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Wave Propagations in Metamaterial Based 2D Phononic Crystal: Finite Element Analysis

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Abstract. In the present work, the acoustic band structure of a two-dimensional (2D) phononic crystal (PnC) containing composite material were investigated by the finite element method. Two-dimensional PC with triangular and honeycomb lattices composed of composite cylindrical rods are in the air and liquid matrix. The existence of stop bands are investigated for the waves of certain frequency ranges. This phononic band gap - forbidden frequency range - allows sound to be controlled in many useful ways in structures. These structures can be used as sonic filters, waveguides or resonant cavities. Phononic band diagrams $\omega=\omega(k)$ for a 2D PnC were plotted versus the wavevector k along the Γ-X-M- Γ path in the first Brillouin zone. The calculated phonon dispersion results indicate the existence of full acoustic modes in the proposed structure along the high symmetry points.

1. Introduction

The PnC’s have been classified according to their physical structure of inclusion and matrix materials. The solid/solid, fluid/fluid, and the mixed solid/fluid composite systems have been studied theoretically and experimentally. These composite media have stop bands in their transmission spectra. In that case, the propagation of the acoustic or elastic waves is strictly forbidden [1, 8, 21]. As in photonic crystal, highly confined waveguides can also be created for elastic and acoustic waves by adding a line defect in PnC [9-14].

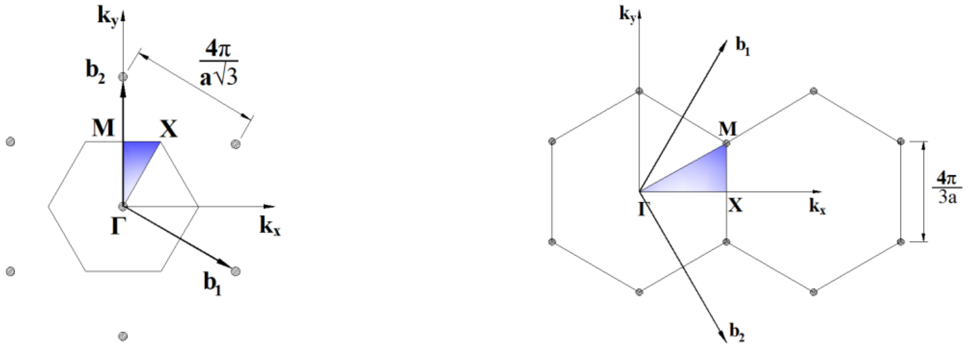
The unusual properties of the dispersion relation in the propagation band results in negative refraction. A flat slab with a negative refraction index behaves as a lens [23]. PnC can be designed as new component in acoustic and ultrasonic range to control sound.

It has been shown that, the width of the complete band gap can be increased by reducing the lattice symmetry [3, 9, 15]. In this work, we consider two dimensional PnC consist of composite cylinders in air. We compare the band structure and transmission spectra of triangular and honeycomb lattice both numerically and experimentally for sonic frequency and numerically for ultrasonic frequency. For ultrasonic frequency, we choice tungsten cylinder inclusion in water. Since, tungsten has high contrast of density and speed of sound [2, 16-19]. We investigate whether band gaps could be identified and obtained by using periodic-boundary finite element method (FEM) for the unit cell of infinite structure. This is investigated by comparing transmission magnitudes with the conventional finite structure [9, 17-18, 20-22].

2. The model and calculation method

The destructive interferences lead to forbidden bands in the periodic structures via wave scattering. If the frequency of incident wave is within the band gap region, total reflection is observed. PnCs are generally divided into two main categories; acoustic and mechanic PnCs. In this study, solid-fluid PnCs are investigated by applying acoustic waves. We assumed that cylindrical rod inclusions are infinitely long along z direction. The periodicity is assigned throughout *xy* directions and acoustic properties of the PnC are also periodic along *xy* direction. We consider that a longitudinal wave propagates in *xy* direction.

Finite element implemented calculation is used for $\Gamma - X - \mathrm{M} - \Gamma$ -directions to obtain eigenvalues and eigenvectors of PnC.



a) b)

Figure1. Brillouin zone of (a) the triangular lattice and (b) the honeycomb lattice.

PnC with triangular and hexagonal lattices are considered. These lattices consist of composite circular cylinders. They are placed in air to form two-dimensional lattices with a lattice spacing of ***a***. Figures 1(a) and 1(b) are the Brillouin regions of the triangular and the hexagonal lattice, respectively. The irreducible part of the Brillouin zone of a triangular lattice is shown in Fig. 1(a) which is a triangle with vertices of Γ, X, M. The irreducible part of the Brillouin zone of a honeycomb lattice is shown in Fig. 1(b), which is also a triangle with vertices of Γ, X, M. The utilized materials properties are given in Table 1.

Table 1. Material parameters used in the analysis

	Composite materials	Air	Tungsten	Water
Speed of sound (m/s)	1420	343	5090	1490
Density (kg/m^3)	690	1.25	19300	1000

For numerical analysis, we used 2D PnC which is most commonly used in the literature [1]. Plane wave signal source with a pressure level of p0=1 [Pa] is applied to PnC with triangular and honeycomb lattices. For normal component of the air particles equal to zero, the absorber boundary condition is applied to the edge of the periodic structure and sound hard boundary conditions is applied to the edge of cylindrical inclusions. To observe the propagation of the acoustic wave in the PnC, we first set the lattice parameter is defined with a value of a=30 mm and the radius of the scatterers is increased from r=7 mm to r=12 mm by a step of 1 mm for both triangular and honeycomb lattice.

We obtained experimentally the acoustic pressure level (dB) of the PnC composed of composite cylinders with radius of 10 mm (r), length of 300 mm (L) and lattice parameter of 30 mm (a) in air. We placed the speaker 1 m away from PnC. The microphone is placed just behind of the PnC for the experimental measurement.

A tone generator software has been used by setting the output frequency100 Hz - 20000 Hz. The sound recorded on the computer by using the M-Audio external sound card and audio-technica pro 44 microphones. The recorded sound data is converted to frequency domain by using standard Fast Fourier Transform (FFT) algorithm as shown in Fig. 3 and Fig5. Due to the circular shape of the equifrequency contour, the group velocity and the wave vector inside the crystal are antiparallel for all directions of propagation inside the crystal [24].

Negative refraction is also investigated for 2D PnC consist of tungsten rods immersed in water with FEM. The group velocity is the gradient of the angular frequency as a function of k point ($v_g = \frac{\partial\omega}{\partial k}$). The group velocity and the incident waves are parallel to wavevector during the incident waves propagating in liquid base.

3. Results and Discussions

3.1. Triangular lattice

We first investigate the case with composite rods placed in the air in triangular lattice with circular cross session. 2D Triangular and honeycomb lattices are considered here and the numerical results are given as follows. For the triangular lattice, the largest absolute PBG is produced for the filling fraction of f = 0.58. The maximum band gap (between the 2nd and 3th bands) has the width (gap–mid gap ratio) of $\Delta\omega/\omega g$ = 0.1355 as can be shown in fig. 2.

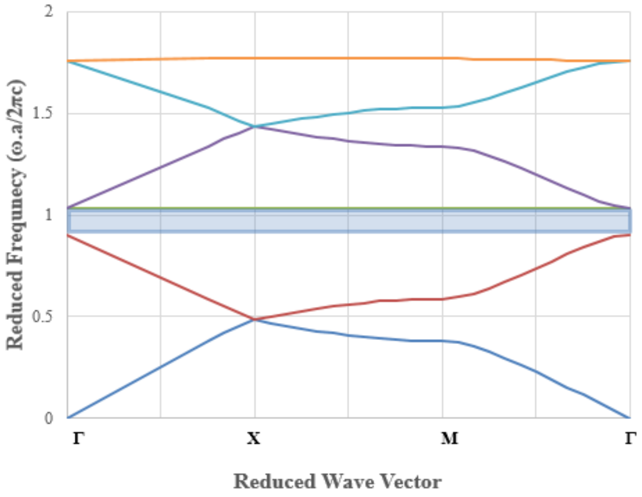
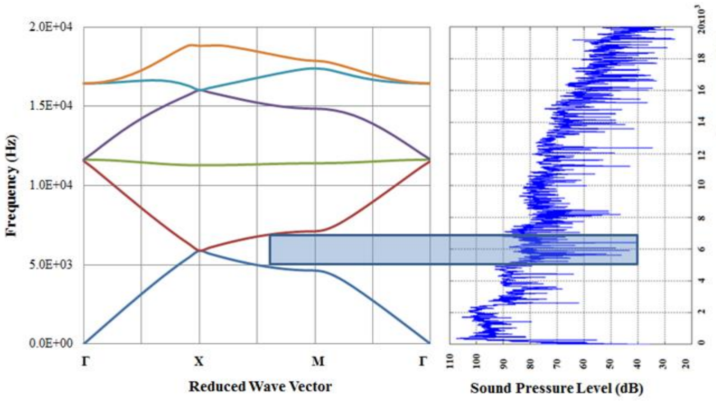


Figure 2. FEM computed band structure for the triangular lattice phononic crystal. The blue shading indicates the presence of resonance band gap.

The upper and lower edges are 0.384 and 0.236 in terms of $\omega a/2\pi c$, where c is the wave velocity in the air ($\Delta\omega$ = 0.148).

Figure 3. a) and b shows band gap and experimental measurement results of PnC with the lattice parameter of a=30 mm and the radius of the rods of r=10 mm. It can be seen that that the PnC with triangular lattice have band gap along X-M direction.



a) b)

Figure 3. a) Band structure b) experimental measurement

3.2. Honeycomb lattice

For the honeycomb lattice, the largest absolute PBG is observed for the filling fraction of *f* = 0.38. The gap between the 1st and 2nd bands has the largest width (gap–mid gap ratio) of $\Delta\omega/\omega g = 0.47$ as can be seen in Fig. 4.

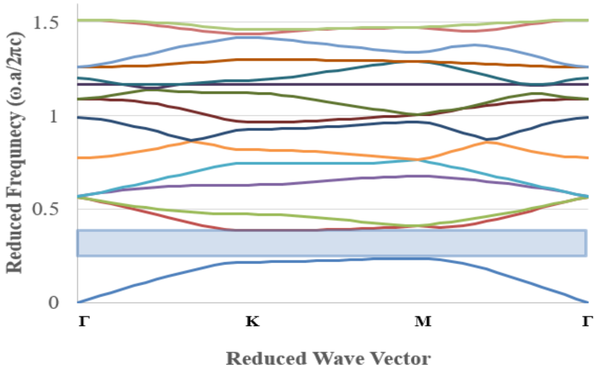


Figure 4. FEM computed band structure for the honeycomb lattice phononic crystal. The blue shading indicates the presence of resonance band gap.

The upper and lower edges are 0.384 and 0.236 ($\Delta\omega$ = 0.147) in terms of a $\omega a/2\pi c$, where c is the wave velocity in the air. Band gap and experimental measurement results for the lattice parameter a=30 mm and radius of the rods r=10 mm are shown in Figure 5. It is seen that the PnC with honeycomb lattice have complete band gap.

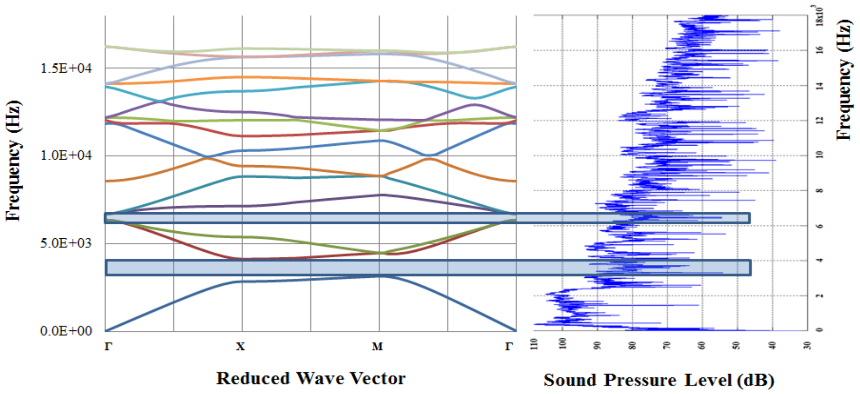
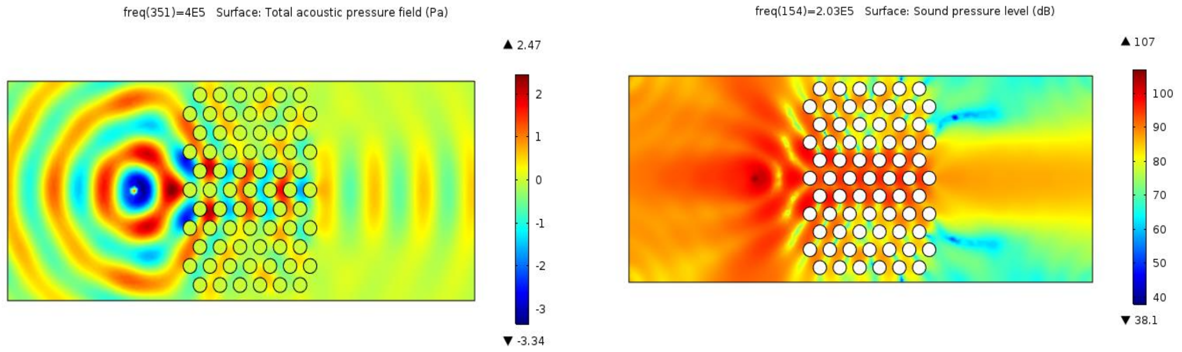


Figure 5. a) Band structure b) experimental measurement

3.3. Acoustic lens effect and negative refraction properties of phononic crystal

The negative refraction can be observed when the waves penetrate to the crystal surface with negative refractive index. If the band structure of the PnC has convex peak at the X point in Fig 2, it could result in negative refraction [2]. The negative refraction properties of PnC may lead to focus acoustic waves by flat lenses.

We investigate the acoustic lens effect and negative refraction properties of the PnC by FEM. PnC consists of tungsten cylindrical inclusion in water. As seen in Fig.6, the PnC with negative refraction properties has acoustic lens effect.



a) b)

Figure 6. Acoustic lens effect of PnC a) Normalised Total Pressure Field (Pa) b) Sound Pressure Level (dB)

The PnC crystal slab is placed in water and a point source is placed at the left side of the slab. Acoustic waves are emitted from the point source and propagate into the PnC slab with negative refractive index. As seen in Fig.6, the transmitted waves are then refocused at the right side of the slab.

4. Conclusion

It’s reported that except at very high filling fraction, the triangular lattice is not suitable to realize a complete band gap. When we compare the triangular and the honeycomb PnC, we found that the complete band gaps in the honeycomb case appear at lower frequencies with respect to the triangular case. We have examined the band gap properties of triangular and honeycomb two-dimensional PnC made up of composite cylinders placed in air for sonic frequency. We have also numerically simulated the band gap properties of triangular and honeycomb two-dimensional PnC made up of tungsten cylinders immersed in water for ultrasonic frequency. The same geometric parameters have been used for an accurate comparison of the two lattices.

The honeycomb lattice demonstrates complete band gap at the lower frequency between the first and the second bands. Since, the increasing filling factor of honeycomb lattice is lower than triangular lattice and symmetry. The calculated transmission spectra and band gap are in a good agreement with the experimental results. As a practical engineering design, the proposed structure could be used to fabricate filter devices or noise isolation materials at the low-frequency sonic region. The negative refraction properties of the PnC could lead to design new types of acoustic metamaterials for example acoustic and ultrasonic cloaking [21].

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