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Design of High-efficiency Sound Absorption and Energy Harvesting Devices Using Acoustic Metasurfaces

音響メタ表面を用いた高効率吸音・環境発電デバイスの設計

Ryota Takami[1], Masaaki Misawa[1],Kenji Tsuruta[1]([1]Okayama Univ.)

高見亮多 [1]，三澤賢明 [1]，鶴田 健二 [1] ([1]岡山大院 自然)

1.Introduction

Energy harvesting is a technology that collects small amount of energy in various forms such as light, vibration, and heat to convert to about μW to mW of electric power to utilize for small electronic devices. In recent years, energy harvesting has attracted much attention due to advances in low power-consumption devices as basis for realization of IoT technology. Research has been underway especially for harvesting from floor and road vibrations, and some of those are already close to practical use. However, there has been less progress in development of technology that converts sound energy directly to electricity. In the present study, we attempt to design such a device based on acoustic metasurfaces. We focus on the Decorated Membrane Resonator (DMR) (1), a structure composed of membranes and air layers, developed originally for highly efficient sound absorption. Combining a piezoelectric element (lead zirconate titanate, PZT) with the DMR structure and optimizing the metasurface structure, we aim at efficient conversion of acoustic energy via a resonant vibration of the film and/or the air to generate power. Here we adopt a double layer DMR structure with piezoelectric film separating an air layer into two regions. Here we confine ourselves to analyze the DMR structure with outer radius of 30 mm, inner radius of 25 mm, height of 20 mm. Thickness of outer layer plastic (Polypropylene, PP) film and that of PZT film are 0.2 mm and 1.0 mm, respectively.

2. Eigenmode and piezoelectricity analyses

Since energy harvesting is performed mainly through a resonant vibration of the piezoelectric element, we begin with identifying the eigen frequency of the piezoelectric film and the piezoelectric voltage generated at the frequency. The lowest possible frequency band of a circular film can be estimated using the equation (2).

$$f \approx \frac{0.475 c_L h}{a} \qquad (2)$$

$$c_L = \sqrt{\frac{E}{\rho(1-\nu^2)}}$$

a; radius h; thickness ρ; density
ν; Poisson coefficient E; Young's modulus

The estimated frequency for the PZT materials with the radius of 25 mm and thickness of 1 mm is about 2865Hz for the lowest vibrational mode.

Next, an incident wave toward the piezoelectric film is applied and the maximum voltage within the film vibrating by the wave is calculated using finite-element method in the range of 500 Hz to 4000 Hz. **Figure 1** shows a power spectrum of the piezoelectric film for a normal incident plane wave of 1 Pa toward the film in the air. It is confirmed that the power generation was large around 2800Hz, which is closed to the estimated eigen frequency of the circular PZT film.

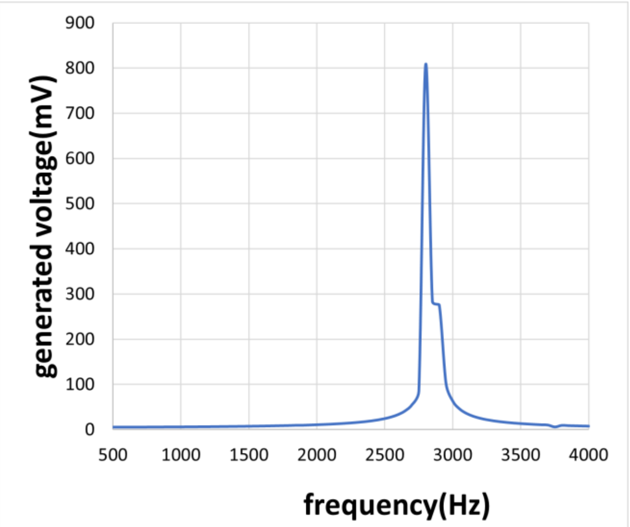

Fig.1 Power spectrum of circular PZT film for 1Pa incident wave

3. Double layer DMR with piezoelectric film in the middle of the air layer

We propose a novel DMR structure in which the piezoelectric film is placed in the middle of the air layer of the basic DMR structure. **Figure 2** shows the side view of the double layer DMR. The circular PZT film is placed at 10 mm below from the PP film in the top of the structure, and the dimensions of the piezoelectric body were designed with a radius of 25 mm and a thickness of 1 mm.

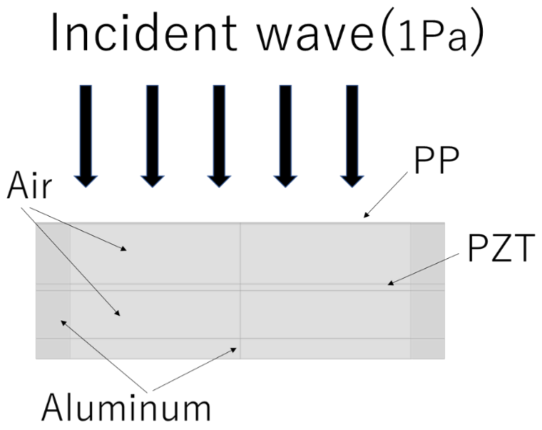

Fig.2 Double layer DMR with PZT film at the middle.

4. Result

Figure 3 depicts frequency spectra of sound absorption and piezoelectric voltage for an incident plane wave of 1Pa normal to the top of the DMR. The figure shows multiple peaks in both sound absorption and piezoelectric voltage. The highest peak of the PZT voltage is about 240 mV around 2800 Hz, which is mainly due to resonant vibration of the PZT film. In addition, 10 to 40 mV of peaks are generated at the sound absorption peaks in the lower frequency band than the lowest eigen frequency of the PZT film. This can be attributed to a hybridization of the modes in the DMR, coupling between eigen modes of PP film, PZT film, and the air layers between them. This leads to more efficient electric power generation than that of in the single layer DMR with PZT film at the bottom. **Figure 4** shows displacement field on the PZT film. This indicates that stress value of PZT film is largest at generated voltage's peak.

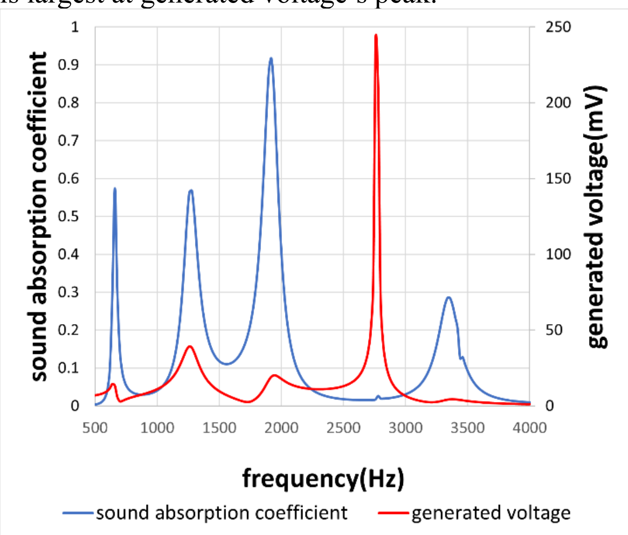

Fig.3 Sound absorption coefficient and piezoelectric voltage of PZT film in the DMR.

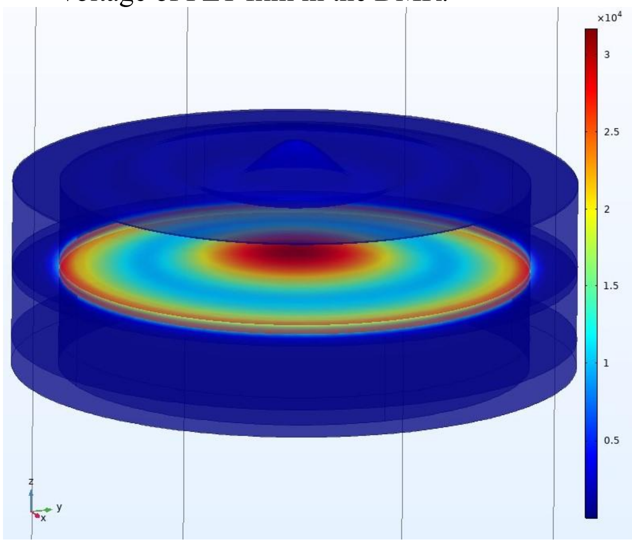

Fig.4 Stress values of PZT film in the DMR at 2760Hz

5. Conclusion

We proposed and examined a double layer DMR structure with a piezoelectric film in the air layer of the DMR for an efficient sound energy harvesting. The finite element simulations revealed that the generated voltage spectrum in the PZT film for a normal incident of sound has multiple peaks in addition to the lowest normal mode of the PZT film due to the hybridization of eigenmodes of the films coupled by the air layers. The proposed model presents novel approach to realization of an energy harvesting device operating for airborne sound.

6.References

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