Band gaps of a fan-like solid-fluid phononic crystal

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Abstract. The vibration problem has a serious impact on modern life. The phononic crystal (PHC) is a periodically arranged composite material, which has good vibration attenuation capability because of its band gap (BG) characteristics. Most of available PHCs are limited to solid structures and the application ranges are limited. In this paper, a new fan-like solid-fluid PHC structure is proposed to suppress vibration in special environment. Firstly, the unit cell of fan-like PHC is built and the corresponding band structure is further calculated by finite element method (FEM). The band structures reveal that this fan-like PHC structure has four BGs below 10000 Hz. In order to illustrate the functionality of the fan-like PHC structure for vibration attenuation, the frequency response function (FRF) of a finite fan-like PHC structure is calculated. The FRF shows that there are strong attenuations in the ranges of BGs. Finally, by adjusting the side length of the square inclusion, the influence of the filling rate of the scatterer on BGs is studied. This new PHC provides new ideas for the vibration attenuation of builds at the riverside.

1. Introduction
Phononic crystals (PHCs) [1] are periodic structures which can generate band gaps (BGs) which can prohibited elastic waves propagation [2,3]. Due to this property, PHCs can be applied to a variety of fields, such as wave-guiding [4,5], filtering [6,7], focusing [8,9], and sensing [10,11]. The most attractive application filed is noise and vibration reduction to suppress the elastic waves [12,13].

PHCs can be fabricated using solids and fluids, the advantage of designing a structure that mixes both solids and fluids is that the acoustic impedance mismatch between the materials is very large, thus, resulting in broader and deeper BGs [14,15].

Tanaka et al [16] calculated the dispersion relations of a two-dimensional solid-fluid PHC consisting of mercury circular cylinders in an Al substrate. This PHC has large transmission dips in the high frequency range. Khelif et al. [17] reported the existence and the interaction of localized defect modes in a full acoustic band gap in a two-dimensional lattice of steel cylinders immersed in water. This PHC structure opened a full band gap which extends from 250 to 325 kHz. Fu-li et al. [18] investigated experimentally and theoretically the PHCs with triangular and honeycomb lattices which composed of arrays of steel cylinders immersed in water. A new type of PHC plate consisting of hollow pillars on a bar-connected plate is proposed by Jin et al. [19]. By filling the hollow pillars with a liquid, they investigated the influence of the inner radius of the pillars and the height of the liquid on BGs. Oltulu et al [20] proposed a 2D solid-fluid PHC consisting of periodic arrays of rigid solid rods embedded in a polar liquid, and researched the effects of elliptical rod orientations on the BGs. This PHC structure can open a BG about 6000 Hz. However, the BG is not low and wide enough.

In this study, with intention of obtaining lower frequency BG, a 2D fan-like solid-fluid PHC structure
is designed. The organization of the paper is as follows. In Section 2, the unit cell of the fan-like PHC is presented. Moreover, BGs are calculated by the finite element method (FEM), and the frequency response function (FRF) of a finite fan-like PHC is calculated. The influence of the filling rate of the scatterer on BGs was studied in Section 3. Finally, a conclusion remarks are drawn in Section 4.

2. The fan-like solid-fluid PHC structure

2.1. The unit cell of the fan-like PHC structure
In this paper, a novel fan-like solid-fluid PHC is proposed. The square lattice unit cell model of this structure is shown in figure 1. It is obvious that the unit cell has four sets of fan blades consisting of elastic beams which surround the square inclusion. In figure 1, the A, B and C represent the scatterer, elastic beams, and fluid material, respectively. Furthermore, A and B are immersed in fluid C.

![Figure 1. The unit cell of fan-like PHC structure.](image)

In figure 1, \(a\) is the lattice constant, \(b\) is the side length of the square scatterer, \(c\) and \(d\) are the lengths of the two elastic beams, \(e\) is, the thickness of all elastic beams.

2.2. The band structures of the fan-like PHC structure
In this paper, the band structures are calculated by FEM using Comsol software. In this calculation, the geometric parameters of the unit cell are as follows: \(a=60\text{ mm},\ b=25\text{ mm},\ c=37.5\text{ mm},\ d=10\text{ mm},\ e=5\text{ mm}\). The materials of A, B and C are steel, PMMA, and water, respectively. Moreover, the materials parameters are listed in table 1. In table 1, \(C_L\) and \(C_T\) represent longitudinal and transverse velocities of sound waves.

| Materials | Density (Kg/m\(^3\)) | \(C_L\) (m/s) | \(C_T\) (m/s) | Young module (E) Pa | Poisson’s ratio (v) |
|-----------|------------------------|---------------|---------------|---------------------|-------------------|
| A (steel) | 7780                   | 5825          | 3226          | \(2.106 \times 10^{10}\) | 0.300             |
| B (PMMA)  | 1142                   | 2670          | 1120          | \(0.2 \times 10^{10}\) | 0.389             |
| C (water) | 1000                   | 1490          | —             | —                   | —                 |

In figure 2, the BGs of the fan-like PHC structure are shown. It can be seen that there are four BGs in this band structure. The range of four BGs is from 2707 to 2750.3 Hz, 3267.3 to 3801.9 Hz, 5349.3 to 5393.4 Hz, and 8239.5 to 8628.1 Hz, respectively.
2.3. The FRF of the fan-like PHC structure

In order to illustrating the functionality of the fan-like PHC structure for vibration attenuation, a model consisting of an 8×8 super cell is designed to obtain FRF of a finite fan-like PHC structure. Because the four BGs are all below 9000 Hz, the FRF was calculated from 0 to 9000 Hz. The FRF is shown in figure 3.

In figure 3, it can be seen that there are attenuations between the ranges of four BGs. Moreover, the strongest attenuation reached -70 dB. Therefore, this structure has a good ability to reduce vibration.
3. The influence of the filling rate of the scatterer on BGs

The different filling rate of the scatterer can be obtained by adjusting the side length of the square inclusion. When the side length increases, the filling rate of the scatterer will become higher.

![Graphs showing the influence of the filling rate of the scatterer on BGs.](image)

Figure 4. The influences of the side length of the square inclusion on four BGs. (a) the first BG; (b) the second BG; (c) the third BG; (d) the fourth BG.; (e) The bandwidth of each of the four BGs.

The BGs of the fan-like PHC structures with different side length of the square inclusion (from 20 to 35 mm) are calculated using FEM. In these calculations, the other parameters are identical as those described in subsections 2.1 and 2.2.

The influences of the side length of the square inclusion on four BGs are shown in figures 4. For the
first BG, when the side length is larger than 23 mm, the first BG appears. Moreover, the bandwidth increases (from 23.5 to 27 mm) and then decreases (from 27 to 35 mm). For the second BG, the starting frequency and the terminating frequency increase with the increase of side length. At the same time, the bandwidth of the second BG widens. For the third BG, it can be seen that the BG only appears between 24.5 and 34 mm. The starting frequency and the terminating frequency increase as side length increases, and the bandwidth is the widest when the side length is 28 mm. For the fourth BG, between 22.5 and 29.5 mm, the BG appears. When side length increases, the starting frequency and the terminating frequency increase. Furthermore, when side length is 24.5 mm, the bandwidth is the widest.

4. Conclusions
In this paper, a fan-like solid-fluid PHC structure is proposed, which has four lower BGs below 10000 Hz. The four BGs of this PHC structure, which range from 2707 to 2750.3 Hz, 3267.3 to 3801.9 Hz, 5349.3 to 5393.4 Hz, and 8239.5 to 8628.1 Hz, respectively, are calculated using FEM. In addition, the FRF of an array 8×8 two-dimensional PHC structure is calculated, and the FRF shows that there are strong attenuations in the ranges of the four BGs. Finally, the influence of the filling rate of the scatterer on BGs is investigated. On the whole, the starting and the terminating frequency of four BGs increase as the filling rate of the scatterer becomes higher. According to different requirements, the corresponding BGs can be obtained by adjusting the filling rate of the scatterer. This solid-fluid PHC structure can be applied to the vibration reduction of building foundations at the riverside and the vibration attenuation of the working environment at riverside factories.

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