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Discussion

Design of radial phononic crystal using annular soft material with low-frequency resonant elastic structures

Nansha Gao [a,*], Jiu Hui Wu [b], Lie Yu [b], Hang Xin [b]

[a] School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an, 710072, China

[b] School of Mechanical Engineering and State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

Using FEM, we theoretically study the vibration properties of radial phononic crystal (RPC) with annular soft material. The band structures, transmission spectra, and displacement fields of eigenmode are given to estimate the starting and cut-off frequency of band gaps. Numerical calculation results show that RPC with annular soft material can yield low-frequency band gaps below 350 Hz. Annular soft material decreases equivalent stiffness of the whole structure effectively, and makes corresponding band gaps move to the lower frequency range. Physical mechanism behind band gaps is the coupling effect between long or traveling wave in plate matrix and the vibrations of corrugations. By changing geometrical dimensions of plate thickness e, the length of silicone rubber $h2$, and the corrugation width b, we can control the location and width of the first band gap. These research conclusions of RPC structure with annular soft material can potentially be applied to optimize band gaps, generate filters, and design acoustic devices.

1. Introduction

During the past two decades, elastic wave propagation in periodic composite structures, known as phononic crystals (PCs) have attracted a growing interest due to their abundant physics and potential engineering applications. The most notable feature of such PCs is the existence of the elastic wave band gaps (BGs), where the elastic wave propagations are prohibited. This feature suggests various potential application such as acoustic filters, silent blocks and efficient waveguides [1–17]. It is obvious that lattice symmetries of PCs in all the above researches are all arranged in Cartesian coordinates. For above PC arranged in square or triangle lattice, BGs are dependent on wave propagation direction. In recent one or two years, circular photonic crystal (CPC) was proposed to obtain omnidirectional BGs. CPC is highly symmetric in radial direction, and the periodicity is considered in r direction of cylindrical coordinate. Horiuchi et al. calculated isotropic BGs of CPC and verified numerical calculation with experiments [18]. They also fabricated a bent photonic crystal waveguide by use of a lattice pattern of a circular photonic crystal that allowed high transmission for a broad band of wavelengths with a small radius of curvature at a bend. The radius r of the dielectric rods and the radial distance d of the CPC are the size parameters that shift the frequency region of the photonic gaps to an upward or a downward frequency region [19]. In recent years, RPCs (RPCs) are reported and investigated [20–27]. Wen-Pei Yang et al. reported and described a class of 2D phononic crystals consisting of a square array of hollow cylinders in air. The inclusions are a dielectric elastomer cylindrical actuator. They found that the acoustic band gaps are changed due to the radial strain of the dielectric elastomer [20]. Yinggang Li et al. studied the propagation of Lamb waves in one-dimensional RPC plates with periodic corrugations [21,24,25]. Ting Ma et al. investigated the band structures of bilayer RPC plate with crystal gliding, they found that crystal gliding in radial direction could open new lowest order gap [22]. A study by Arpan Gupta et al. found that periodic obstruction to the sound wave by the scatterers leads to an interesting phenomenon of the band gap, which results in a high sound attenuation in the band gap region. The designed RPC was tested experimentally and by the finite element simulation. The experimental results were in good agreement with the simulation and show high sound attenuation of 30 dB [23]. These studies above show us that RPC has much new physical phenomena, and the researches of RPC would be a very potential field. Up to now, the low-frequency BGs of RPCs have been focused in the high frequency, and these corresponding BG locate in the range of several thousand Hz. In this paper, we propose a new simple RPC structure in this paper for low-frequency vibration and noise abatement. Numerical calculation results show that RPC with annular soft material can yield low-frequency band gaps below 350 Hz.

* Corresponding author.
E-mail address: gaonansha@hotmail.com (N. Gao).

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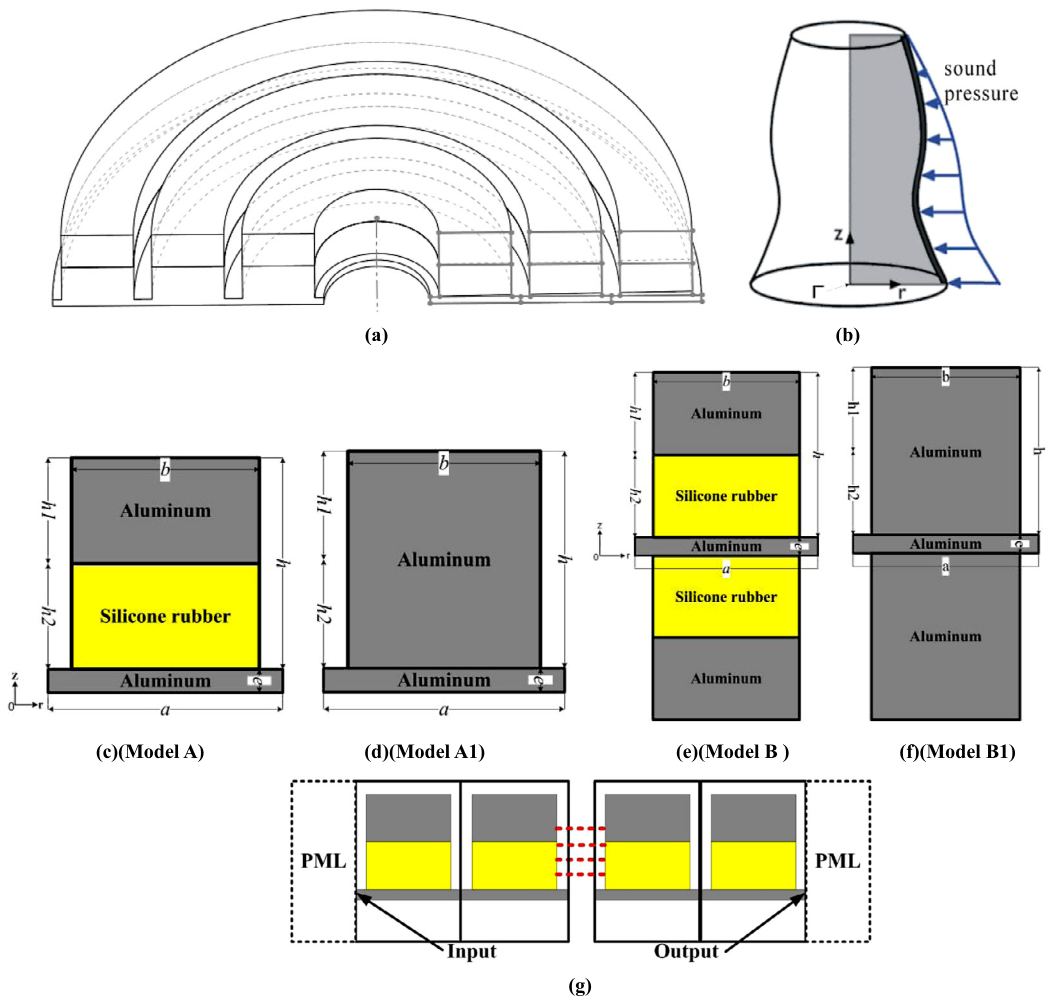

Fig. 1. Schematics of RPC with annular soft material. (a) The three-dimensional model of the proposed RPC structure; (b) Rotating a two dimensional geometry to recover a three-dimensional solid; (c), (d), (e) and (f) show the model A, A1, B, B1 respectively; (g) Schematic diagram of finite periodic system of 10 unit cells of the Model A. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

This paper is organized as follows. In Section 2, the setup of the numerical model analysis and the method of calculation for RPC structure based on the axial symmetry in cylindrical coordinates are used. Section 3 presents the calculated results and the behavior of the BGs in the RPC structure, discusses the physics mechanism behind the opening of BGs. Section 4 shows us the effects of the geometrical dimensions on the BGs. Finally, we present conclusions in Section 5.

2. Model and methods of calculation

The RPC structure model proposed in this paper is shown in Fig. 1. Fig. 1(a) sketches profile of three-dimensional RPC structure. Radial symmetry is achieved by periodic arrangement of unit cells in r-direction. Lattice constant in r-direction is a (mm). In Fig. 1(b), blue arrows indicate sound pressure. The z axis is perpendicular to the plate. The infinite system of the RPC structure is formed by repeating the unit cell of the two-dimensional axial symmetry model periodically along their directions and rotating the axial symmetry model about z-axial to recover the three dimensional RPC plate model, as shown in Fig. 1(a). Fig. 1(c)–(f) shows the different RPC structures after named model A, A1, B and B1 respectively. The thickness of the middle layer aluminum plate rubber layer are e and $h2$, and the thickness of the upper layer aluminum plate is $h1$. The geometrical dimensions are as follows: $a = 100$ mm, $e = 1$ mm, $b = 80$ mm, $h1 = h2 = 50$ mm. To theoretically investigate the propagation of elastic wave in the proposed RPC structures, the finite element method based on the two-dimensional axial symmetry in cylindrical coordinates is used to calculate the band structures, the transmission spectra, and the displacement fields of the eigenmodes. The governing equation considered here is

$$\rho\ddot{u} = \nabla\left[\left[\lambda(r) + 2\mu(r)\right](\nabla \cdot u)\right] - \nabla \times \left[\mu(r)\nabla \times u\right] \tag{1}$$

$$\nabla \cdot \boldsymbol{v} = \frac{\partial u}{\partial r} + \frac{\partial v}{\partial \phi} + \frac{\partial w}{\partial z}, \qquad \nabla \times u = \begin{bmatrix} i & j & k \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \phi} & \frac{\partial}{\partial z} \\ u & v & w \end{bmatrix} \tag{2}$$

The eigen equation (1) is solved by COMSOL Multiphysics. In the axial symmetry, stress–strain application model, displacement u together with stresses and strains components in ϕ direction are assumed to be 0. Displacement uor and z are defined in this model. The dependent variable $uor = u/r$ introduced to avoid division by r, which causes problems on the axis where $r = 0$, and w is the displacement in z direction. Periodic boundary condition is applied to one unit cell in r direction

$$u(r + a, z) = u(r, z)e^{i \cdot k_r \cdot a} \tag{3}$$

Free boundary is applied to plate surface on z direction. The structure of this paper is the one-dimensional structure in the radial direction. So the reduced Brillouin zone is a straight line (from $\Gamma(0, 0)$ to $R(1, 0)$). In this paper, Bloch–Floquet boundary condition is different from two-dimensional or three-dimensional PC structure. Dispersion curves $\omega = \omega(k)$ and eigen displacement field can