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Design of multiple-resonant phononic metasurface for sound absorbing and energy harvesting devices

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1. Introduction

Sound absorbing material is required for developing quiet and comfortable products such as automobiles and architectures. Conventional absorbing materials are made from plastics/resins, such as polyurethane or melamine foams[1)]. However, these materials generally require a thickness that matches a half or a quarter of the wavelength of target acoustic waves. Especially for low-frequency acoustic waves, achieving both thinness and high absorption performance has been a long-standing issue.

In recent years, artificial sound-controlling materials called acoustic metasurfaces[2)] have been attracting much attention as an alternative to conventional ones. By utilizing acoustic resonances, acoustic metasurfaces have high absorption, reflection and transmission performances with sub-wavelength scale. Especially, we have focused on membrane-type acoustic metasurfaces. Decorated Membrane Resonator (DMR)[3)] consists of polypropylene membrane and internal sealed air layer. By hybridizing two resonances of membrane and air layer, the surface becomes impedance-matched to airborne sound at specific frequency. In addition, by inserting PZT at the bottom of the air layer, it becomes possible to harvest electricity from the increase of internal sound pressure at the same frequency.

In this study, we designed multilayer acoustic metasurface by stacking Helmholtz resonator and periodic array of stubs on DMR as a base structure. In addition, we applied this structure to phononic structure for omnidirectional acoustic metasurfaces.

2. Multiple-resonant acoustic metasurfaces based on Decorated Membrane Resonator (DMR)

Figure 1 shows the schematic of basic DMR structure and the spectra of sound absorption and generated voltage. By using impedance-matching to acoustic wave, DMR can absorb over 90% of the incident acoustic wave and convert it into 0.1mV voltage at the resonant frequency. However, it also indicates that the DMR have narrowband absorbing/generating effect by high-Q resonance.

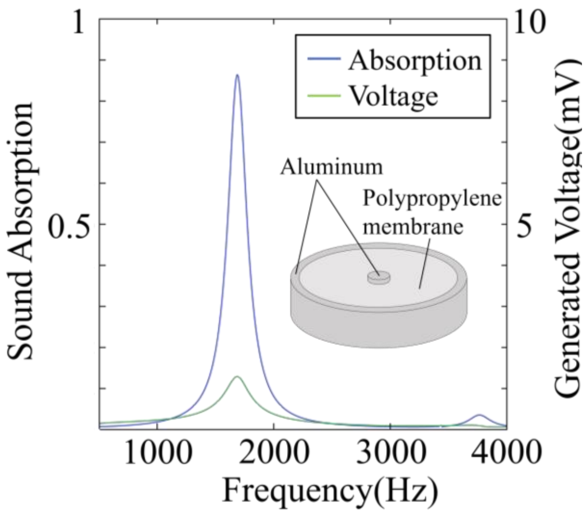

Fig. 1 The schematic of simple DMR and its sound absorption and voltage generation spectrum

Generally, the noise to be reduced have broader spectrum than DMR. So, designing acoustic metasurfaces with broadband effect is effective to sound shielding technology.

As methods to designing broadband DMR structure, we have focused on non-circular membranes[4)] or multilayer structures[5)]. In this study, we adopted the idea of stacking Helmholtz resonant structure on DMR[6,7)] and designed multiple-resonant structure consisting of three resonant structures. Focusing on empty space around the orifice of Helmholtz resonator, we attempted to apply a periodic array structure of pillars[8)] on the substrate to localize acoustic wave to orifice.

Figure 2 shows the schematic of multiple-resonant structure and the FEM results of sound absorption and generation spectrum. This result revealed that it appeared three resonances with over 90% absorption and 1~4 mV power generation. We found that these resonances have different modes of sound pressure distribution and membrane displacement. In addition, each resonant mechanism shares same inner air layer, so the thickness of this structure is not too large. The height is 25mm that keeps sub-wavelength scale which is a unique characteristic of acoustic metasurfaces.

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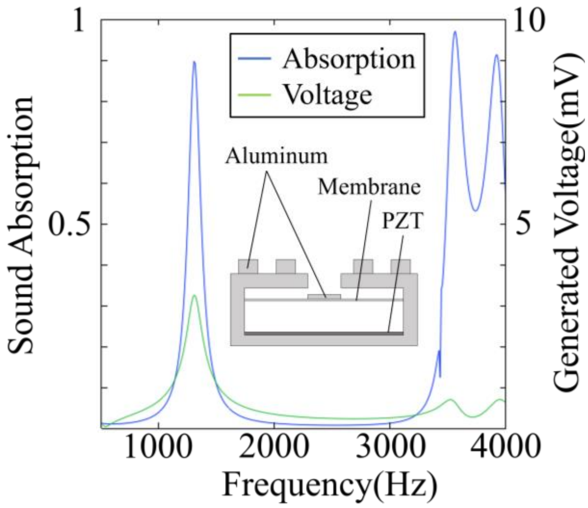

Fig. 2 FEM result for absorption and voltage generation spectrum of the multiple-resonant structure

3. Application to phononic-structured acoustic metasurfaces

In the practical situation, acoustic metasurfaces consist of a periodic arrangement of unit cell structures. In previous study, we confirmed that pilling up peaks of different scale DMRs is effective to widen responses[9]. In this study, we have also attempted to apply multiple-resonant structure to phononic structure.

Figure 3 illustrates the phononic-structured acoustic metasurface based on multiple-resonant structure. Unit cells are arranged in a closest-packed structure. By changing the scale of each unit cells, we simulated absorption/generation characteristics of whole structure. Sound absorption coefficient is calculated by the ratio of reflection sound pressure to background sound pressure above the whole structure. Voltage generation is shown by the sum of each unit cells.

As a result, it was confirmed that broadening responses could be achieved by pilling up different peaks even when using the multiple-resonant structure. However, absorption/generation characteristics of each peak were lower than single-structural acoustic metasurfaces. Moreover, since the incident waves propagate from various directions, an omnidirectional absorption performance is also required. So, we need to consider further about the arrangement or the scale of each unit cells to compatible broadband and high responses.

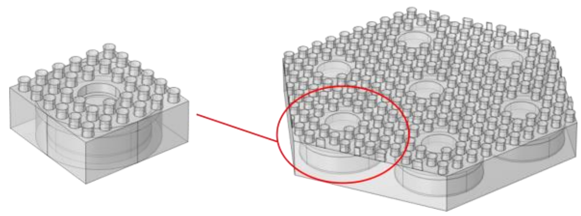

Fig. 3 Phononic structured acoustic metasurface

4. Conclusion

We designed multiple acoustic-resonant structure consisting of membrane-type resonator, Helmholtz resonator and periodic array of pillars. This structure can be used as an acoustic metasurface that exhibits high absorption/generating voltage characteristics for acoustic waves at audible bands despite its thinness. The FEM results indicate three resonant frequencies with over 90% absorption and about 0.1 µW generation. In addition, we have attempted to consider about phononic-structuring of this unit cell. We plan to further optimize structure and arrangement for noise controlling devices with higher performance.

Acknowledgment

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