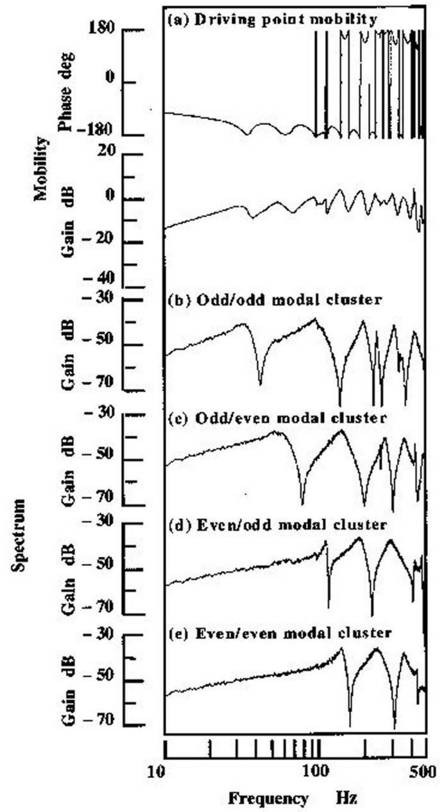

Figure 2: Smart sensor outputs after cluster control.

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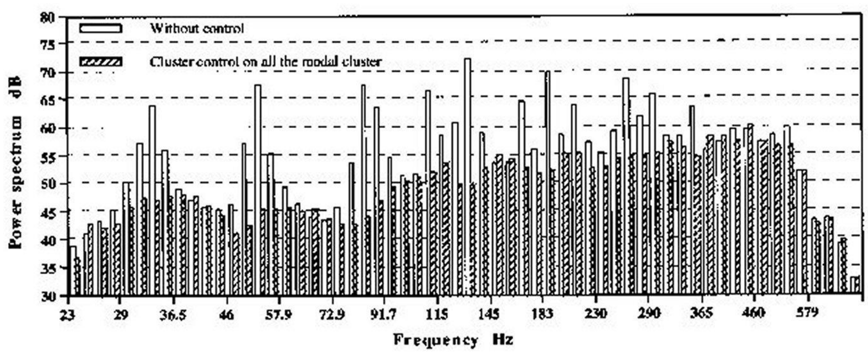

Figure 3: Sound power spectrum before and after cluster control.