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Optimum design of phononic crystal perforated plate structures for widest bandgap of fundamental guided wave modes and maximized in-plane stiffness

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ABSTRACT

This paper presents a topology optimization of single material phononic crystal plate (PhP) to be produced by perforation of a uniform background plate. The primary objective of this optimization study is to explore widest exclusive bandgaps of fundamental (first order) symmetric or asymmetric guided wave modes as well as widest complete bandgap of mixed wave modes (symmetric and asymmetric). However, in the case of single material porous phononic crystals the bandgap width essentially depends on the resultant structural integration introduced by achieved unitcell topology. Thinner connections of scattering segments (i.e. lower effective stiffness) generally lead to (i) wider bandgap due to enhanced interfacial reflections, and (ii) lower bandgap frequency range due to lower wave speed. In other words higher relative bandgap width (RBW) is produced by topology with lower effective stiffness. Hence in order to study the bandgap efficiency of PhP unitcell with respect to its structural worthiness, the in-plane stiffness is incorporated in optimization algorithm as an opposing objective to be maximized. Thick and relatively thin Polysilicon PhP unitcells with square symmetry are studied. Non-dominated sorting genetic algorithm NSGA-II is employed for this multi-objective optimization problem and modal band analysis of individual topologies is performed through finite element method. Specialized topology initiation, evaluation and filtering are applied to achieve refined feasible topologies without penalizing the randomness of genetic algorithm (GA) and diversity of search space. Selected Pareto topologies are presented and gradient of RBW and elastic properties in between the two Pareto front extremes are investigated. Chosen intermediate Pareto topology, even not extreme topology with widest bandgap, show superior bandgap efficiency compared with the results reported in other works on widest bandgap topology of asymmetric guided waves, available in the literature. Finally, steady state and transient frequency response of finite thin PhP structures of selected Pareto topologies are studied and validity of obtained bandgaps is confirmed.

1. Introduction

Phononic crystals (PhCr) are acoustic meta-materials with promising manipulation capabilities on propagation of sound and elastodynamic waves (Deymier, 2011). PhCrs are indeed heterogeneous materials produced by periodic modulation of

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acoustic impedance in a lattice structure through either integration of two or more contrasting materials, or making void inclusions in a single material.

The main feature of PhCrs making them known as acoustic bandgap materials is the existence of frequency ranges over which propagation of vibroacoustic waves is prohibited. This phenomenon is caused by constructive reflection and superposition of waves at the interface of periodic heterogeneities i.e. Bragg and Mie resonant scatterings (Olsson III and El-kady (2009)). Therefore the efficiency of PhCr is wave length dependent and the frequency range of bandgap is limited by its lattice periodicity constant or in other words its feature size. However, due to the strong wave length scale heterogeneity of PhCrs, they possess other astonishing wave manipulation properties. Introducing any kind of defect in phononic lattice e.g. by altering the features of a few adjacent cells, leads to advent of local resonance modes within phononic bandgap frequency. This capability is used to trap and guide waves inside defects specially tuned for desired frequencies (Zhu and Semperlotti, 2013, Olsson III and El-kady (2009)). Moreover, studying the equal frequency contours of PhCrs show flat and concave wave fronts below bandgap frequency applicable for self-collimation and steering of waves (Wang et al., 2013, Lin et al., 2009). Consequently, it is worthwhile to adjust the phononic properties so that the width and location of bandgap is optimized for application of interest. The efficiency of PhCr is principally defined by the features of its irreducible representative element (Unitcell) i.e. its geometry, topology and composition.

The focus of this paper is to investigate the optimum topology of PhCr plate (PhP) unitcell with 2D periodicity for maximized bandgap width of guided waves. Guided waves are structural waves confined by traction free surfaces of thin walled structures, so called plate waves when guided by parallel faces of plates. In-plane symmetric (S) and anti-plane asymmetric (A) Lamb waves as well as symmetric shear horizontal (SHS) and asymmetric shear horizontal (SHA) in-plane waves are the well-known guided wave modes generated in a plate structure. Special characteristics of guided waves confined by finite thickness of such structures, make them ideal for non-destructive evaluation purposes (Su and Ye, 2009, Veidt et al., 2008) as well as production of low loss resonators, filters and waveguides (Mohammadi, 2010, Lin et al., 2014). The guided wave dispersion in PhP is governed by its transversal anisotropy i.e. plate's thickness in addition to its planar anisotropy measured by lattice periodicity and unitcell constitution.

The bandgaps of plate waves in 2D PhPs of prescribed topologies have been extensively studied (Pennec et al., 2010, Wu et al., 2011, Charles et al., 2006, Khelif et al., 2006). PhPs produced by either periodic insertion, attachment or perforation of cylindrical inclusions on a background plate have been generally considered in these studies. Phononic lattice with different patterns e.g. square, rectangular or polygonal have been considered. The phononic unitcell itself could contain a specific pattern of circular inclusions like the work by Li et al. (2009) who studied plate wave gaps in PhPs with Archimedean-like tilings. However, optimum topology of PhCrs and acoustic meta-materials have been widely investigated, e.g. (Olhoff et al., 2012, Hussein et al., 2006, Rupp et al., 2007, Manktelow et al., 2013, Krushynska et al., 2014, Hedayatrasa et al., 2015). Essentially topology with maximum relative bandgap width (RBW) between subsequent modes of interest is desired (Sigmund and Jensen, 2003). RBW is the ratio of bandgap width over midgap frequency, and so seeking maximum RBW results in a topology which can provide widest bandgap at lowest frequency range for specific unitcell size. Consequently, the relevant topology supports phononic wave manipulation over widest frequency range through miniature unitcells compared to wavelength.

Most of topology optimization studies in relation to 2D periodic PhCrs have been concerned with bandgaps of in-plane and/or anti-plane bulk waves while only few works have been devoted to bandgaps of guided waves in 2D PhPs. Halkjær et al. (2006) studied the optimum topology of porous Polycarbonate PhP with rhombic unitcell for maximized RBW of first couple of flexural (asymmetric) plate waves. The Mindlin plate theory was implemented for definition of band structure of bending waves and gradient based optimization was performed through moving asymptotes method. Since the best topology for maximized RBW did not have acceptable stiffness, new objective was introduced to conversely search widest bandgap width at higher frequency ranges. Finally the discontinuities of optimized topology were locally modified for satisfactory stiffness and manufacturability. In another investigation by Bilal and Hussein (2012) the optimum topology of thin porous silicon PhPs for maximized RBW of basic flexural waves was studied. The Mindlin plate's theory was implemented and topology of square unitcell was optimized through genetic algorithm (GA) as an evolutionary based method.

Single material porous unitcell with uniform through thickness constitution have been commonly considered, in which, the achieved topology could be simply produced by perforation of a uniform background plate. The high acoustic impedance contrast produced by the porosities, usually filled with air, leads to relatively wide acoustic bandgaps. Bandgaps of such porous materials are governed by wave reflection and scattering at the interface of inhomogeneities produced by perforation profile. Therefore the search for highest RBW naturally results in topologies with nearly isolated domains and in other words thin connectivity. The finer the topology resolution the thinner connectivity in the optimized topology for maximized bandgap. Moreover, porous topology with lower effective stiffness can produce bandgap at lower frequency range and so higher RBW due to its lower wave speed. Thus largest achievable RBW is extremely dependent on assumed unitcell's resolution and relevant topology generally has low structural worthiness i.e. stiffness. Nevertheless, none of earlier works on topology optimization of porous PhCrs (Halkjær et al., 2006, Bilal and Hussein, 2012, Dong et al., 2014a) took into consideration the structural worthiness of achieved topologies. Although the mesh dependency of topology can be controlled by constraining the minimum length scale of the features, this technique cannot assure the optimality of stiffness. Furthermore, if the topology resolution is not fine enough, this approach may degrade the optimality of bandgap due to imposed feature size constraint to the entire topology area.

In earlier studies the bandgaps of asymmetric guided wave modes have been solely explored (Halkjær et al., 2006, Bilal