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NOISE CONTROL FOR A BETTER ENVIRONMENT

Lightweight membrane-type acoustic metamaterials with through-holes

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ABSTRACT

Membrane-type acoustic metamaterials with attached small masses have been reported to break the classical mass law on traditional acoustic materials and can effectively insulate low-frequency noises. In this work, we propose lightweight membrane-type acoustic metamaterials with through-holes instead of the masses. Our acoustic metamaterials yield high transmission loss (TL) at selective frequencies below 1st eigenfrequency of the membrane vibration in the low-frequency regime (<1000 Hz). The sound insulation frequencies can be tuned by varying the through-hole diameters. The experimental data of the TL with four-microphones impedance tube measurements agrees well with FEM simulation results. The acoustic near-field pressure and particle velocity in the vicinity of the membrane were experimentally visualized with sound intensity PU probe measurements, and numerically calculated. These analyses indicate that the mechanism of the high TL is based on the destructive interference between two types of acoustic near-fields generated from airborne sound through the holes and vibration sound of the membrane. The proposed design has promising potentials as a new type of thin and lightweight noise control devices with air-flow.

Keywords: Acoustic metamaterials, Lightweight, Low-frequency sound insulation
I-INCE Classification of Subject Number: 30

1. INTRODUCTION

Lightweight soundproofing has been required in a variety of industrial fields, e.g. aerospace and automobile. For high sound insulation in the low-frequency regime, heavy materials have been used in accordance with the mass law.

Membrane-type acoustic metamaterials (MAMs) with attached masses on the membranes have been developed to achieve lightweight soundproofing in the low-frequency regime over the past decade[1-7]. These MAMs consisted of multi-celled arrays.

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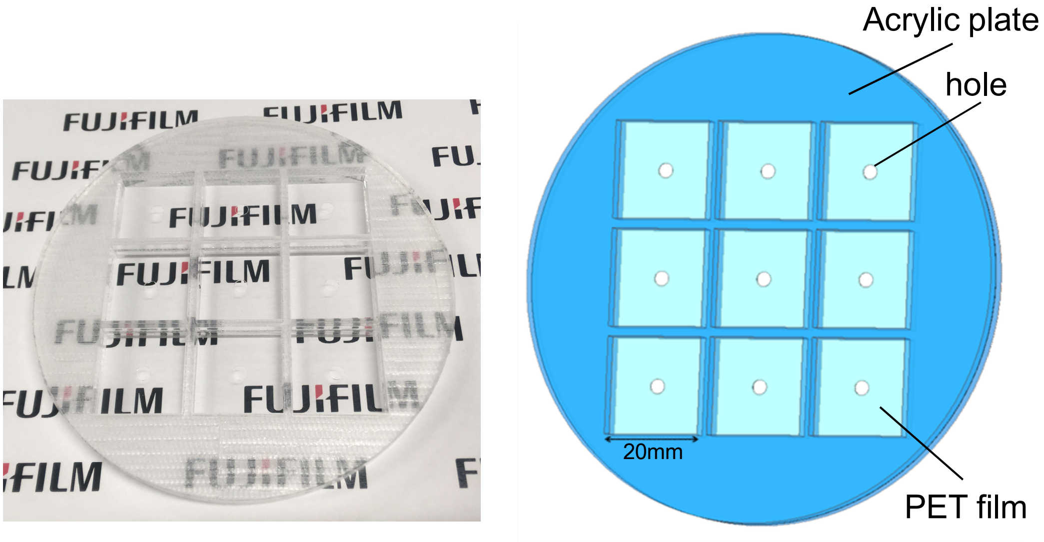
The size of a single cell was smaller than wavelength of sound so that the diffraction effects can be neglected. Small masses were attached onto those prestreched membranes at each single cell to control the resonant behaviour of the membrane vibration. The MAMs had high transmission loss (TL) peaks at frequencies between two vibrational eigenmodes, which demonstrated performances beyond the mass law. Since average displacement of the membrane in the unit cell at the TL peak is approximately zero, the MAMs perform like a hard wall at a macro scale and reflect sound effectively. However the MAMs with small masses have difficulties in manufacturing on an industrial scale due to the attachment of the masses and stretching process of membranes.

In this work, we present a lightweight membrane-type acoustic metamaterial with through-holes which has achieved high-performance soundproofing in the low frequency regime without any masses and prestretched membranes. The mechanism of the sound insulation has been elucidated in terms of both far-field and near-field acoustics. Furthermore, we have confirmed experimentally the near-field sound interference using sound intensity PU probe.

2. MATERIALS

Fig.1 shows the front view of a basic sample structure. Unit cells of our MAM consist of plastic membranes with through-holes fixed to a rigid plastic frame. The membrane is 100 μm thick polyethyleneterephthalate (PET) film which is sandwiched with two acrylic plates of thickness 3 mm with nine (or four) openings which are 20 (or 25) mm square and fix it by adhesive material tapes without prestrech. The openings are corresponding to unit cells. The through-holes of diameter 1-3 mm were formed at the centre of the unit cells.



(a) (b)

Fig. 1 – (a) Photo image and (b) schematic image of membrane-type acoustic metamaterials with through-holes.

3. METHOD

3.1 Experimental setup and measurement procedure

TL of our samples (20 mm square, nine unit cells) as a function of frequency from 200 to 2000 Hz was measured with four-microphones impedance tube method as shown in Fig.2. The TL can be defined as TL(dB) = $10 \times \log_{10}(1/T)$. Here T is the transmittance. The near-field in the vicinity of surface area of the square-cell opposite to sound input was scanned and visualized by sound intensity PU probe (Microflown Technologies) with 3 mm of spatial resolution as shown in Fig.3. In this measurement, we used the sample of lager unit cells (25 mm square, four unit cells) to make spatial scanning measurement easier.

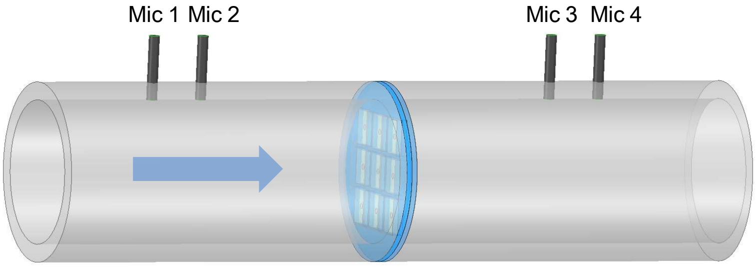


Fig. 2 – Measurement setup image with four-microphones impedance tube system.

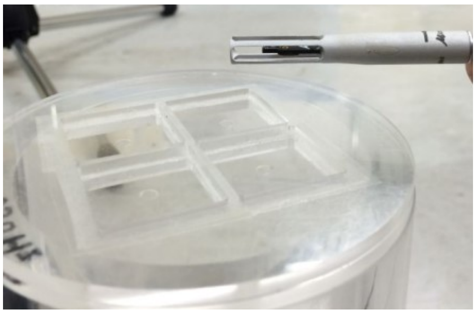


Fig. 3 – Scanning near-field using sound intensity PU probe in the vicinity of the metamaterials.

3.2 Numerical simulation

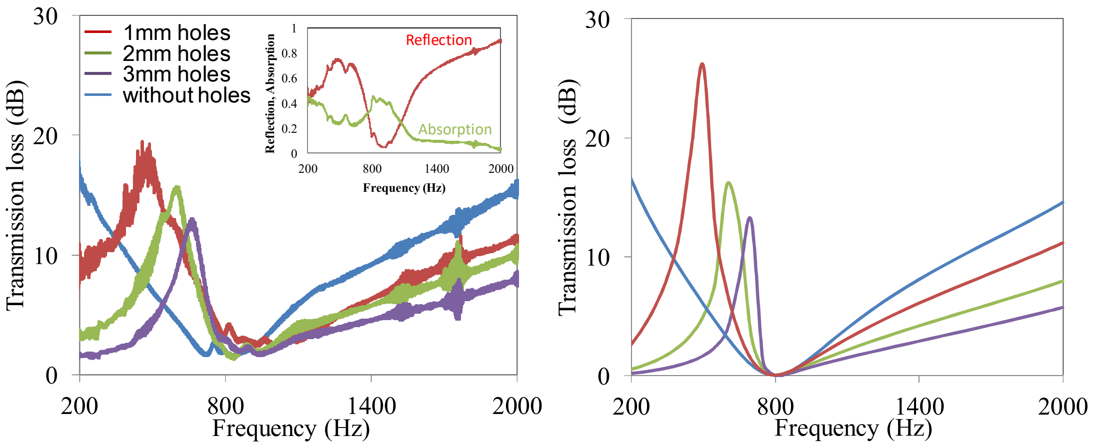
Numerical simulation of our MAMs was performed with the finite element method (FEM) using COMSOL Multiphysics (COMSOL Inc.). TLs were calculated, and the simulation was also used to find out mechanism of the sound insulation.

4. RESULTS AND DISCUSSION

The measured TLs of three samples (unit cell of 20 mm square) with three different diameters of holes (1, 2, 3 mm) and a membrane sample without through-holes are shown in Fig.4(a). And the inset of Fig. 4(a) shows reflection and absorption spectra of the MAM with 1 mm diameter of holes. Each sample perform high TL peak (466Hz, 590Hz, 653Hz) below 1st eigenfrequency of membrane vibration without through-holes at 800 Hz, appeared as TL minimum. The TL peak shifts to lower frequency as decreasing the diameter size. Simulation results of the TLs using FEM, shown in Fig.4(b), agree well with the experimental results except TL peak magnitude of the MAM with 1 mm diameter hole.

Fig.5(a) explains the mechanism of the sound insulation from far-field viewpoint and the equivalent circuit schematic diagram of our MAM is shown in Fig.5(b). There are two ways that sound passes through in the single unit cell. One is a direct transmission through the hole and the other is vibration of the membrane. The phase of sound passing through the former advances $\pi/2$ due to the acoustic inductance of the hole. On the other hand, the phase of sound passing through the latter delays π/2 due to the acoustic capacitance of the membrane vibration in a frequency below the 1st eigenmode. As a result of destructive interference between these two types of sounds with relative π phase difference behind the metamaterials, the transmitted sound vanishes and the incident sound is reflected almost perfectly if the amplitudes of two types of sound are almost same. Since the amplitude of sound passing the through-hole depends on its diameter, the TL peak frequency shifts by changing it. As shown the inset of Fig.4, the MAM with 1 mm diameter holes has 30 % absorption due to the resistance of small holes which is omitted parameter of the FEM simulation. It decreases relative phase difference between the two types of sounds less than π. As a result, the measured TL peak magnitude is smaller than that of simulation.

The simulation result of pressure and particle velocity in the near-field region of the metamaterial unit cell at TL peak frequency is shown in Fig.6(a). The arrows describe particle velocity and colour mapping describes sound pressure on the logarithmic scale. The sound pressure in the incident side of membrane is much higher than that in the opposite side. This shows sound is insulated by the hole and membrane unit cell. The particle velocity directions at the hole is opposite to that on the membrane (both ends of the membrane in the Fig.6(a)). This means the destructive interference as described above are induced in the near-field region. Therefore the transmitted sound vanishes in the range much smaller than the sound wavelength. The experimental result of the near-field scanning using sound intensity PU probe is shown Fig.6(b). The sound intensity amplitude mapping and directions agree well with simulated results. Therefore the near-field destructive interference mechanism is confirmed experimentally.



(a) (b)

Fig 4 – (a) Experimental result of the transmission losses. Inset: Reflection (red line) and Absorption (green line) spectra of the MAM with 1 mm diameter of holes. (b) Numerical result of them.

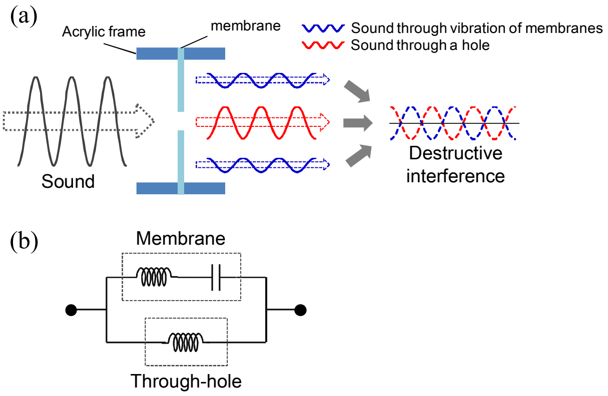
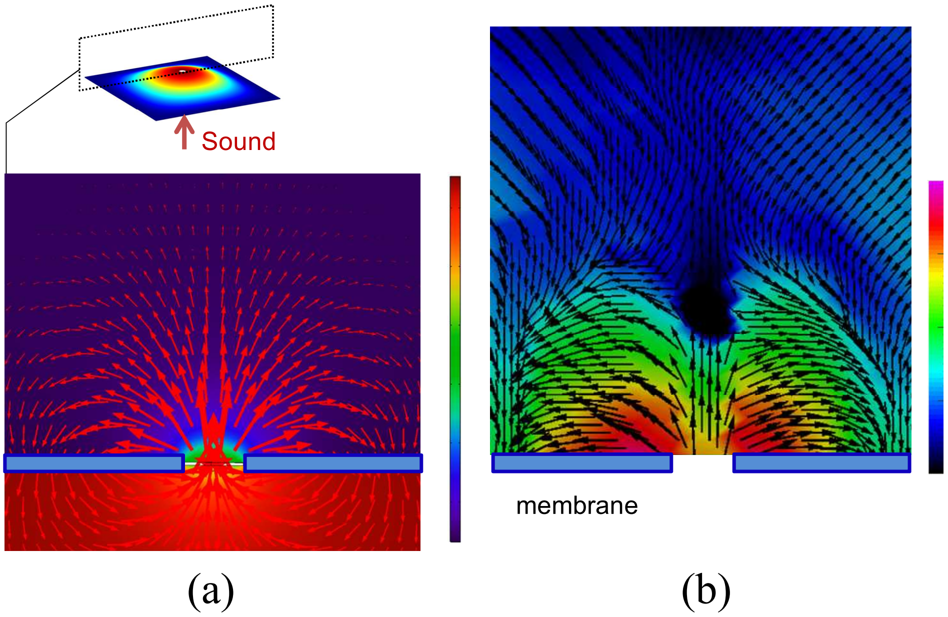


Fig 5 – (a) Schematic diagram of sound insulation mechanism. Two types of sound interfere destructively. (b) Schematic equivalent circuit diagram of the metamaterials.



(a) (b)

Fig. 6 – (a) Simulated near-field sound pressure and particle velocity in the vicinity of the unit cell. Colour map represents sound pressure and red arrows represent sound particle velocity vectors on the logarithmic scale. (b) Experimental result of near-field sound intensity measurement with sound intensity probe on the logarithmic scale.

5. CONCLUSIONS

We have developed lightweight membrane-type acoustic metamaterials with through-holes on non-prestretched membranes instead of attached masses. High TL at selective frequencies below the 1st eigenfrequency of membrane vibration has been achieved. We have elucidated the mechanism of high TL by numerical calculations and experiments, which is destructive interference between the airborne sound through the holes and the membrane vibration sound in near field region. The peak frequency is controllable with changing the hole size.

The proposed metamaterial is a new type of thin and lightweight noise control devices with air-flow. Perforated non-prestretched plastic films without attached masses are easy to manufacture on an industrial scale. Therefore our lightweight metamaterials for low frequency sound insulation and manipulation have broadband promising potentials.

6. REFERENCES

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