Wave Motion 54 (2015) 66–75

Contents lists available at ScienceDirect

Wave Motion

journal homepage: www.elsevier.com/locate/wavemoti

Piezoelectric-sensitive mode of lamb wave in one-dimensional piezoelectric phononic crystal plate

Yi-Fan Zhu [a], Ying Yuan [b], Xin-Ye Zou [a,*], Jian-Chun Cheng [a]

[a] Key Laboratory of Modern Acoustics, MOE, Institute of Acoustics, Department of Physics, Nanjing University, Nanjing 210093, PR China

[b] The School of Mathematics and Physics, Jiangsu University of Technology, Changzhou 213001, PR China

HIGHLIGHTS

- We investigate the transmission modes in piezoelectric phononic crystal plate.
- The influences of piezoelectricity and electrical boundary conditions are studied.
- An important mode named as piezoelectric-sensitive mode is defined.
- The physical mechanism of piezoelectric-sensitive mode is discussed.

ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form 21 October 2014
Accepted 26 November 2014
Available online 10 December 2014

Keywords:
Piezoelectric periodic structures
Transmission mode
Piezoelectric-sensitive mode

ABSTRACT

We investigate the transmission modes in one-dimensional piezoelectric phononic crystal plate, which is consisted of piezoelectric ceramics placed periodically in epoxy. The influences of piezoelectricity and different electrical boundary conditions on the Lamb waves in the composite plate are studied in detail, and an important elastic wave mode named as piezoelectric-sensitive mode (PSM) is defined. Furthermore, the influences of the piezoelectric constants, the filling fraction and the ratio of thickness to lattice pitch on PSM are given, and the physical mechanism of PSM is also discussed. The numerical results show that PSM has a relatively larger frequency shift and significant change in the displacement distribution when piezoelectricity is considered; the electromechanical coupling coefficient of PSM is much larger than the other modes. It reveals that PSM is an important and useful mode in piezoelectric periodic structures. This investigation is helpful in controlling the band gaps and also gives a potential application in design of sensing system and different piezoelectric devices.

1. Introduction

It is well known that phononic crystal (PC) is a novel acoustic functional material made of materials with different elastic properties, and it has many excellent characteristics, such as localized defect modes, negative refraction, and complete bad gaps [1–3]. PC has many applications in acoustic devices, such as transducers, filters, and so on. Thus, the corresponding composite structures become the topics of many theoretical [4–9] and experimental [10–12] studies. So far, the phononic crystals for bulk wave mode and surface wave mode have been widely investigated [13–18]. Recently, many researchers focus on Lamb modes in PC plates because of its potential applications in sensing systems and high-frequency wireless communication [19–24]. The experimental observation is analyzed via the dispersion relation of Lamb modes, which demonstrates that the ratio of the plate thickness to the lattice period is an important parameter for the formation of the band gap [19,24].

* Corresponding author. Tel.: +86 25 8359 3327.
E-mail address: xyzou@nju.edu.cn (X.-Y. Zou).

http://dx.doi.org/10.1016/j.wavemoti.2014.11.012

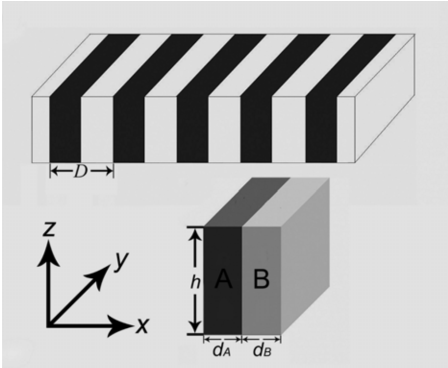

Fig. 1. The 1-D periodic composite plate consisted of alternating materials A and B.

However, the investigation of elastic waves in the composite plate is more complicated because the longitudinal and transversal strain components are coupled to each other. Chen et al. [19] observed the existence of band gaps for low-order Lamb wave modes in one-dimensional (1-D) PC plates, and examined the effects of the ratio of the plate thickness to the lattice spacing and the filling fraction on the formation of band gaps. As we know, elastic waves in the PC plates not only have similar modes as Lamb modes in classic homogeneous plate but also have some more complex characteristic because of the periodicity of PC. Chen et al. [25] have found that the shear-horizontal modes will convert to Lamb modes and couple with the flexural and dilatational modes in certain directions.

On the other hand, studies on piezoelectric composite structures have increased because they have abundant physical connotations due to the transformation from elastic energy to electric energy [26–29]. Zou et al. [30] have studied the effects of substrate and boundary conditions on the band gaps of lamb waves in 1-D piezoelectric composite plates. By utilizing different effects of open-circuit (OC) and short-circuit (SC) boundary conditions on piezoelectric composite plates, many controllable piezoelectric devices can be achieved, such as switchable phononic wave guiding, filtering, harvesting, and rectifying [31–33]. However, so far, there are few reports about the detailed studies on transmission modes in 1-D piezoelectric PC plate. Here, we investigate different transmission modes in 1-D piezoelectric PC plate under different conditions, such as non-piezoelectricity (NP), OC and SC. The effects of piezoelectricity and different electric boundary conditions on transmission modes are also analyzed. Meanwhile, an important transmission mode named as piezoelectric-sensitive mode (PSM) is defined, and its physical mechanism is also revealed. The results imply that PSM has some special physical properties and can be controlled by choosing different parameters of the composite plate. The PSM has rich potential applications in design of sensing system and other acoustic devices based on the piezoelectric materials, and the corresponding band gaps can also be effectively controlled by regulating PSM.

2. Model and method of calculation

The piezoelectric composite plate has a periodic structure as shown in Fig. 1. It is composed of alternating material A and material B with widths of d_A and d_B, respectively. The lattice spacing is given as $D = d_A + d_B$, and the filling ratio f is defined as $f = d_A/D$. The system is bounded by the planes $z = 0$ and $z = h$, and it is assumed to be translational invariant in the y-direction. Thus, all field components are independent of the y-direction and the Lamb wave propagates along the x-direction.

In this work, we fix $f = 0.5$, $d_A = d_B = D/2 = 1$ mm, and $h = 2$ mm. Materials A and B are piezoelectric ceramic PZT-5H and epoxy, respectively. The material parameters are shown in Table 1. The PZT-5H used in the model is electric-polarized in z-direction. We earth planes $z = 0$ and $z = h$ when short-circuit boundary condition is applied in the piezoelectric model. The stress and displacement continuous condition is applied on the side surfaces of the PZT part of each unit cell. It is supposed that the non-polarized PZT-5H taken as material A in the NP model has the same elastic constants and density as PZT-5H, but no piezoelectricity.

In the inhomogeneous linear elastic medium with no body force, the equations governing the motion of lattice displacement $u(x, z, t)$ and electrical displacement $D(x, z, t)$ in this inhomogeneous system are given by:

$$\rho(x)\ddot{u}_j = \partial_i T_{ij}, \tag{1}$$

$$\partial_i D_j = 0, \tag{2}$$

$$T_{ij} = c_{ijkl}(x)\partial_l u_k + e_{lij}(x)\partial_l \varphi, \tag{3}$$

$$D_i = e_{ikl}(x)\partial_l u_k - \varepsilon_{il}(x)\partial_l \varphi, \tag{4}$$

where $i, j, k, l = x, z$. $T_{ij}(x, z, t)$, $D(x, z, t)$, $u(x, z, t)$, $\varphi(x, z, t)$, $\rho(x)$, $c_{ijkl}(x)$, $e_{lij}(x)$, and $\varepsilon_{il}(x)$ are the stress vector, electrical displacement vector, displacement vector, electric potential, x-dependent mass density, elastic stiffness, piezoelectric, and dielectric constant tensors, respectively.