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Optimization and experimental validation of stiff porous phononic plates for widest complete bandgap of mixed fundamental guided wave modes

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ABSTRACT

Phononic crystal plates (PhPs) have promising application in manipulation of guided waves for design of low-loss acoustic devices and built-in acoustic metamaterial lenses in plate structures. The prominent feature of phononic crystals is the existence of frequency bandgaps over which the waves are stopped, or are resonated and guided within appropriate defects. Therefore, maximized bandgaps of PhPs are desirable to enhance their phononic controllability. Porous PhPs produced through perforation of a uniform background plate, in which the porous interfaces act as strong reflectors of wave energy, are relatively easy to produce. However, the research in optimization of porous PhPs and experimental validation of achieved topologies has been very limited and particularly focused on bandgaps of flexural (asymmetric) wave modes. In this paper, porous PhPs are optimized through an efficient multiobjective genetic algorithm for widest complete bandgap of mixed fundamental guided wave modes (symmetric and asymmetric) and maximized stiffness. The Pareto front of optimization is analyzed and variation of bandgap efficiency with respect to stiffness is presented for various optimized topologies. Selected optimized topologies from the stiff and compliant regimes of Pareto front are manufactured by water-jetting an aluminum plate and their promising bandgap efficiency is experimentally observed. An optimized Pareto topology is also chosen and manufactured by laser cutting a Plexiglas (PMMA) plate, and its performance in self-collimation and focusing of guided waves is verified as compared to calculated dispersion properties.

1. Introduction

Phononic crystals (PhCrs) are acoustic metamaterial lattices with promising capabilities in manipulating elastodynamic and acoustic waves. The fundamental characteristic of PhCrs is exponential attenuation of waves over frequency ranges known as bandgaps. Principally when the wave is subjected to periodic in-phase reflections from the heterogeneities introduced by consecutive unit-cells of the phononic lattice (i.e. Bragg reflection), then transmitted wave energy is highly attenuated. So the wavelength has to be smaller or in the order of lattice periodicity to be manipulated by the Bragg reflection.

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However, locally resonant features may exist which lead to opening/widening low-frequency bandgaps at their resonance frequencies through destructive local oscillations [1]. Although transmission of waves through PhCrs is banned over bandgap frequency range, defects may be designed in the phononic lattice to resonate and/or transmit wave energy along specified paths within bandgap frequency [2,3]. Moreover, due to the strong heterogeneity of PhCrs around bandgap frequencies, the PhCr can function as a focusing or self-collimating lens at particular frequencies above or below bandgap [4,5].

The features of irreducible cell of phononic lattice i.e. unit-cell define its bandgap efficiency. The acoustic impedance mismatch of constitutive materials and the shape and topology of unit-cell are its key characteristics to be designed for desired efficiency. It is generally desired to have the widest bandgap at lowest frequency range so that phononic controllability of wave is enabled over wider frequency range through smallest feature sizes. Hence, for known unit-cell shape and constitution, the topology can be optimized in order to achieve maximum relative bandgap width (RBW), defined as bandgap width over mid-gap frequency.

PhCrs can be designed for bandgaps of bulk waves, surface waves and also guided waves. PhCr plates (PhPs) which manipulate guided waves have great application in design of low-loss ultrasound devices (e.g. filters, resonators, and waveguides). Also PhPs are applicable in guided wave structural health monitoring for launching, steering and collecting wave beams for inspection purpose. One great approach in producing PhPs is to make periodic heterogeneities by through-thickness perforation of a uniform background plate. The production of such single material PhP is relatively easy, and high contrast of solid background with vacuum- or air-filled porosities leads to a very high percentage of reflected wave energy at the interfaces (100% for vacuum-filled). The wave propagation characteristics of such periodically perforated plates and their application in steering of guided waves have been numerically and experimentally evaluated in the literature, e.g. [6–9].

As for optimization of PhCrs, most of preceding works in the literature have addressed the optimized topologies of 2D PhCrs for manipulation of in-plane and/or anti-plane bulk waves with respect to lattice periodicity plane (e.g. [10–13]) some of which addressed porous topologies [14,15]. Two other works reported optimized porous topologies for maximized RBW of asymmetric guided wave modes through genetic algorithm (GA) [16] and gradient based [17] approaches. The optimized topology of elastomeric PhPs for maximized deformation induced tunability under equibiaxial stretch was also studied by the authors [18] and wide switchable bandgaps were introduced with deformation induced opened/closed bandgap.

It is noteworthy that when considering porous PhPs, the optimized topology with maximized RBW favors maximum isolation of scattering features leading to stronger interfacial reflections. Furthermore, lower effective stiffness of topology leads to lower modal frequencies and so lower bandgap frequency range. Consequently, the optimization problem converges to structurally unworthy topologies unless appropriate constraints are applied on the topology. Although, the minimum feature sizes of topology can be prescribed through an appropriate filtration approach like the work by Dong and Su [14], such constraint cannot ensure the optimality of stiffness of achieved topology.

A robust approach was recently introduced by the authors [19], in which the effective in-plane stiffness of PhP was taken into account as a second objective to be maximized through a multi-objective genetic algorithm. Relatively thin and thick unit-cells with aspect ratios (width to thicknesses) 10 and 2, respectively, were optimized for maximal RBW. Complete bandgap of guided waves, exclusive bandgap of asymmetric modes and exclusive bandgap of symmetric modes were obtained and computationally validated. A compliant material was considered as the void porous area for simplicity in evaluation of randomly generated topologies.

In this paper, thin PhPs with an aspect ratio of 10 are optimized through an improved optimization algorithm for complete bandgaps of guided wave modes with mixed in-plane and anti-plane polarization (i.e. symmetric and asymmetric modes) and selected Pareto topologies are experimentally validated. Two optimized topologies are chosen from the stiff regime and the complaint regime of Pareto front and aluminum PhP specimens are produced by a water jetting machine. The transmission of excited signals from and to specific points of PhPs are measured by piezoelectric transducers and relevant spectra are verified as compared to calculated modal band structures. A third topology from the stiff regime of Pareto front is also selected and produced by laser cutting of a Plexiglas (PMMA) plate. The produced PMMA PhP is subjected to a tone-burst at particular central frequency above the bandgap which is expected to produce collimated wavefronts as evidenced by its calculated flat equal frequency contour (EFC). The wavefront leaving the PhP section into the uniform area is scanned by the laser Doppler vibrometer (LDV) and verified as compared with relevant EFCs.

The layout of paper is as follows. The optimization objectives, constitutive equations, and implemented multiobjective optimization algorithm are first discussed. Then the obtained Pareto front and selected optimized PhP topologies are presented and explained. Finally, the produced PhP designs are presented and their experimental evaluation is discussed.

2. Topology optimization of PhP

Relatively thin 2D PhP unit-cell with an aspect ratio (width to thickness) of $a/h = 10$ is considered and square symmetry is prescribed which leads to an orthotropic phononic lattice plate with in-plane symmetry. The required heterogeneity of PhP unit-cell is produced by through thickness perforation of background plate with specified pattern. The unit-cell is discretized by a 32×32 resolution with 136 independent design variables. A binary design variable defines whether the relevant topology pixel is perforated (defined as 0) or not (defined as 1). Aluminum base material with elastic modulus $E_s = 70$ GPa, Poisson's ratio $\nu_s = 0.34$ and density $\rho_s = 2700\ \mathrm{kg/m^3}$ is considered for the constitutive material of porous PhP. Then the optimum topology of PhP unit-cell is explored to achieve the following two objectives concurrently: