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Wave propagation in single column woodpile phononic crystals: Formation of tunable band gaps

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ABSTRACT

We study the formation of frequency band gaps in single column woodpile phononic crystals composed of orthogonally stacked slender cylinders. We focus on investigating the effect of the cylinders' local vibrations on the dispersion of elastic waves along the stacking direction of the woodpile phononic crystals. We experimentally verify that their frequency band structures depend significantly on the bending resonant behavior of unit cells. We propose a simple theoretical model based on a discrete element method to associate the behavior of locally resonant cylindrical rods with the band gap formation mechanism in woodpile phononic crystals. The findings in this work imply that we can achieve versatile control of frequency band structures in phononic crystals by using woodpile architectures. The woodpile phononic crystals can form a new type of vibration filtering devices that offer an enhanced degree of freedom in manipulating stress wave propagation.

1. Introduction

Phononic crystals (PCs) are defined as artificially fabricated structures in periodic architectures. They have received significant attention in the last decade as an emerging technology for controlling elastic and acoustic wave propagation (Kushwaha, 1996; Liu et al., 2000; Vasseur et al., 2001; Hussein et al., 2007). In particular, PCs can exhibit forbidden frequency bands – called band gaps – with tailored frequency limits. Previous studies have shown the versatility and tunability of frequency band structures in PCs by (i) manipulating the geometry and mechanical properties of unit-cell elements, (ii) imposing various boundary conditions, and (iii) changing assembling architectures of constituents (Herbold et al., 2009; Boechler et al., 2011; Yang et al., 2012).

Among various types of previously designed PCs, woodpile PCs are assemblies of periodically stacked longitudinal components – often embedded in matrices – in 3D architectures (Jiang et al., 2009; Wu and Chen, 2011). These woodpile PCs can offer an enhanced degree of freedom in adjusting their frequency band structures by modifying design parameters, such as rod spacing, alignment angles, and stacking sequences. By leveraging such controllability, their optical counterpart called woodpile "photonic" crystals has been studied extensively to demonstrate rich behavior of frequency band structures in the electromagnetic spectrum (Lin et al., 1998; Noda et al., 2000). In acoustics, researchers have investigated the woodpile

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architectures to create band gaps primarily through the interactions with the surrounding fluidic media. For example, Wu and Chen (2011) investigated the formation of acoustic band gaps in woodpile PCs with the focus on modeling pressure field patterns of air around the simple cubic lattices. Jiang et al. (2009) studied the elastic wave propagation in composite structures consisting of hard polymer matrix and rigid woodpile structure for underwater acoustic wave absorption. Most research on woodpile PCs, however, has been based on rigid architectures or simple translational oscillations of unit cell elements without fully considering their development of complex deformation modes.

In this research, we investigate tunable phononic band gaps in single column woodpile PCs made of orthogonally stacked cylinders. The slender rods in woodpile architectures develop bending resonances in low frequency regimes, which can significantly influence the dispersive behavior of elastic waves along the stacking direction of PCs. In principle, such characteristics of woodpile PCs are equivalent to the physical mechanism of locally resonant PCs (i.e., sonic crystals or acoustic meta-materials in a broader sense), that attracted attention due to their capability of forming low frequency band gaps without requiring large lattice constants (Liu et al., 2000; Hirsekorn, 2004; Jiang et al., 2009). Unlike these conventional PCs, however, the woodpile PCs use intrinsic bending modes of unit-cell elements to achieve local resonances, without necessitating complicated architectures of mass-in-mass configurations or multi-layered structures composed of hard and soft materials. Functionally, these simple woodpile PCs can reduce wave dissipation substantially, resulting in distinctive cutoff frequencies and high transmission gains in pass bands.

To investigate the effect of the cylinders' dynamics on the formation of band gaps, we test a series of woodpile PC specimens with different rod lengths and boundary conditions. Based on the natural modes of these cylinders, a simple numerical method using a discrete element model is developed. Despite its simple monoatomic configuration, we observe that woodpile PCs create multiple band gaps whose cutoff frequencies are characterized by the resonant modes of the cylinders. We find that these band gaps can be adjusted by changing the rod lengths or by manipulating pre-compression applied to the woodpile PCs due to the nonlinear Hertzian contact among the cylindrical elements. The formation of surface modes is also detected, resulting from the localized vibrations of cylinders at the boundaries. The mode shapes of such propagating and localized waves are investigated by using the discrete element model, and the theoretical band structures of the woodpile PCs are found to be in good agreement with the experimental measurements.

The rest of the paper is structured as follows. First, we describe the experimental setup in Section 2. We then introduce a theoretical model of the woodpile PCs in Section 3. Based on this model, we develop a numerical method in Section 4 to calculate frequency band structures. Section 5 describes a comparison between analytical, numerical, and experimental results. Lastly, in Section 6, we conclude the paper with summary and future work.

2. Experimental approach

The overall configuration of the experimental setup is shown in Fig. 1. The assembled woodpile PCs consist of vertically stacked 23 cylindrical rods, whose centers form orthogonal contacts with neighboring elements. The rods are made of fused quartz (density $\rho = 2200\ \text{kg}/m^3$, elastic modulus $E = 72$ GPa, and Poisson's ratio $\nu = 0.17$). We test five specimens of woodpile PCs with different rod lengths (L=40, 50, 60, 70, 80 mm), while keeping their diameters identical (D=5.0 mm).

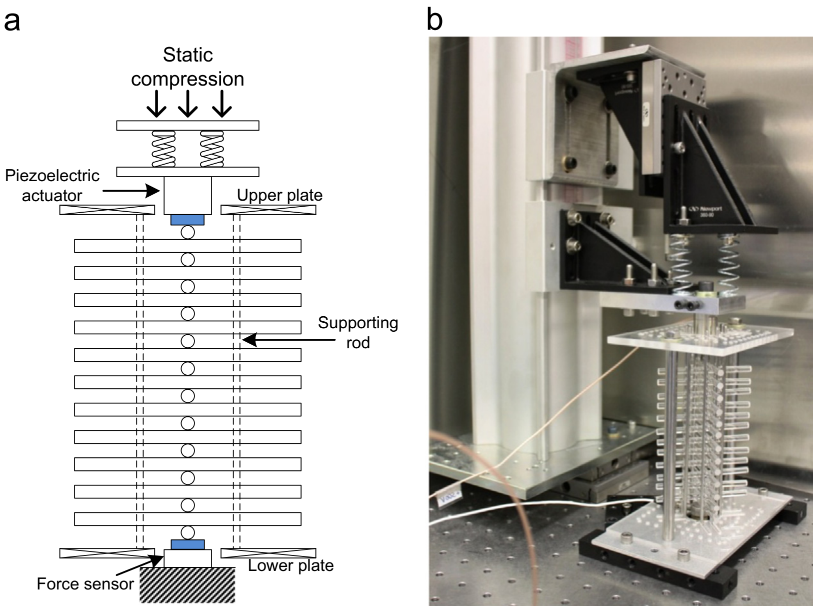

Fig. 1. (a) Schematic diagram of the test setup and (b) digital image of the experimental setup.