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Design of Non-circular Membranes Metasurfaces for Broadband Sound Absorption

広帯域吸音のための非円形膜メタ表面の設計

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1. Introduction

Sound absorption/insulation have been one of the key technologies in developing next-generation architectures and automobiles. Conventional sound absorbers have required thicknesses comparable to the wavelenghth of audible sounds leading to large mass which limits their efficiency. In this study, we focus on the Decorated Membrane Resonator (DMR) [1], which is one of the acoustic metasurfaces that are sufficiently smaller in size than the wavelength of sound waves and exhibit unique acoustic responses such as incident-wave reflection/diffraction to arbitrary directions. It has been shown that the DMR can achieve nearly 100% sound absorption at the resonance frequency. However, the sharp peak at the resonant frequency hampers to utilize the structure in practical applications that have ambient sound environments with relatively wide frequency spectra. We have previously proposed a structure that combines DMR and Helmholtz-resonator structure[2] and a structure that aims at superposing sound absorption peaks by arranging multiple DMRs with different diameters [3].

In the present study, we propose a new structure with a wide band by changing only shape of the membrane in a single structure. Using three dimensional finite-element analysis, we find optimal structure for efficient absorption of sound with a frequency spectra within 500-1500Hz, targetting to an in-vehicle noise.

2. Simulation method

A series of numerical simulations on the metasurface model was performed using COMSOL Multiphysics® [4], a commercial 3D finite-element method (FEM) software developed by COMSOL AB. To evaluate the absorption characteristics, we calculated the absorption coefficient based on the transfer-function method [5]. This method needs to measure the sound pressure at two locations with a microphone, which is simulated by measuring pressure at two different points in the FEM calculations.

3. Multiple resonance membrane structure

The DMR originally proposed in Ref. [1] has the circular membrane and the excited modes are simple concentric leading to the sharp absorption at a resonance frequency. Here, we examined the membrane-shape dependence on the sound absorption characteristics. Specifically, we investigated the multiplexing of resonance conditions with a structure that breaks the symmetry of the membrane's shape.

Fig. 1 depicts the structures to be studied. Fig. 1 (a) shows a "two membranes structure" in which two circles of the same radius are arranged with their center mutually shifted. Fig. 1(b) shows a "three membranes structure" in which three circles are similarly arranged. Note that the membranes are not overlapped within the dotted line and therefore the thickness is uniform everywhere in the membranes. We adopt polypropylene for fabricating the entire structure, including membrane, in order to reduce total weight of the structure.

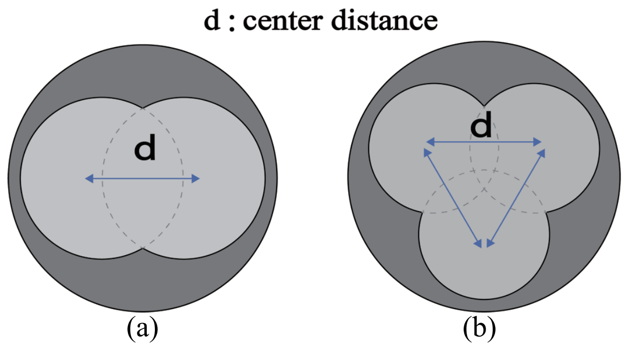

Fig. 1 (a) Two membranes structure
(b) Three membranes structure

4. Optimization of structure

Here, we assume sound spectrum of the noise source can be represented by a simple Gaussian form with peak around 1000Hz, as shown in **Fig. 2**. We then search for the optimum structure that absorbs the sound most efficiently. By changing the center distance d in Fig. 1, we obtain the sound absorption performance Q evaluated by

$$Q = \int as\, df \qquad (1)$$

at each center distance. Here $a(f)$ is a sound absorption coefficient evaluated by numerical simulation described in Se. 2 and $s(f)$ is the spectrum of the noise source depicted in Fig. 2.

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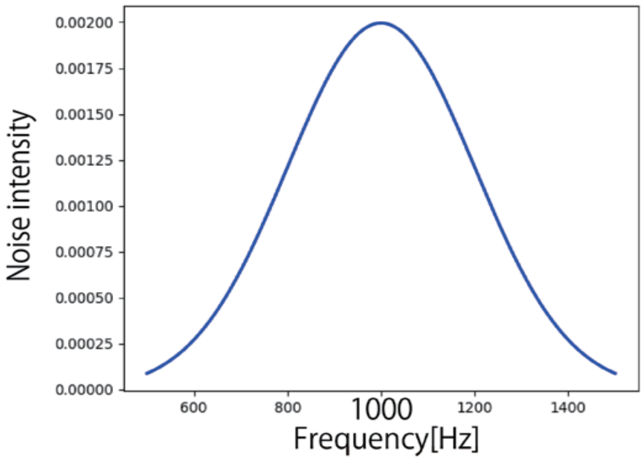
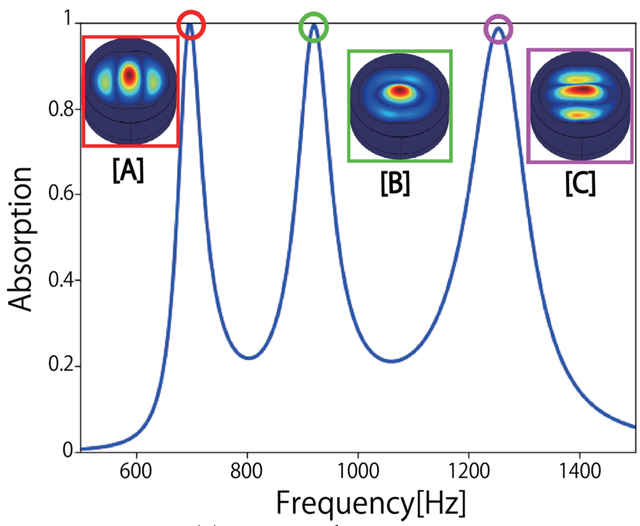


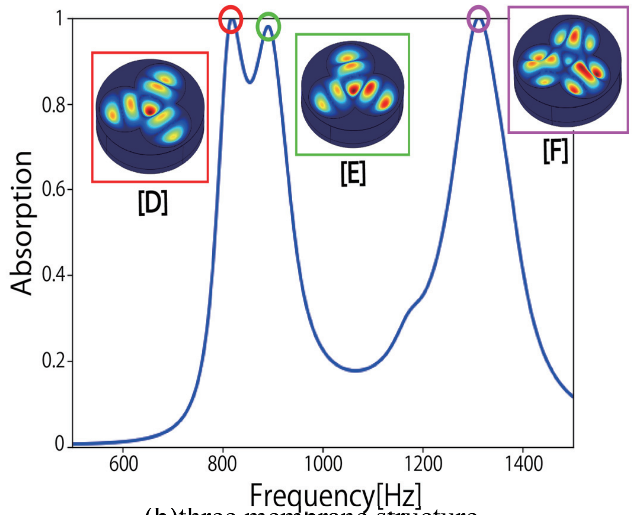
Fig. 2 A model spectrum for noise source

5.Result

Fig. 3 (a) shows the sound absorption spectrum of the optimized two-membranes structure. By breaking the symmetry, we successfully obtained wider absorption spectrum via separating the single peak in the original DMR into three while maintaining a high value for all the peaks generated. The analysis shows that these peaks [A], [B], and [C] are due to non-concentric modes. Fig. 3 (b) shows the sound absorption coefficient for the optimized three-membranes structure. It has a high sound absorption coefficient in the bandwidth of 800-950Hz, and three sound absorption peaks are formed similarly to the case of the two-membranes structure. The peaks [D] and [E] form a concentric displacement distribution mode as in the conventional DMR, while the peak [F] is a new mode in which each membrane resonates simultaneously.



(a)two membranes structure



(b)three membrane structure

Fig. 3 Absorption spectra for optimized DMR structures.

6. Conclusion

We proposed a composite structure with multiple circular membranes, optimized the structure for high sound absorption performance, and verified the possibility of wideband sound absorption by numerical analysis. As a result, we succeeded in designing a high sound absorption effect for a wideband noise source between 500 and 1500 Hz. This has been realized by multiplexing the resonant modes through breaking the symmetry of membrane's shape, while keeping a high sound absorption coefficient at each mode. Actual fabrication using a 3D printer and a sound-absorbance measurement of the proposed structures are in progress.

Acknowledgment
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