TUNABLE ACOUSTIC METAMATERIAL WITH AUXETIC BEHAVIOR

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ABSTRACT

Metamaterials, artificial materials composed of periodic microstructures, present novel behaviours like negative Poisson’s ratio, negative effective mass density, negative refraction, and others not found in nature. Most of metamaterials present their bandgaps in constant frequencies. Recently, many studies focus on the tunable acoustic metamaterials which change their bandgaps in different frequencies with deformation mechanism. It is so called deformation-driven tunable acoustic metamaterial. This study presents planer and cubic auxetic structures as the deformation-driven tunable acoustic metamaterials which can deform in the linear-elastic region and then cause the change of band structure. The results were calculated by commercial software package COMSOL Multiphysics® and showed variation in bandgaps tuned by applying deformation. These proposed structures would be exploited to turn the bandgaps on or off directionally within the linear-elastic region. This open avenue for the design of acoustic switches making a new possibility to manipulate the wave propagation.

1 INTRODUCTION

In these decades, there are researches prospered on study of novel acousto-elastic interaction in phononic crystals and metamaterials based on their unique characteristics of unique dispersion curve that apply on wave manipulation. Those present greatly focused property that is the ability to open phononic bandgap [1-3].

In Fig. 1 and Fig. 2, these are planer and cubic auxetic structural materials (PAM and CAM) that we designed and are derived from the previous work [4]. These are new type of two- and three-dimensional auxetic structural material constituted of anti-tetrachiral. Auxetic structural materials known as negative Poisson’s ratio materials are featured their counterintuitive behavior based on applying tensile loads in one direction they expand in other directions. In Fig. 3, it shows positive and negative Poisson’s ratio. In other study, the auxetic property is used to cause the effect of indentation resistance and applied on cushions design. There is a figure shown as Fig. 4 about the effect of indentation resistance. In Fig 4a, the non-auxetic material below the impact flows away in the lateral direction, leading to a reduction in density and, therefore, a reduction in the indentation resistance of the material. In the other case, for an auxetic material in Fig 4b, material flows into the vicinity as a result of lateral contraction accompanying the longitudinal compression due to the impact. Therefore, auxetic materials densify under the impact in both the longitudinal and transverse directions, leading to increased indentation resistance. This study focuses on the two materials we proposed and then discuss these structures in undeformed and deformed configurations.

The unique propagation of acoustic and elastic waves in periodic composite materials is caused by bandgaps, in which sound and vibration are forbidden in any directions [1]. So that, realizing tunable and switchable acoustic metamaterials based on mechanical deformation is discussed in lately researches [5-9]. Moreover, turning on or off the bandgap though deforming structures is presented in this study. It opens promising avenue for design of acoustic switches.
Fig. 1 (a) Mold for PAM. (b) Experimental specimen (two layers of PAM).

Fig. 2 The (a) representative volume element of CAM and (b) 3D printing prototype of CAM.

Fig. 3 (a) Positive and (b) Negative Poisson’s Ratio Material.

Fig. 4 Indentation Resistance in (a) Non-auxetic and (b) Auxetic Materials.
2 METHOD

2.1 FINITE ELEMENT ANALYSIS FOR PAM

Geometry of auxetic structure was investigated, then the commercial finite element software package COMSOL was utilized for acoustic band structure numerical simulations, discussing the relation between geometric deformation and band structure. Extending the discussion on dispersion between undeformed and deformed structures, the frequency range of the band gap was observed and proved the tunable band structure. In addition, the wave attenuation behavior was investigated experimentally. The frequency response was obtained, and sound attenuation was observed, confirming the simulation results of tunable band gap.

The path of frequency sweep needed to be clarified. The path was as shown in Fig. 5. The planar structure was placed in the middle and except the structure with gray cube was air. The side length of the unit cell was L. Because of structural symmetry, reduced Brillouin zone was a black cube frame as shown in figure. The red block $\Gamma - X - M - \Gamma$ was the sweep path related to the wave transmission direction $\Gamma - X$. Sweeping frequency along the $\Gamma - X - M - \Gamma$, the band structure of the unit cell could be investigated and then obtained the dispersion curve. For the boundary condition in simulations, the surfaces were set periodic boundary conditions, and the wave vectors were defined and applied. The range of sweeping frequencies was from 0 Hz to 20 kHz and the frequency step size was 200 Hz.

![Fig. 5 Frequency sweep path of the unit cell](image)

2.2 FINITE ELEMENT ANALYSIS FOR CAM

The mainly way in our study is finite element method (FEM). It was employed to calculate the deformation with the negative Poisson’s ratio and the band structures of the cubic auxetic structural materials (CAM). All the calculation and the simulation in this study are finished with the commercial software package COMSOL Multiphysics®.

In dynamic analysis, first we built the original structure with SolidWorks software and then input to COMSOL Multiphysics®. There is the Fig.6-1 shown the original structure in the SolidWorks software. At the same time, for the deformed structure case, we also imported the deformed mesh to the COMSOL Multiphysics®. It is our team calculated them with Abaqus software previously and the results are shown as Fig. 6-2a and Fig. 6-2b. When we put the deformed meshes of the compression model and the tension model into COMSOL, we received the manufacturing window shown as Fig. 6-3. Then we could start to calculate the dispersion curve. In order to plot the dispersion curve, we chose the eigenfrequency study of the acoustic pressure model to calculate these two cases. Due to periodic distribution of energy in the periodic arrangement structure, we considered the first Brillouin zone (FBZ) only. It brought benefit to save the calculating time in our work. The space of FBZ in the three-dimensional anti-tetrachiral is shown as Fig. 6-4. It was defined to calculate the dispersion relation which was used to obtain the dispersion curve.
Fig. 6-1 The original structure was built with SolidWorks software.

Fig. 6-2 The deformed mesh of (a) tension and (b) compression.

Fig. 6-3 The deformed mesh of (a) tension and (b) compression.
3 RESULT

3.1 NUMERICAL RESULTS FOR PAM

Fig. 7 was dispersion result of undeformed unit structure. From dispersion curve, it was observed that there was no wave number in Γ - X path in 8000 Hz-9000 Hz and 16000 Hz-17000 Hz as shown in the figure with gray region. It meant that there was no acoustic wave passing through, and wave transmission attenuation at this frequency might happened.

The unit structure was enlarged and reduced proportionally and through dispersion analysis to observe the tendency of band structure. Fig 8 was the results after the integration. Here Γ – X – M – Γ path was analyzed, and the gray region in Γ – X direction was band gap. In Fig 8(a), it was observed that as the unit structure was enlarged proportionally, the overall tendency of band structure was almost the same. However, when frequency scale was adjusted the same, the tendency of band structure was overall downward as the structure was enlarged which was as shown in Fig 8(b).
Fig. 8 Band structure of the overall size changed. \( t = 1 \text{mm}, \) change \( L \) (a) Overall tendency (b) Frequency scale was adjusted the same

Then, the side length was fixed and detailing dimensions was changed to observe the band structure. \( L \) was fixed to 20mm and beam width \( t \) was adjusted. The results were as shown in Fig. 8. There were differences in 8000Hz and 16000Hz where the band gaps became broader as beam width \( t \) increased.
Axial tensile strains $\varepsilon = (L - L_0)/L_0 = 0.02, 0.06, 0.1$ were applied on unit cell and compressive strains $\varepsilon = -0.02, -0.06, -0.1$ were applied as well. With unit cell deformed, the change of band structure was discussed and observed. The results were as shown in Fig 10 and Fig 11. The gray regions in the figure was the band gap in $\Gamma - X$ direction. In tensile results, the band gap was gradually narrower in $\Gamma - X$ direction as the structure stretched. In compressive results, the band gap was gradually broader in $\Gamma - X$ direction as the structure compressed. These gray regions at these frequencies were acoustic attenuation. Through geometric deformation with structure stretched and compressed, the band gap could be adjusted to reach the effect of tunable frequency.
3.2 NUMERICAL RESULTS FOR CAM

It was divided into two parts in the result which we obtained from the study. One was the original model and the other was the deformed model. All of them were calculated by COMSOL Multiphysics®.

3.2.1 RESULTS OF THE ORIGINAL MODEL

The dispersion curve of the cubic auxetic structural materials (CAM) could be obtained by dynamic FEM simulation. For the original model, the representative dispersion curve of the undeformed configurations are shown as Fig. 12-1. To compare the band structure of the three-dimensional anti-tetrachiral before and after deformation, the structure was calculated along the boundary G-X1 (X-axis), G-X2 (Y-axis) and G-X3 (Z-axis). The definition of the direction is the same as Fig. 6-2. The results of the dispersion curve support that there is no bandgap in the undeformed original model in any principal direction.

Fig. 12-1 The dispersion curve of the original model in the X, Y, and Z directions.

3.2.2 RESULTS OF THE DEFORMED MODEL

There is no bandgap in the original model but the deformed model. All of the deformed models were given the force until their strain in 5mm. When the structure was compressed, bandgaps were directionally switched on. We separated the results into compress cases and tension cases shown as from Fig. 12-2 to Fig. 12-7. It was applied only one unidirectional loaded force in each figure. After we read those results and figures, we found that bandgaps showed up in certain cases. During the compression in x direction, the bandgap appeared in y direction. According to the anisotropic behavior in x and y direction, the bandgap appeared in x direction during the compression in y direction. Moreover, when the material was stretched, the bandgap was switched on in another direction. When the material was stretched in x direction, the bandgap appeared in x direction, the bandgap appeared in y direction when the material was stretched in y direction, and the bandgap appeared in z direction when the material was stretched in z direction.

Fig. 12-2 The dispersion curve (a) in G-X1, (b) in G-X2, and (c) in G-X3. (Compress in x direction)
Fig. 12-3 The dispersion curve (a) in G-X1, (b) in G-X2, and (c) in G-X3. (Compress in y direction)

Fig. 12-4 The dispersion curve (a) in G-X1, (b) in G-X2, and (c) in G-X3. (Compress in z direction)

Fig. 12-5 The dispersion curve (a) in G-X1, (b) in G-X2, and (c) in G-X3. (Tension in x direction)

Fig. 12-6 The dispersion curve (a) in G-X1, (b) in G-X2, and (c) in G-X3. (Tension in y direction)
The conclusion of PAM and CAM are presented in 4.1 and 4.2, respectively.

4.1 CONCLUSION OF PAM

In the study, a tunable planar auxetic metamaterial (PAM) for controlling and filtering acoustic waves was investigated. The commercial finite element software package was utilized for numerical simulations. A planar auxetic metamaterial (PAM) was placed periodically, and its acoustic band structure was obtained to reach the effect of tunable band gap. In addition, the wave attenuation behavior at a specific frequency was investigated experimentally, and the experimental results were compared with those obtained from numerical simulations.

4.2 CONCLUSION OF CAM

The appearing bandgaps are summarized in Table 1 according to different directions. An “O” mark represents a bandgap appearing in the direction. According to Table 1, the bandgap appeared in G-X1 during the compression in y direction and appeared in G-X2 during the compression in x direction. The cubic auxetic structural materials (CAM) has x, y direction anisotropic properties. So both of the bandgaps were between 9100 Hz and 9800 Hz. The tunability of bandgap suggests that the out-going direction of the sound around 9500 Hz could be manipulated by the deformation of the structure. Fig. 13 is the schematic diagram of the manipulation. When the sounds around 9500 Hz went through the cubic auxetic structural materials (CAM), the out-going direction could be controlled by our acoustic switcher. The bandgap could appear in x or y direction. During the compression in y direction, the sounds around 9500 Hz could not go through the cubic auxetic structural materials (CAM) in x direction, and can propagate through the y direction. During the compression in x direction, the sounds around 9500 Hz could not go through the cubic auxetic structural materials (CAM) in y direction, and can propagate through the x direction. The direction of the bandgap in the same frequency range could be manipulated by the deformation of the structure. This concept is also a step further from the others acoustic switchers.

Moreover, the cubic auxetic structural materials (CAM) could be exploited to turn on or off the bandgap in the linear-elastic region, making the transformation in bandgap a reversible and repeatable process. Reversible control via an external triggering stimulus provides an opportunity for tunable acoustic switches. Our tunable device has the advantage of previous non-linear elastic tunable devices in the repeatability and long lifetime. Dynamic tunability of acoustic properties would provide a significant step toward the adoption of acoustic metamaterial for practical device applications such as acoustic tunable switchers where the properties change upon the activation of an external stimulus.
Fig. 13 Schematic Diagram of the Acoustic Switcher

Table 1 The appearing bandgaps

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<th>Compression</th>
<th>Tension</th>
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<td>Scanning X (G-X₁)</td>
<td>X Y Z</td>
<td>X Y Z</td>
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