Vibration absorption performance of membrane-type metamaterial on a thin plate

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ABSTRACT

This work aims to investigate the vibration absorption performance of membrane-type metamaterial on a thin plate. Simulation work was conducted on membrane-type metamaterial using membrane resonators with various configurations of decorated masses. The bandgap property of membrane-type metamaterial with multiple masses was investigated. It was found that a slight adjustment of location for the decorated masses could result in a 45 Hz change of the membrane-type metamaterial bandgap location. Through the simulation work, the vibration transmissibility of a thin plate attached with membrane resonators was studied and it was showed that this membrane-type resonator could effectively suppress the vibration of a thin plate.

Keywords: Vibration, Membrane, Metamaterial
I-INCE Classification of Subject Number: 47

1. INTRODUCTION

The development and application of metamaterial with localized resonant resonators have been vastly investigated in the recent decade [1-3]. The invention of phononic crystal (PC) can be considered as a result of the study of negative property phenomena (e.g. in terms of bulk modulus, mass density) by Veselago [4], which theoretically demonstrated that in certain conditions, the material can reveal negative properties that are not observed in natural properties of conventional materials. In PC materials, the periodicity of structure can be constructed to generate a particular Bragg bandgap that can stop the propagation of structural vibration waves. The periodicity of structure is therefore very important for the PC material, although it has also created a limitation for its application in the low frequency range. When the incident structural wave is at a relatively lower frequency, the structural wavelength will be larger, which leads to the requirement to increase the size of PC accordingly. One of the solutions of this dilemma is by utilising the localised resonance phenomenon that was proposed by Liu et al [5]. They fabricated a new material that can attenuate the propagation of structural wave in a sub-wavelength lattice constant, which can be considered as the acoustic metamaterial (AM). Yang et al. [6] proposed the membrane-type acoustic metamaterial (MAM), which was composed by a pre-stressed membrane fixed on a rigid frame and mass attached on the membrane. The membrane resonator can be regarded to be equivalent to the mass-
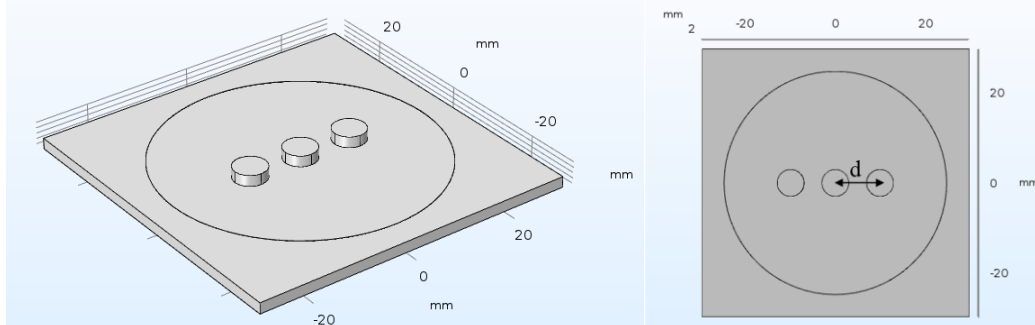
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spring model. Compared with other metamaterials, MAM is generally lighter and cheaper to be manufactured. Its resonance frequency can also be tuned by the applied tensile stress [7]. In the majority of former studies, MAM was typically used for the sound isolation [8-12], with only limited studies have looked into its potential for absorbing structural vibration. Sun et al. [13] placed two single membrane resonators on a plate and demonstrated the feasibility of using membrane resonators for structural vibration control. However, the use of membrane resonator has not yet been fully investigated, particularly in terms of how their configuration can be optimized.

This work investigated the bandgap property and vibration absorption performance of membrane resonator with different configurations of decorated masses attached on membrane. Simulation is conducted using the commercial finite element analysis (FEA) software COMSOL Multiphysics. The model of membrane resonator is developed using periodic boundary conditions for the investigation of its bandgap property. It was found that the change of configuration of decorated masses can be an effective way for enabling the tuning of membrane resonator's resonant frequency and therefore the associated bandgap location. In addition, the change of mass for the decorated masses was also found to be linked with the vibration absorption performance.

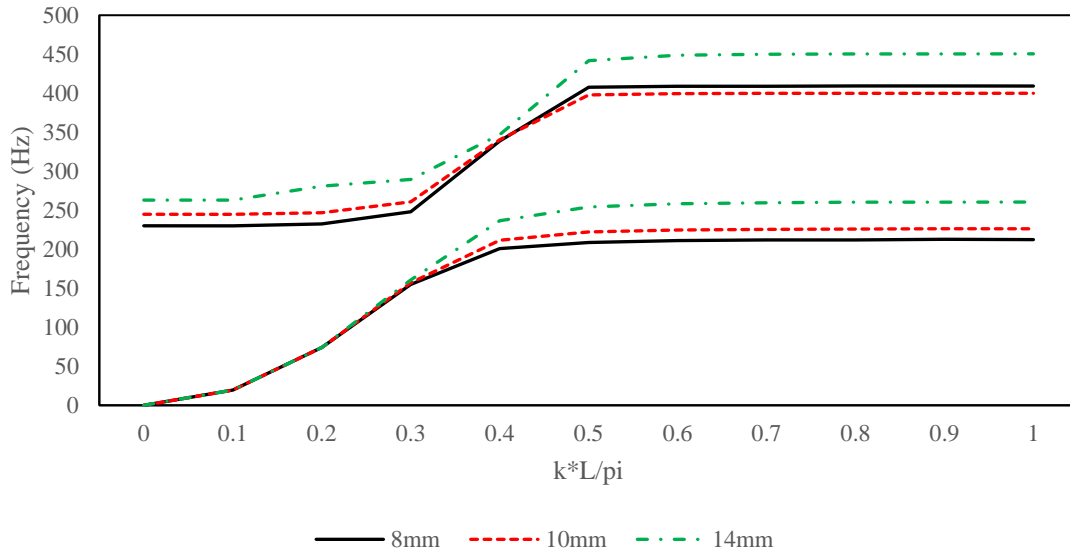## 2. DESIGN OF THE MEMBRANE RESONATOR'S STRUCTURE

Previous studies have indicated that the fabrication of a membrane resonator can be relatively easy compared to other types of metamaterial. By changing the applied tension level of the membrane, the membrane-type metamaterial's bandgap location can be adjusted accordingly. This is believed to be an effective way to tune the operation frequency of membrane-type metamaterial, as investigated by a number of researchers [14, 15]. However, as the membrane resonator is very sensitive to the applied tension, the inconsistency in fabrication may cause serious inaccuracy in its operation frequency [16]. Therefore, it will be helpful to develop a tuning method that is easier to be accurately conducted, and cause less inconsistency to the design. Since aside from the membrane tensile stress, the decorated mass is another decisive factor of the membrane resonator's resonant frequency. In this case, we implement changes to the allocation of attached masses to study its influence to the vibration absorption performance.

Normally, in a membrane resonator, a single mass is attached to the middle of the membrane. In this work, the membrane resonator with 3 attached masses were studied. A 3D model was constructed in COMSOL Multiphysics. The configuration of the unit cell was presented in Figure 1. The masses are aligned averagely in the middle line of the membrane, the distance d between each other was chosen as the parameter for reference. The materials for the membrane, frame and mass were chosen as rubber, epoxy and copper respectively. The Young's modulus, density and Poisson's ratio of membrane are 20 MPa, 980 kg/m3 and 0.49 respectively, and the side length L of the resonator is 60mm.

Figure 1. The configuration of the membrane resonator

In MAM, the membrane resonator is considered as a unit cell. In order to investigate its one dimensional bandgap property, two opposite edges of the resonator were applied with the Floquet boundary condition. By setting the wave vector scanning from 0 to π/L and plotting the eigen frequency of the model, the dispersion relation can be obtained. In addition, by setting the distance d to 8, 10 and 14mm, the shifting of the bandgap edges was obtained and presented in Figure 2.

Figure 2. Band structure of the MAM with various distances between the attached masses

According to the figure, it is found that when the distance between masses was increased, the location of bandgap would be shifted up. When the distance was increased from 8mm to 14mm, the bandgap location (lower edge) was changed from 214Hz to 259Hz, which is a relatively significant change of location. In former studies of MAM, the main method used for adjusting the location of bandgap is by changing the external force applied to the membrane [14].

To examine the mechanism of the bandgap formation, the mode shapes of the resonator with an infinite periodic structure are presented in Figure 3. In accordance to Figure 2, the bandgap is formed by the first order resonance, which is the out-of-plane vibration of the decorated mass. The periodicity can also generate a Bragg bandgap, but it is not taken into consideration in this work. Furthermore, for the 1st resonant mode, the moving part of the unit cell is only the decorated masses and the centre region of the membrane, while the frame is mainly stationary. However, in the 2nd resonant mode, the decorated masses and the frame are both vibrating in the opposite direction, so the vibration will still be able to be transmitted to the target structure.
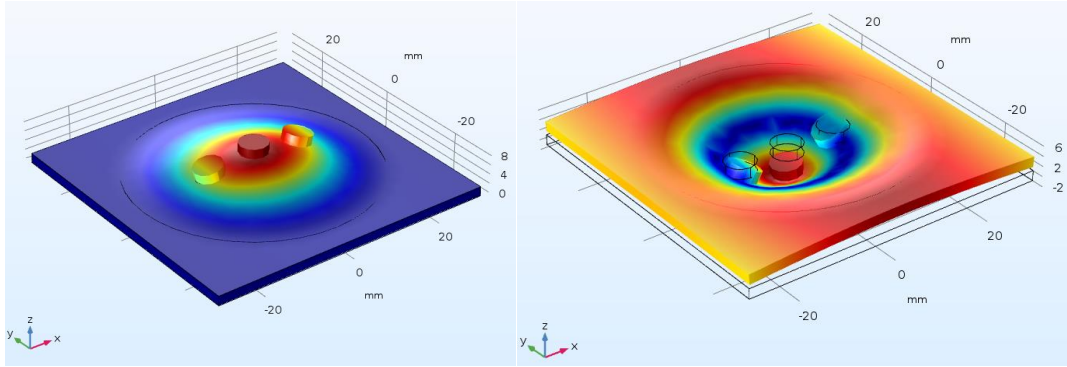
Figure 3. Left: the 1st mode shape of membrane unit cell; Right: 2nd mode shape of the membrane unit cell.

3. VIBRATION TRANSMISSIBILITY ON A THIN PLATE

To examine the vibration absorption performance of the aforementioned membrane resonator, a finite combination of 1×8 units of membrane resonators are constructed and attached to a thin aluminum plate. The size of the plate was set as: $600 \times 100 \times 2$mm. For metamaterial, periodicity is not compulsory for its functioning. However, in order to compare with the band structure results in Section 2, a periodic combination of resonators is utilized.

Figure 4 shows the configuration of the structure. The left edge of the plate is fixed, and prescribed displacement is set at the right edge of the plate as the incident excitation. A frequency domain scanning is then conducted and the response signal is picked up from Point A. For comparison, the frequency response of a bare plate is also included in this study.
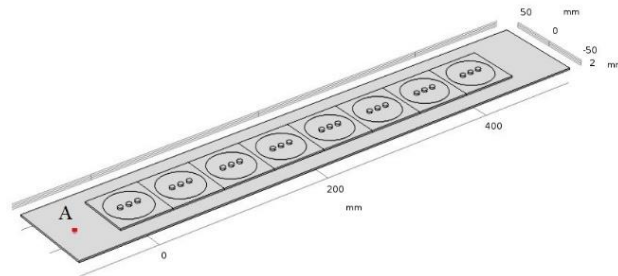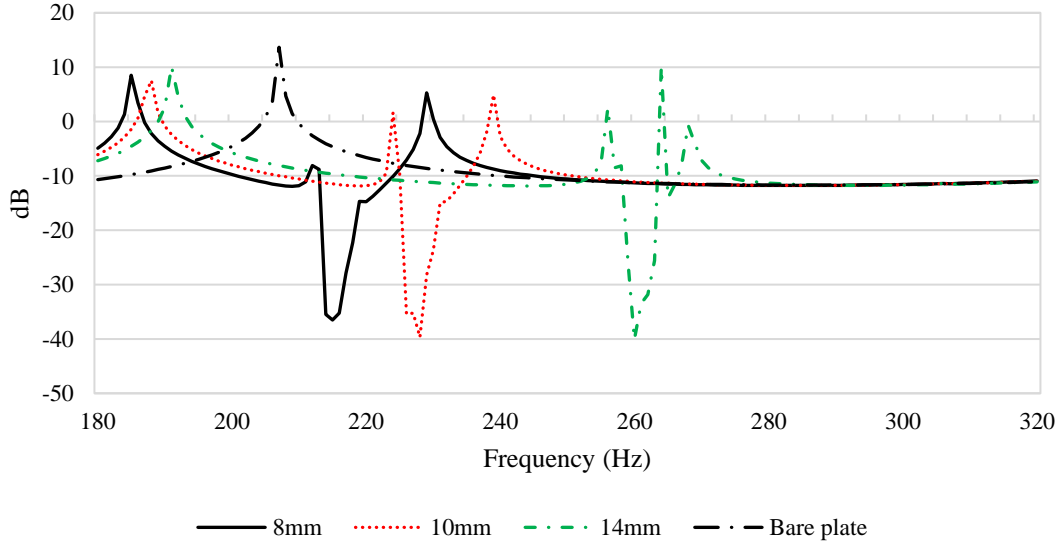

Figure 4. Configuration of a thin plate with membrane-type metamaterial array

The results of frequency domain scanning are presented in Figure 5. Based on the figure, when the distance between each mass was increased, the resonant frequency would be shifted to the higher frequency range. By adjusting the distance from 8mm to 14mm, the bandgap was shifted from $214 - 220$Hz to $259 - 264$Hz, while the bandwidth is mainly unchanged at about 5 Hz. This is consistent with the bandgap analysis previously described and it demonstrates that the changing distance of decorated masses can be used to effectively tune the location of the bandgap. In accordance to the figure, the use of resonators has managed to reduce the vibration transmissibility of the thin plate by about 40dB at most. It should be noted that the total mass of the resonators is about 41g, which is 12.65% of the weight of the plate.

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When the distance between the masses is 10mm, the obtained bandgap range is 226-231Hz. If the incident wave is outside the bandgap range, the structural wave will propagate through the plate and resonators directly because it cannot excite the resonant mode of the resonators. However, when the incident wave is within the bandgap range, the first resonance mode will be excited. As aforementioned, for the first resonant mode, the decorated masses are in motion, while the frame mainly remains stationary. As a result, the vibration energy can be absorbed by the resonator cell so to minimize the vibration transmission in the plate.

Figure 5. Frequency response of membrane resonators. The distance between decorated masses are defined as 8, 10 and 14mm, respectively. The dash-dotted line indicates the response of a bare aluminium plate.

4. CONCLUSIONS

The vibration absorption performance of membrane-type metamaterial on a thin plate has been investigated in this work. For this investigation, the vibration mode shapes of the resonator are examined to investigate the mechanism of bandgap formation. It is found that by changing the allocation of masses decorated on the membrane, the resonance frequency of the membrane resonator can be tuned accordingly. Compared with the method of tuning the force applied to the membrane, this method can be easier to implement and more accurate results can be achieved during the fabrication process. In this simulation study, the results show that the change of distance of decorated masses from 8mm to 14mm can shift the bandgap from 214 – 220Hz to 259 – 264Hz. This can provide an alternative way of adjusting membrane-type metamaterial's operation frequency.

5. ACKNOWLEDGEMENTS

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