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Fundamental study of mechanism of band gap in fluid and solid/fluid phononic crystals

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ABSTRACT

Phononic crystals (PCs) have possessed outstanding features to control/manipulate the propagation of the acoustic/sound wave. In this paper, the local resonant elements, such as local resonant cavity in fluid PCs and local resonant inclusion in solid/fluid PCs, are introduced. The effect of geometry parameters, Poisson's ratio, Young's modulus on the band gap solid/fluid PCs are investigated in detail. It is found that wider multiple band gaps are obtained for the fluid PCs with local resonant cavity of “ + ” hole compared with square and circle holes. More importantly, the very low-frequency band gaps can be obtained by introducing the local resonant inclusion with consideration of fluid-structural interaction for solid/fluid PCs. In addition, we have compared the sound transmission loss in fluid and solid/fluid PCs. The numerical results have clearly indicated that solid/fluids PCs with consideration of fluid-structural interaction can block the propagation of stress wave effectively compared with fluid PCs. The theoretical study and numerical simulation conducted in this work have provided a new avenue to design more innovative fluid and solid/fluid PCs.

1. Introduction

Phononic crystals (PCs) are artificial materials with many appealing properties that cannot be found in nature, which has received substantial attention in the literature [1–6]. The idea of PCs is originated from electromagnetic metamaterials with simultaneously negative electric permittivity and magnetic permeability [7]. With combination of periodic two or three more base materials with different microstructures, the overall performance of PCs can be tailored by appropriate choices of changing the microscopic size and configuration of the individual constituents instead of chemical components. The potential applications of PCs include acoustic cloaking [8], fluid sensor [9], imaging [10], energy harvesting [11,12] and sound attenuation [6]. In doing so, the design methodology of PCs has explored an entirely new route to develop more innovative materials and structure.

The most promising feature of PCs is the appearance of band gap [13], within which the elastic/acoustic waves are prohibited in all directions. Such unique but very useful characteristic of PCs is extremely important in the practical application of control of noise and vibration. Generally, there are two types of working mechanics to create the band gap of PCs, which include Bragg scattering and local resonance. It is noted that Bragg band gaps usually exist in the frequency region where the wavelength of the waves is in the same order of magnitude with the lattice constant, which limits the practical application of PCs in low-frequency region [14]. To this end, Liu et al. developed locally resonant sonic materials (LRSMs), which is made of spherical lead inclusions with a rubber coating and embedded in an epoxy matrix. Both experiment and theory validated that the lattice constant of PCs could be much smaller than the longitudinal wavelength of the wave in epoxy in the creation of low frequency band gap [15]. Consequently, Wang et al. proposed two dimensional binary locally resonant phononic crystals, which are composed of periodic soft rubber cylinders in epoxy host [16].

The tuning of band gap of PCs is always a very active research area. In the past, a large amount of research has been done to study the relation between the band gap and scatterer properties such as sizes, shapes, and lattice structures [17]. Liu et al. [17] have comprehensively studied the effect of the pore shapes on the band gap of PCs. In addition, the influence of release holes on the band gaps of solid-solid PCs was investigated by Soliman et al. [18]. Feng et al. [19,20] demonstrated that the band gaps of finite PCs could be tuned by the initial stress. The band gaps are found to be determined by several factors, including material and geometry parameters. Wang el al. studied the band gap properties of two-dimensional PCs with cross-like holes using the finite

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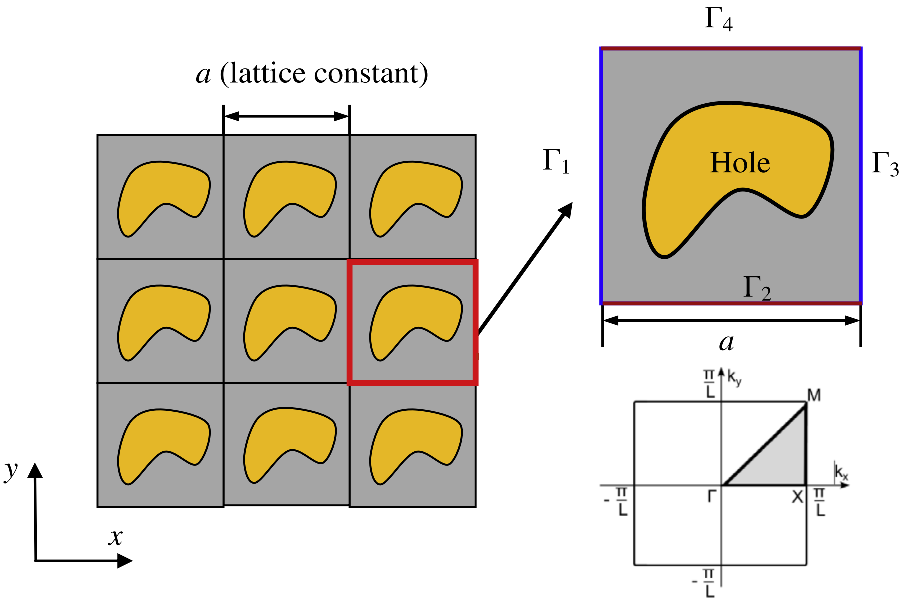

Fig. 1. Fluid PCs with a hole.

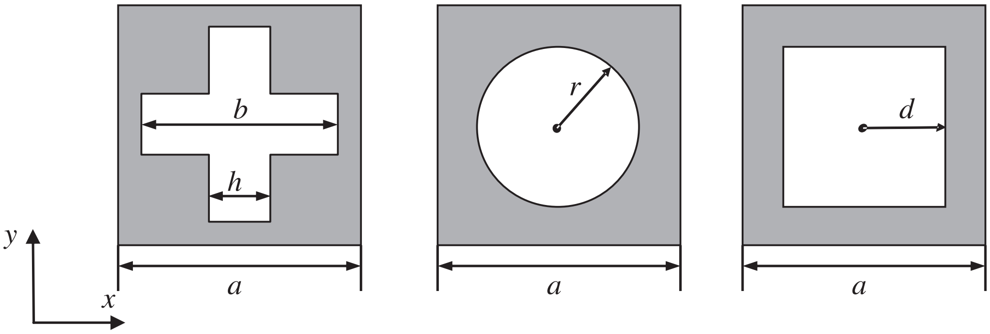

Fig. 2. Fluid PCs with different geometry of hole (a = 0.15 m).

element method (FEM) [21]. Based on the theoretical study and numerical simulation, it is observed that non- convex ("+" geometry) provides wider and lower band gaps compared with convex geometry such as square and circular holes. However, the past analysis of band gap with non-convex hole was only focused in solid/ solid PCs.

In general, we can define fluid/fluid, solid/solid, fluid/solid and solid/ fluid PCs [22]. In the fluid PCs, longitudinal wave in the fluid PCs exists, and the fluid PCs offers an innovative platform for acoustic fluid sensors that are still in the earlier stage development [23]. It is well known that mixed transverse and longitudinal waves with different velocities propagate within the solids, while only the longitudinal (acoustic) mode exists in ideal fluids [24]. However, the fluid--structural interaction [25,26] must be taken into account at the interface between the solid and fluid in the analysis of solid/fluid PCs [27,28], which makes it difficult predict the physical responses of PCs with solid and fluid components. Furthermore, the mechanism of band gap in the solid/fluid PCs with consideration of fluid-structural interaction is still not fully investigated.

In parallel with theoretical studies of PCs, modeling and simulation is also crucial to advance the future development of PCs. As a reliable, robust and effective approach, FEM is extensively employed to study the acoustic and elastic waves in periodic PCs. Compared with finite difference method (FDM), FEM is very powerful to deal with complex geometry efficiently. In 2004, Wang et al. proposed a lumped-mass FEM with faster convergence rate to analyze the propagations of elastic wave in two dimensional PCs [29]. Liu and Gao developed an explicit dynamic FEM to compute the band-structure of 2D PCs [30]. Furthermore, the X-extended Finite Element Method (X-FEM) was formulated to compute the band structure of 3D mechanical metamaterials with complicated geometry [31]. Consequently, Li et al. proposed different types of smoothed finite element method (S-FEM) in the simulation of band gap of PCs [32–35].

The purpose of the present paper is to explore the mechanism to tune the band gap in fluid and solid/fluid PCs using standard FEM. The local resonant elements, such as local resonant cavity in fluid PCs and local resonant intrusion in solid/fluid PCs, are introduced. First, we investigate the geometry of hole including convex and non-convex holes on the band gap of fluid PCs. Then, the effects of geometry parameters and material properties of solid scatterer on the band gap of solid/fluid PCs are further studied in this work. The thorough study in the analysis of band gap and sound transmission loss of fluid and solid/ fluid PCs is able to provide a useful guideline to design PCs. The layout of the paper is structured as follows. In Section 2, the mathematical model for fluid and solid/fluid PCs using FEM is presented. The parameter study of band gap in fluid and solid/fluid PCs is analyzed in Section 3. The conclusions are made in Section 4.

2. Stress wave model in fluid and solid/fluid PCs

2.1. Fluid PCs

As shown in Fig. 1, the hole is embedded into isotropic fluid. It is noted that only longitudinal wave exists in fluid PCs. The governing equation of longitudinal wave in fluid PCs is expressed as follows: