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Optimal Design of Exciter Array to Minimize Bending Mode Effect of Multi-Actuator Panels in Beamforming

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ABSTRACT

Recently, flat-panel loudspeakers have been applied to many product designs as a way to solve space constraints when installing speakers. In addition, multi-actuator panels with multiple exciters on the panel can be used for sound field control such as sound field synthesis and beamforming, instead of conventional cone-type loudspeaker arrays. At this time, the bending mode of the panel adversely affects the control performance. Conventional multi-actuator panel solves this problem by using a panel having a large damping loss factor. However, it is difficult to apply this method when the material properties or geometry of the structure cannot be changed. In this regard, this study aims to minimize the bending mode effect of the panel on beamforming performance through the optimal exciter array design. Vibration localization factor is used to investigate the bending mode effect of the panel. Simplified forms of vibration localization factor based on mode frequency and modal participation factors are used to optimize the exciter position. The optimized exciter array design minimizes the bending mode effect of the panel in a controllable frequency range, reducing abrupt changes of beamforming performance.

Keywords: Flat-panel loudspeaker, Multi-actuator panel, Bending mode effect, Beamforming, Array optimization
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1. INTRODUCTION

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In recent years, flat-panel loudspeakers have been increasingly applied to structures that lack space for installing conventional cone-type loudspeakers such as flat-panel displays or mobile phones.

Flat-panel loudspeakers emit sound through the vibrations of the structure without using additional cones, so there is no restriction on the installation space[1]. However, when compared with cone-type loudspeakers, it also has disadvantages in terms of sound quality such as frequency response and transient characteristics[2]. The low sound quality of the flat-panel loudspeaker is due to the bending mode of the panel [3].

In addition, the bending mode of the panel adversely affects not only the sound quality but also the beamforming performance of the multi-actuator panel (MAP). For commercial MAP, a panel with large structural damping is used for independent vibrations of each exciter. The use of a panel with large structural damping allows the vibration energy of the exciters to be concentrated near the excitation point, enabling sound field control like a conventional loudspeaker array[4]. On the other hand, if the damping of the panel is not large enough, the independency of each exciter and the beamforming performance may be degraded due to the bending mode effect.

In this study, beamforming performance is improved by minimizing the bending mode effect of the MAP by optimizing the position of the exciter without changing the damping of the panel. Modal overlap and vibration localization factor are used to quantify the bending mode effect of the panel, and simplified objective function based on modal parameter is used for exciter position optimization. Finally, the localization factor and the directivity before and after the exciter position optimization are compared to confirm whether the bending mode effect and the beamforming performance of the panel are improved.

2. MODAL PARAMETERS AND BENDING MODE EFFECTS OF PANEL

2.1 Vibration response of point-excited panel

When the vibrations of the point-excited thin plate are represented by the mode-superposition method, the vibration response at the excited position can be separated into terms for the two modal parameters as follows[5],

$$v(x_j, y_j) = \sum_{n=1}^{\infty}\left[\left(\sum_{i=1}^{N} A_i \psi_n^i \psi_n^j\right)\frac{j\omega}{\Lambda_n\left\{\omega_n^2\left(1+j\eta_n\right)-\omega^2\right\}}\right]. \qquad (1)$$

ψ_n^i and ψ_n^j are modal participation factors, representing the n-th mode shape at i-th and j-th points, respectively. ω_n and η_n are the frequency and damping loss factor of n-th mode, respectively. The first term includes the magnitude and phase information of each mode at the excitation point, and the second term represents the contribution of each mode at the excitation frequency.

2.2 Modal overlap

Modal overlap (MO) is defined as the number of modes excited above a certain magnitude at the excitation frequency[6]. It can be seen from Equation 1 that the closer the excitation frequency and the mode frequency are, and the larger the damping, the higher the contribution of the mode.

2.3 Vibration localization factor

The localization factor (LF) is defined as the ratio of the vibration energy in the region near the i-th excitation point to the vibration energy in the entire panel region[6].

$$LF(\omega) = \frac{\int_{S_i} D^2\left(x, y, j\omega\right) dS}{\int_{S} D^2\left(x, y, j\omega\right) dS} \tag{2}$$

If the magnitude and phase of each mode are the same at the i-th point, the vibration energy is concentrated near the excitation point where the various modes are uniformly overlapped and the LF is increased. Therefore, it is possible to determine whether a single bending mode occurs by measuring LF.

3. ARRAY OPTIMIZATION

3.1 Objective function

In order to minimize the bending mode effect of the panel, it is necessary to find a point where LF becomes maximum. However, in order to calculate the LF, a response is required in the entire area of the panel, so that a computation cost is incurred. Therefore, in the optimization of the exciter position, the following simplified equation is used.

$$B^i_{n-1,n} + B^i_{n,n+1} \tag{3}$$

$B^i_{n-1,n}$ and $B^i_{n,n+1}$ represent the magnitude and phase difference between the n-1-th and n-th modes, n-th and n+1-th modes at the i-th point, respectively. If the magnitude and phase difference of the adjacent two modes are small at each excitation point, it can be expected that the LF increases due to the uniform overlap of the respective modes. It is therefore possible to minimize the bending mode effect by minimizing Equation 3.

3.2 Optimization results

As the simulation model of the MAP, an aluminum panel with a size (0.6 m x 0.3 m x 3 mm) and a damping loss factor of 0.00135 was used. Six exciters were arranged at uniform intervals on the horizontal line at the same distance from the horizontal centerline of the panel to maintain the symmetry of the sound field. The X axis and Y axis positions of each exciter before and after the optimization are shown in Table 1.

Table 1 – Initial and optimal positions of the 6 exciters.

	Exciter #	1	2	3	4	5	6
Initial	X position (m)	-0.150	-0.090	-0.030	0.030	0.090	0.150
	Y position (m)	-0.023 and 0.023					
Optimal	X position (m)	-0.190	-0.110	-0.038	0.038	0.110	0.190
	Y position (m)	-0.081 and 0.081					

4. SIMULATION RESULTS

4.1 Beamforming configuration

The simulation model for investigating beamforming performance of MAP is shown in Fig. 1.

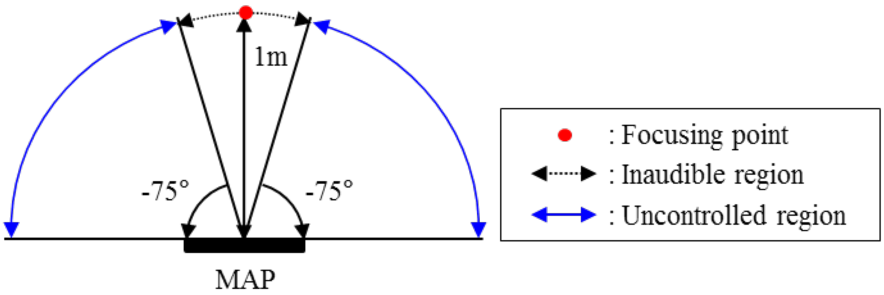

Fig. 1 – Beamforming configuration of MAP

Focusing point is the point where acoustic energy is concentrated, and inaudible region is the area where acoustic energy is minimized. Uncontrolled region is excluded from the control region for beamforming. The acoustic energy difference method was used for the beamforming and the parameters were optimized for each frequency to keep the acoustic energy of the focusing point above a certain level [7].

4.2 LF and directivity

Fig. 2(a) and Fig. 2(b) shows the LF and directivity plot before and after the exciter position optimization. Compared with Fig. 2(a) and Fig. 2(b), it can be seen that the LF and directivity increase around 2500 Hz after the excitation position optimization.

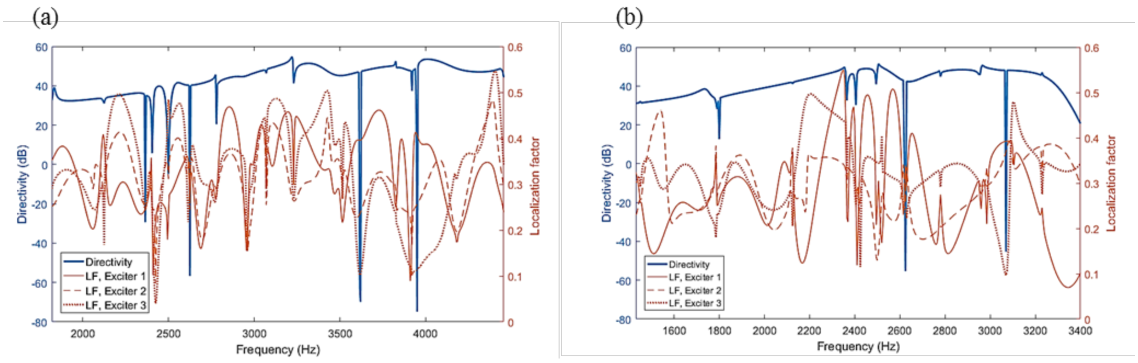

Fig. 2 – LF and directivity plot; (a) initial, and (b) optimal exciter position

4.3 Gain plot

Fig. 3 (a) and Fig. 3 (b) shows the gain plot before and after the exciter position optimization. Compared with Fig. 3(a) and Fig. 3(b), it can be seen that the sudden change in sound pressure near 2500 Hz is reduced after the exciter position optimization. Therefore, it can be confirmed that the bending mode effect and the beamforming performance of the MAP can be improved through exciter position optimization.

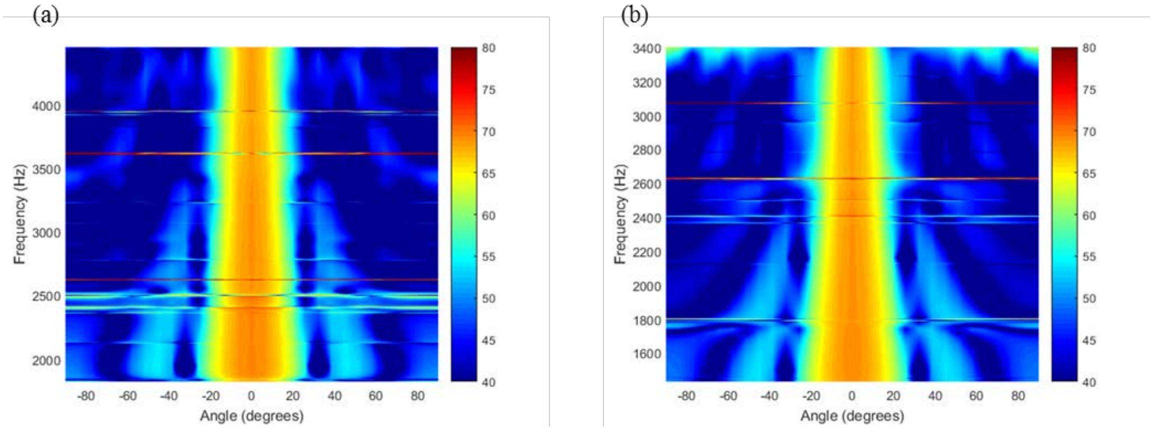

Fig. 3 – Gain plot; (a) initial, and (b) optimal exciter position

5. CONCLUSIONS

In this study, optimization of the exciter position was performed to reduce the bending mode effect of the MAP. MO and LF were used to quantify the bending mode effect. In the excitation position optimization, a simplified objective function based on modal parameters was used instead of MO and LF, which have high calculation cost. As a result of comparing the LF, directivity and gain plot of the initial and optimum exciter positions, it was confirmed that the bending mode effect of the MAP was reduced as a result of the exciter position optimization. The results of this study can be used to reduce the mode effect of the system in vibration and sound control.

6. ACKNOWLEDGEMENTS

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