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Complete band gaps in a polyvinyl chloride (PVC) phononic plate with cross-like holes: numerical design and experimental verification

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ABSTRACT

In this work the existence of band gaps in a phononic polyvinyl chloride (PVC) plate with a square lattice of cross-like holes is numerically and experimentally investigated. First, a parametric analysis is carried out to find plate thickness and cross-like holes dimensions capable to nucleate complete band gaps. In this analysis the band structures of the unitary cell in the first Brillouin zone are computed by exploiting the Bloch–Floquet theorem. Next, time transient finite element analyses are performed to highlight the shielding effect of a finite dimension phononic region, formed by unitary cells arranged into four concentric square rings, on the propagation of guided waves. Finally, ultrasonic experimental tests in pitch-catch configuration across the phononic region, machined on a PVC plate, are executed and analyzed. Very good agreement between numerical and experimental results are found confirming the existence of the predicted band gaps.

1. Introduction

Phononic materials (PMs) are composite materials with a periodic distribution of elastic properties and mass density according to a particular lattice symmetry. They are made, for instance, of elastic scatterers with high acoustic mismatch with respect to the hosting matrix. PMs have shown the existence of frequency band gaps (BGs), i.e. frequency ranges in which such materials do not support the propagation of elastic waves [1,2]. In force of their intrinsic features, PMs are suitable for the development of advanced technological devices such acoustic filters, ultrasonic silent blocks, resonators, sound lenses as well as for innovative applications including wave focusing and waveguiding [3–10].

Recently, properties and characteristics of phononic plates have been extensively studied. Literature reviews on the subject can be found in the comprehensive papers by Pennec et al. [1] and by Wu et al. [11]. In particular, different types of phononic plates have been considered, including (i) plates composed by two binary constituents, (ii) plates made-up of single constituent material with a periodic distribution of studs or gratings on the plate surface, as well as (iii) mono-material plates with a periodic distribution of empty holes.

Regarding the first type (i), Hsu and Wu [12], using the plane wave expansion method, as well as Sun and Wu [13], by means of the finite difference time-domain method, have studied the band structures of Lamb-type waves in plates made of circular iron cylinders embedded in an epoxy matrix. The influence of the plate thickness for square and triangular lattices of the inclusions has been analyzed and discussed as well. Similarly, Yao et al. [14] have examined the influence of anisotropic inclusions on the band gaps of Lamb-type waves existing in a plate made of circular lead cylinders embedded in elastic isotropic epoxy matrix.

Studies on plates of type (ii) with studs have been proposed in Refs. [15–18], among others. As for the plates of the first type, in which the soft inclusions can generate locally resonant band gaps, these works have shown that complete band gaps can be nucleated by the local resonances of the studs. Works on plates with a periodic grating on the surface have been also investigated [19,20]. In particular, it has been quantitatively verified that the width of the band gap is related to the depth of the grooves.

Among the latter type (iii) of plates, holes perpendicular to the propagation plane (i.e. parallel to the mid plane of the plate) or aligned through the plate thickness have been investigated. For instance, Liu et al. [21] studied numerically the group velocity of the zero order antisymmetric (A_0) Lamb mode in a phononic plate with a single cylindrical hole orthogonal to the propagation plane of the plate, whereas Chen et al. [22] investigated the dispersion properties of Lamb-type waves with respect to the number of holes within the height of the phononic plate.

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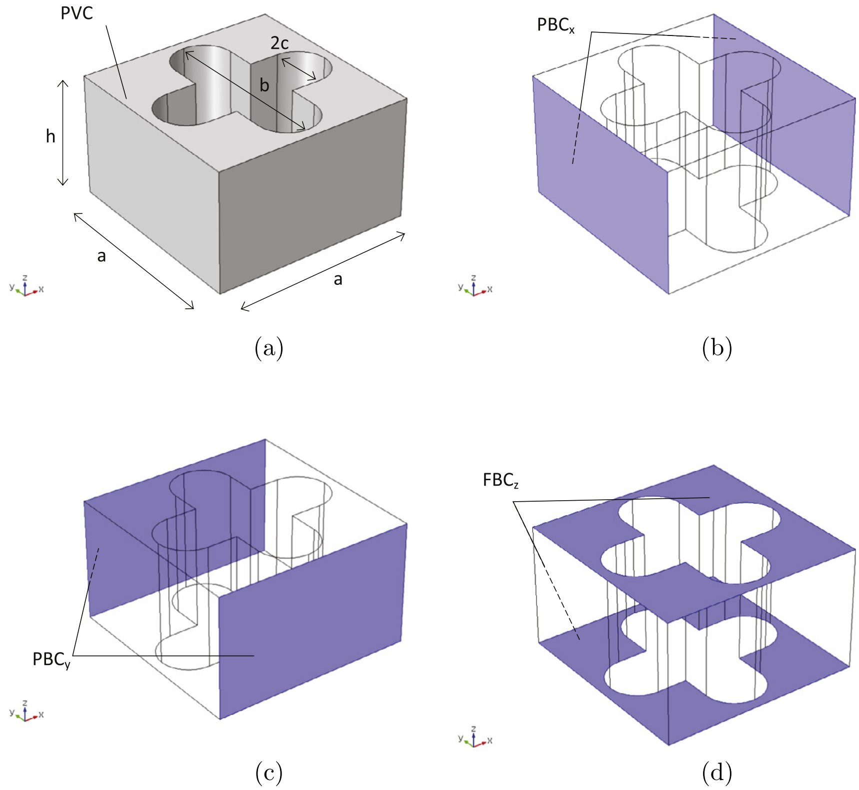

Fig. 1. (a) Unitary cell characterized by rounded cross-like cylindrical holes in a PVC matrix. (b–c) Representation of the imposed periodic boundary conditions at surfaces orthogonal to the *x*- (PBC_x) and *y*- (PBC_y) axes; (d) free boundary conditions imposed at surfaces orthogonal to the *z*-axis (FBC_z).

Whilst works dealing with holes perpendicular to the propagation plane are limited, those considering trough thickness holes are numerous. Among these latter, the authors have focused on the recent work of Wang and Wang [23], in which a thorough numerical study proves that cross-like holes, if compared to holes of different shapes such as circular and square ones, can nucleate multiple and complete wide band gaps at lower frequencies.

In this study, numerical and experimental evidence of complete BGs existing in a polyvinyl chloride (PVC) phononic plate with a square lattice of trough thickness rounded cross-like holes, which unitary cell is shown in Fig. 1a, is presented. To the best of authors' knowledge, to date such a geometrical shape for the holes has not been considered. The shape for the holes was selected after having performed an extensive numerical campaign, also based on the outcomes of Ref. [23], aimed at finding complete guided waves band gaps in a PVC plate below 50 kHz. In particular, for the assumed hole geometry and lattice constant *a*, i.e. for a fixed filling fraction *f*, a parametric analysis was conducted on the plate thickness *h* in order to find wider band gaps. It was found that for a ratio of $h/a = 12/20 = 0.6$ two complete band gaps exist. Then it was verified that circular and square holes were not able to nucleate any band gap for the same filling fraction (41%) and unitary cells arrangement.

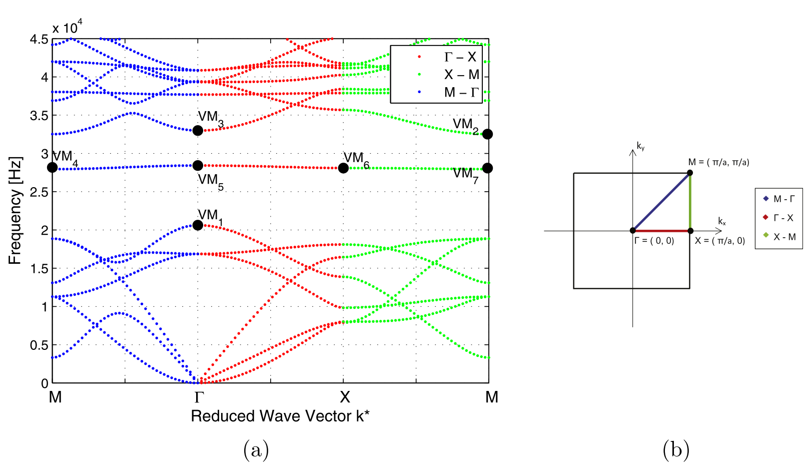

Fig. 2. (a) Band structures for the unitary cell presented in Fig. 1. Coordinates of the vibration modes (*VMs*) of Figs. 3 and 4 are also presented. (b) The first irreducible Brillouin zone $M - \Gamma - X$.