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PARAMETRIC STUDY IN THE FORMATION OF A VIRTUAL SPEAKER AND BAFFLE ON A THIN PANEL

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Any thin panel can be converted into a speaker and baffle system, if the actuator array surrounding the panel is properly tuned. Different from the sound radiation from a plate excited by an actuator attached to the panel, the sound quality and radiation efficiency become similar to the actual loudspeaker system. Limitations in the location and space of conventional speaker systems can be also avoided. To this end, the concept of acoustical holography can be adopted so as to realize a rendered vibration field, i.e., speaker and baffle, on a panel by using the inverse determination of magnitude and phase weightings for the array actuators. Considering the sound radiation characteristics, the rendering parameters like speaker size, location, number of modes, actuator number, and actuator spacing affect the end result. In this work, relationships between rendering parameters and radiation performance are studied. To validate the present control method, numerical simulation is performed on a thin, simply-supported, rectangular plate. It is seen that the radiated sound has two dip patterns in its typical spectrum. One is related to the speaker size: dips appear when the Helmholtz number, determined by bending wavenumber and speaker radius, coincides with radial mode. The other dip pattern is mostly affected by the speaker location. It is also shown that the redundancy of actuators due to their relative positions can be eliminated by assuring the independency among actuator positions.
Keywords: virtual speaker and baffle, vibration field rendering, actuator array

1. Introduction

General electronic devices or vehicles include audio systems in order to transfer auditory information for the users. As devices have been developed to be lighter, thinner or more compact in an aesthetic point of view, supplemental equipment including additional speaker and amplifier which need exorbitant price and the extra space for them has been required to obtain the satisfactory sound so far. A thin panel can be virtually converted into a set of speaker and baffle by using actuator array at the periphery of the panel [1,2]. Such virtual speaker-baffle system can be used for compensating the low frequency responses of the pre-installed speaker by rendering virtual woofer at the central zone of the panel [3]. In this work, to understand the relationships between acoustic performance and rendering parameters including speaker size and location, a theoretical study is conducted by employing the numerical simulations with a simply-supported plate.

2. Theoretical background

If single actuator excites a certain location in the panel, bending wave propagates through the panel in all directions from the excitation point. The actuator has its own vibratory characteristic which affects the observations points depending on its location and dynamic characteristics of the panel. In order to render a designated vibration pattern on a panel, multiple actuators are necessary and the relationship between the input signals of actuators and the velocity responses at the measuring points can be written in a matrix form as

$$\mathrm{G}_{M\times N}\mathrm{E}_{N\times 1} = \mathrm{V}_{M\times 1}, \tag{1}$$

where M is the number of observation points, N the number of actuators E the matrix of electric input signals of actuators, V the vector of the vibration field, and G the transfer function between the input signals and the vibration responses. In this work, simply-supported plate is used to evaluate the performance of the virtual speaker. Measurement frequency response functions (FRF) rather than numerical FRF can be employed if transfer function matrix G is hard to obtain analytically because of the unclear boundary condition of the system which is not easy to define precisely. Complex actuator weightings E, which consists of information on both magnitude and phase, can be calculated in to render vibration pattern as follows:

$$\mathrm{E}_{N\times 1} = \mathrm{G}^{\dagger}_{N\times M}\mathrm{V}_{M\times 1} = \left(\mathrm{G}^{H}\mathrm{G}\right)^{-1}\mathrm{G}^{H}\mathrm{V}\,. \tag{2}$$

Here, G^H denotes the conjugate transpose of the matrix G [4,5].

3. Numerical parametric study

3.1 Virtual speaker and baffle as a target rendering

Desired vibration patterns for virtually performing a speaker composed of a speaker zone, radiating zone controlled to maintain and be in a uniform phase for generating sound, and a baffle zone, outside of the speaker zone with no-change in vibration as a baffle. Characteristics of radiated sound from the virtual speaker are affected by several parameters which is related with its size and location of speaker. To validate the present control method, numerical simulation is performed on a thin, simply-supported, rectangular plate, which is 800 mm in length, 500 mm in width with golden ratio, and 1mm in thickness. Material properties of panel are as follows: density is 7800 kg/m^3, Young's modulus 210 GPa, and Poisson's ratio 0.3. For obtaining a transfer function matrix between actuator weightings and vibration response, eigenfuntion superposition method is adopted [1] and 300 modes, of which resonant frequencies are within 2.5 kHz, are used with 0.01 loss factor. Uniformly distributed 36 actuators placed at the periphery of the plate with 70 mm spacing in length and 60 mm spacing in width are used for formation of virtual speaker. 2911 Observation points are uniformly selected with 10 mm spacing except actuator locations in the plate.

3.2 Acoustic performance of the radiated sound

In this research, radiated sound power, which can be obtained by using Rayleigh's integral of the velocity information on the plate surface [8,9], is considered as a performance by varying the size and the location of virtual speaker. A low frequency range less than 500 Hz is considered. Desired vibration filed is composed of speaker zone with 1 mm/s vibration amplitude and the other baffle zone with no vibration amplitude.

3.2.1 Effect of speaker size and bending wavenumber

For identifying the effect of the speaker size, radiated sound power depending on the Helmholtz number, determined by bending wavenumber and speaker radius, is illustrated in Fig. 1. When the Helmholtz number becomes 3.8 and 7.0, these dips are appeared as considering both size and frequency. One can easily notice that they are same with zeros of Bessel function of the first kind and first order and also related radial part of the modes of vibration of a circular plate. For defining effective frequency range, size of speaker should be considered.

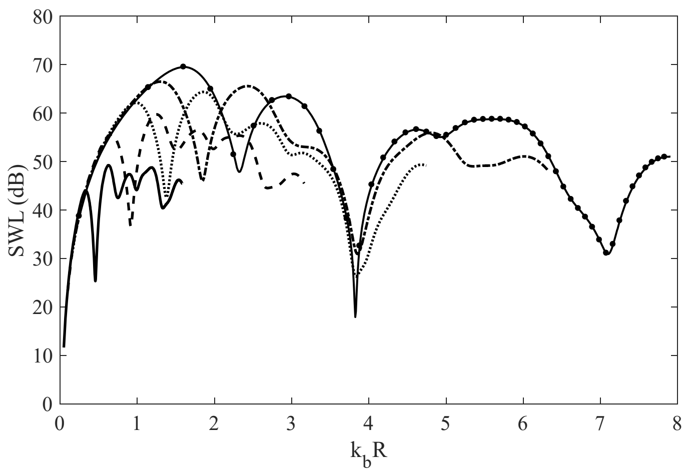

Figure 1. Radiated sound power in Helmholtz number domain when the virtual speaker is located at the center of the panel: ——, R=0.025 m; ------, R=0.05 m; ·········, R=0.075 m; – · – · , R=0.1 m; —•—, R=0.125 m.

3.2.2 Effect of speaker location and bending wavelength

Dip pattern related with speaker location can be found by comparing performances of different locations, regardless of the size. Candidates of locations for comparison as follows: 1) x_s=0.2 m, y_s=0.25 m; 2) x_s=0.4 m, y_s=0.25 m. Here, x_s and y_s are x and y coordinates of speaker location. Performances of each candidate are shown in Fig. 2. From the results, dips only related with the location are appeared when distances between the center of the speaker location and vertices or edges of plate are fit with integer multiplications of bending wavelength.

4. Independence among actuator locations

Several actuators positions can be related with each other, so this redundancy yields the problem in terms of input energy efficiency. In order to eliminate their relative positions, assurance about the independency among actuator positions should be identified. In this work, effective independence (EfI) method is adopted to by considering contributions for the linear independence of the transfer function matrix. It can be decomposed by using the singular value decomposition as follows:

$$\mathrm{G} = U \Sigma W^{H} . \tag{3}$$

Here, U denotes left singular matrix, W right singular matrix, and Σ diagonal matrix with singular values. Because column of row vectors of singular matrices represent the quantitative independence of matrix, EfI value can be expressed as

$$E_q = diag\left(W_q W_q^{H}\right), \tag{3}$$

where, W_q means the matrix spanned by the firs q-column vectors of W [4,10,11]. Position where it has smallest EfI value is the most redundant and linearly dependent location. Uniformly distributed 236 actuators placed at the periphery of the plate with 10 mm spacing are chosen as initial candidates of positions. Location of 36 actuators is decided by employing EfI method discarding one by one or group by group, and positions which is at the nodal or anti-nodal line of dominant modes for target vibration field are considered to compare. Input powers with each case are shown in Fig. 3, and differences of radiated sound power are less than 1 dB. Linearly independent position is better location for obtaining high input efficiency rather than choose randomly or considering several positions related with dominant modes. Iterative eliminating one by one selection method shows the highest efficiency.

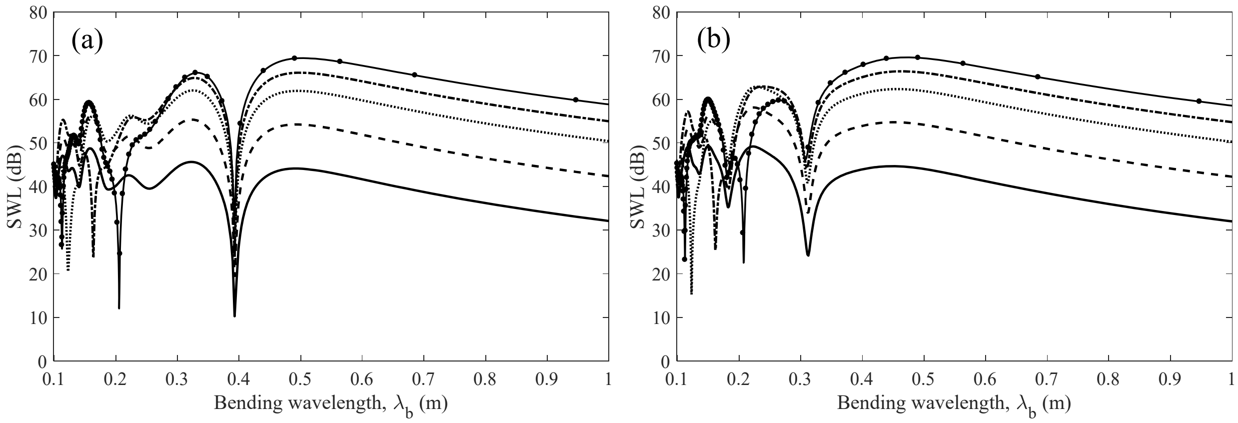

Figure 2. Radiated sound power from the candidate virtual speaker depending on the speaker zone size in bending wavelength domain: ——, R=0.025 m; ------, R=0.05 m; ·········, R=0.075 m; ‒ · ‒ · , R=0.1 m; —●—, R=0.125 m. (a) x_s=0.2 m, y_s=0.25 m; (b) x_s=0.4 m, y_s=0.25 m.

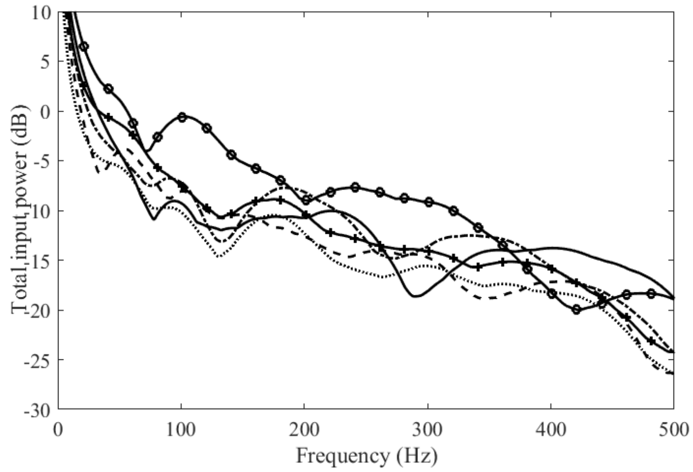

Figure 3. Input power of 36 actuators when the virtual speaker is located at the center of the panel and R=0.075 m: ——, nodal line of dominant modes; ------, anti-nodal line of dominant modes; ·········, q=1; ‒ · ‒ · , q=10; —●—, q=20; —✚—, q=50. Here, q is the number of removed actuators at each iteration.

5. Conclusions

In this work, a virtual speaker system with baffle is created on a planar panel by using array actuators located at the boundary of the thin plate. Virtual speaker composed of localized vibration field, called speaker zone, which has high amplitude vibration with a uniform phase and the other area, called baffle zone, has no-change in vibration condition. Acoustic performance depending on speaker parameters including size and location is simulated on the simply-supported plate and the relationship between of them is identified. Dips in spectrum are occurred depending on the both speaker size and location. Also, to improve efficiency of the input power, redundant positions of actuators should be removed. This location can be decided by calculating the EfI value which describes independency among actuator positions. It is shown that input power efficiency from locations determined by EfI method is higher than that from actuators located at the nodal line or anti-nodal line of dominant modes for target vibration field. These information can be used as an important guide-line to design or form virtual speaker in a thin planar panel.

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REFERENCES

1 J.-H. Woo and J.-G. Ih, “Vibration rendering on a thin plate with actuator array at the periphery," *Journal of Sound and Vibration*, **349**, 150-162 (2015).

2 J.-G. Ih and J.-H. Woo, “Rendering of a desired vibration pattern on a thin plate by controlling the traveling bending waves from peripheral actuators,” *Proceedings of the 22th International Congress on Sound and Vibration*, Florence, Italy (2014).

3 J.-H. Woo, D.-Y. Kim and J.-G. Ih, “Virtual formation of a woofer at the roof panel of a vehicle by using array actuators," *SAE International Journal of Passenger Cars- Mechanical Systems*, **9**, pp.1086-1090 (2016).

4 B.-K. Kim and J.-G. Ih, "On the reconstruction of vibro-acoustic field over the surface enclosing an interior space using the boundary element method," *Journal of the Acoustical Society of America*, **100**, 3003-3016 (1996).

5 M. R. Bai, J.-G. Ih, and J. Benesty, *Acoustic Array Systems*, John Wiley, Singapore, Chap.6 (2013).

6 L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*, John Wiley & Sons, Inc., New Jersey, Chap.7 (2000).

7 J. Borwick, *Loudspeaker and Headphone Handbook*, Focal Press, Oxford, Chap.7 (2001).

8 J. W. S. Rayleigh, *Theory of Sound*, Dover Publ., London, Chap.16 (1896).

9 J. C. Pascal, "Systematic measurements errors with two microphone sound intensity meters," *Journal of Sound and Vibration*, **83**, 53-65 (1982).

10 D. C. Kammer, ‘‘Effect of modal error on sensor placement for on-orbit modal identification of large space structures,’’ *J. Guidance Control Dyn.* **15**, 334–341 (1992).

11 W.-H. Cho, J.-G. Ih, and T. Toi, “Positioning actuators in efficient locations for rendering the desired sound field using inverse approach," *Journal of Sound and Vibration*, **358**, 1-19 (2015).