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Tunable Lamb wave band gaps in two-dimensional magnetoelastic phononic crystal slabs by an applied external magnetostatic field

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A B S T R A C T

This paper theoretically investigates the band gaps of Lamb mode waves in two-dimensional magnetoelastic phononic crystal slabs by an applied external magnetostatic field. With the assumption of uniformly oriented magnetization, an equivalent piezomagnetic material model is used. The effects of magnetostatic field on phononic crystals are considered carefully in this model. The numerical results indicate that the width of the first band gap is significantly changed by applying the external magnetic field with different amplitude, and the ratio between the maximum and minimum gap widths reaches 228%. Further calculations demonstrate that the orientation of the magnetic field obviously affects the width and location of the first band gap. The contactless tunability of the proposed phononic crystal slabs shows many potential applications of vibration isolation in engineering.

1. Introduction

Phononic crystals (PCs) are functional periodic structures which consist of materials with different elastic properties. They have attracted considerable research since they exhibit multi-physical phenomena, such as the negative refraction [1,2], localized defect modes [3,4], complete frequency gaps [5–10]. Elastic waves of any modes within the complete frequency gaps are forbidden to propagate along any direction. This confers to PCs potential applications in acoustic wave reflectors, filters, switches, etc. Moreover, for yielding desirable operation properties, it's very necessary to control a frequency band gap explicitly and conveniently.

Recently, there has been a growing interest in using PCs with magnetic materials to tune band gaps [11–20]. For example, Wang et al. have investigated the elastic wave propagation in the magneto-electro-elastic phononic crystals and considered the effects of the piezoelectricity and piezomagnetism on the band structures [12]. Bou Matar et al. have presented an equivalent piezomagnetic material model for the magnetoelastic PCs with external magnetostatic field [13–15]. Their results demonstrate that the external magnetic field can be applied to control the band gaps. Ding et al. have studied the influence of external magnetic field and pre-stress on the characteristics of band gaps of PCs based on the nonlinear constitutive equations of magnetostrictive materials [16]. After that, a mechanical-magneto-thermal model has been proposed by Zhang et al., and they suggest that the demagnetization effect should not be ignored [17]. Bayat et al. have investigated the band structure properties of a soft magnetorheological phononic crystal (PC) [18]. Their studies indicate that large deformations and external magnetic field could transform the location and width of band gaps.

Taking the coupling among magnetic, electric, pre-stress, temperature, and elastic phenomena into account, the studies above are very remarkable in reporting meaningful changes in the band structures of PCs. However, without considering the magnetic and mechanical boundary conditions, all of them have analyzed only the bulk waves. As is known to all, Lamb waves [21–25] propagated in PC slabs are extremely useful for various sensors, noncontact and nondestructive evaluation in industry. Therefore, the theoretical researches about the magnetoelastic PC slabs with external magnetostatic field have become necessary.

In order to investigate the effects of the external magnetostatic field on the magnetoelastic PC slabs, an equivalent piezomagnetic material model based on existing research is used. And the demagnetization effect is studied in detail. The first band gap (FBG) of Lamb mode waves in the homogenous brass slab with an array of square stubbed rods is considered just to simplify the physical model. With different orientations and amplitude of the magnetostatic field, the tunability of the characteristics of the two-dimensional PC slabs is investigated in detail by using the finite element method (FEM). Through our researches, a kind of PC slabs, which can achieve contactless tuning of the complete band gap by using applied magnetic field, is obtained.

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2. Theory

2.1. Model of the unit

The system considered in the computations is a square lattice of magnetoelastic square stubbed rod deposited on a homogenous slab, as depicted in Fig. 1. The constant of lattice of the phononic crystal is a and the length of the side of the square stubbed rod is d. The z-axis is chosen to be perpendicular to the slab and parallel to the rod length. The length of the square stubbed rod is denoted by h_1 and the thickness of the slab is denoted by h_2.

A magneto-elastic wave in a cubic ferromagnet magnetized to saturation is considered here. In the inhomogeneous linear elastic medium without body force, its propagation can be described by the piezomagnetic constitutive equations as [14,20]:

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j}, \tag{1}$$

$$\frac{\partial b_i}{\partial x_i} = 0, \tag{2}$$

$$\sigma_{ij} = c_{ijkl} \frac{\partial u_k}{\partial x_l} + q_{lij} \frac{\partial \varphi_m}{\partial x_l}, \tag{3}$$

$$b_i = q_{ikl} \frac{\partial u_k}{\partial x_l} - \mu_{il} \frac{\partial \varphi_m}{\partial x_l}. \tag{4}$$

where $i, j, k, l = x, y, z$. ρ, u_i, b_i, x_i, σ_{ij}, c_{ilkl}, q_{lij}, φ_m and μ_{il} are the mass density, particle displacement, magnetic induction, Eulerian coordinates, stress tensor components, elastic constants, piezomagnetic tensor, magnetic potential, and magnetic permeability matrix, respectively. The surface and interface boundary conditions have to be specified to calculate the dispersion relations with the unit cell. The interfacial condition between two materials is considered to be perfect. That is to say, the potential of the magnetic field and the displacement in two phases are continuous at the interface. The top surface and all sides of the square stubbed rod are set to be stress free which requires nullity of mechanical stress. To consider the demagnetization effect and the vacuum environment in which the PC slabs are studied, the open-circuit magnetic boundary conditions [20] is enforced on the surface regions of the magnetoelastic inclusion.

2.2. The influence of the applied external magnetostatic field

First, we consider the case where an external magnetostatic field is applied along one of the crystallographic axis of the PC slabs (Fig. 2). To be able to consider the varying amplitude of the applied magnetic field, we use an equivalent piezomagnetic material model with field dependent effective elastic constants C^H_{ijkl}, piezo-

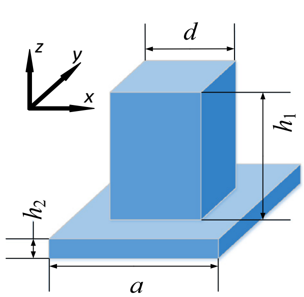

Fig. 1. Schematic diagram of the square unit cell of a homogeneous slab with the magnetoelastic square stubbed rods.

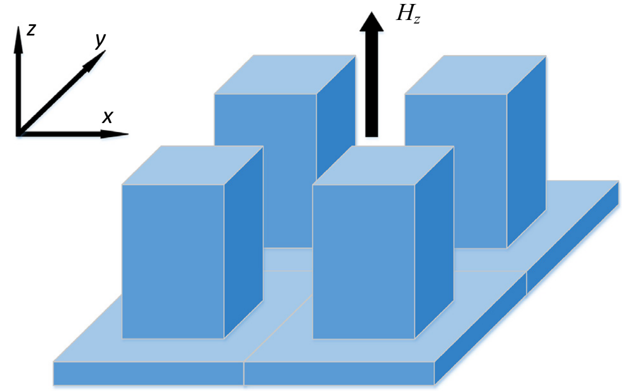

Fig. 2. Schematic view of the PC slabs with the applied external magnetic field along the z-axis.

magnetic constants q_{lij} and magnetic permeability μ_{ij}. With the assumption of uniformly oriented magnetization, the model is studied at the square rods of infinite length. When the magnetic field H_z is applied along z-axis, the only changed elastic elastic constants, piezomagnetic constants, and magnetic permeabilities are given by [15]:

$$C^H_{44} = C^H_{55} = C_{44} - \frac{B_2^2}{4\mu_0 M_s \left(H_0 + \frac{2K_1}{\mu_0 M_s} + \frac{2B_1^2}{\mu_0 M_s (C_{11} - C_{12})}\right)}, \tag{5}$$

$$q_{24} = q_{15} = -\frac{B_2}{2\left(H_0 + \frac{2K_1}{\mu_0 M_s} + \frac{2B_1^2}{\mu_0 M_s (C_{11} - C_{12})}\right)}, \tag{6}$$

$$\mu_{11} = \mu_{22} = \mu_0 \left(1 + \frac{M_s}{H_0 + \frac{2K_1}{\mu_0 M_s} + \frac{2B_1^2}{\mu_0 M_s (C_{11} - C_{12})}}\right), \quad \mu_{33} = \mu_0. \tag{7}$$

where μ_0, M_s, K_1, $B_1(B_2)$ and H_0 are the magnetic permeability of vacuum, the saturation magnetization, the magnetic anisotropy constants, the magneto-elastic constants and the internal magnetic field, respectively.

In Eqs. (5)–(7), the internal magnetic field H_0 is the sum of the external magnetic field H_z and the demagnetizing field H_D. According to the assumption and the consideration of the model, the demagnetizing field H_D is the only term related to the geometrical shape and size of the rods. Therefore, the use of the model is valid when the demagnetizing field is handled correctly in our studies.

When the applied magnetic field is along the z-axis, the influence of the demagnetizing field of the neighboring stubbed rods is negligible. Therefore, an isolated rod is considered here, and its demagnetizing field H_D is given by [26]:

$$H_D = -N \cdot M. \tag{8}$$

where N is the demagnetizing factor, and M is the magnetization intensity. In the case of a square stubbed rod of finite length h_1, oriented along the z-axis, the simple and approximate demagnetizing factor is [27]:

$$N_z = \frac{1}{2n+1}. \tag{9}$$

where $n = h_1/d$ is the dimensional ratio. This expression remains a good approximation as soon as $0.5 \leqslant n \leqslant 2$.

Then, we consider the case where an external magnetostatic field H_x is applied along the x-axis of the PC slabs. The only changed parameters of the equivalent piezomagnetic material have the same expressions with Eqs. (5)–(7), just applying an index