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Published in:
202115th International Congress on Artificial Materials for Novel Wave Phenomena, Metamaterials 2021

DOI:
10.1109/Metamaterials52332.2021.9577166

15th International Congress on Artificial Materials for Novel Wave Phenomena – Metamaterials 2021
New York, USA, Aug. 2nd –7th, 2021

2021 Fifteenth International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials) | 978-1-7281-5018-5/21/$31.00 ©2021 IEEE | DOI: 10.1109/Metamaterials52332.2021.9577166

Phononic crystal with free-form waveguiding and broadband attenuation

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***Abstract* – Waveguiding is highly desirable for multiple applications but is challenging to achieve in wide continuous frequency ranges. In this work, we developed a three-dimensional phononic crystal with broadband waveguiding functionality. Waveguiding is achieved by combining two types of unit cells with different wave scattering features to create an arbitrary-curved defect path. The unit cell design is governed by contradictory requirements to induce narrow- and broad-band wave attenuation along the path and within the phononic medium, respectively. This is achieved by modulating structural parameters to activate Bragg's scattering, local resonances and inertial amplification mechanism and interplay between them. We demonstrated numerically and experimentally the waveguiding with strong wave localization and confinement in additively manufactured three-dimensional structures along straight, angle- and arbitrary-curved paths. This work opens new perspectives for the practical utilization of phononic crystals in ultrasonic sensors, medical devices, and acoustic energy harvesters.**

I. Introduction

Broadband wave manipulation is highly desirable for various applications. Recent progress in this direction has been achieved by means of phononic materials - artificial periodic materials composed of carefully designed unit cells that enables control over structural waves due to their architecture.

The most interesting functionalities of phononic materials are wave attenuation and waveguiding. The first can be achieved by activating (non-)resonant wave scattering, while the latter is typically obtained by creating a defect path within a phononic medium, through which wave energy is transmitted with, ideally, minimal losses. The defect can be created by replacing unit cells with a homogeneous material or by modifying the unit-cell geometry. Various proposed phononic solutions for wave attenuation and waveguiding still suffer from narrow-band performance [1], [2] or require non-linear or special materials to implement tunable functionality [3]. Besides, the waveguiding is often limited to linear or planar defect paths [1], [4]. Finally, experimental realizations are still scarce, especially for three-dimensional configurations.

Here, we propose mono-material lattice phononic structures with extra-broadband functionalities that addresses the mentioned drawbacks. We implemented these designs by means of the Multi Jet Fusion (MJF) technique and validated their wave attenuation and waveguiding properties at broadband frequencies and for arbitrary-curved defect paths. The broadband wave attenuation and waveguiding are achieved by simultaneously activating Bragg's scattering, local resonance, and inertial amplification mechanisms as proposed previously for one-dimensional structures [5].

II. Phononic designs and fabrication

Our phononic structures are mono-material three-dimensional cubic lattices consisting of center cubes connected by beams. The representative unit cells of size a contain a central cube of length b and six perpendicular or inclined beams of a square cross-section with length l and thickness t (Fig. 1). We consider three structures with different beam thickness (thick- and thin-beam configurations) or inclination angle (inclined beam configuration) of the beams with respect to the cubes. The representative unit cells and the fabricated samples are shown in Fig.1.

The MJF-manufactured structures are composed of 5x5x5 unit cells with *b=10 mm* and *l=5mm.* The thick- and thin-beam designs have *t=5mm* and *t=3.5mm*, respectively, and lattice constant *a=20mm.* The inclined-beam structure has *2mm*-thick beams inclined by *θ=45*° and lattice pitch *a=17.07mm*. The structures are made from powdered thermoplastic polyamide (PA12) with *60µm* median particle size, which are fused with a binding agent by means of infrared light (a commercial HP MJF 3D printer).

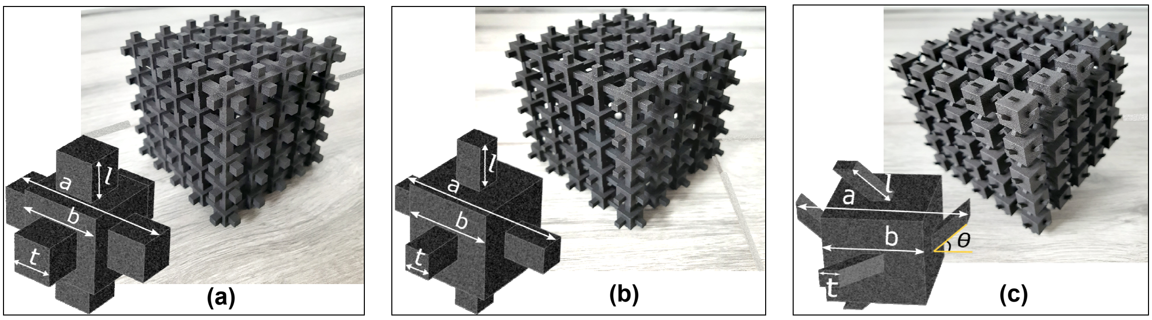

Fig. 1. The representative unit cells and MJF samples of the designed phononic materials: (a) thick-beam, (b) thin-beam, and (c) inclined-beam configurations.

III. WAVE ATTENUATION AND WAVEGUIDING IN PHONONIC STRUCTURES

The dynamic characteristics of the phononic materials were studied numerically (COMSOL Multiphysics 5.5) and experimentally (pitch-catch transmission tests).

The wave attenuation in the thick-beam structure is associated with the Bragg's scattering of longitudinal and torsional waves in the beams. The width of the induced bandgap is *14.5*% with 21.57 kHz as mid-frequency. The thin-beam structures have broader bandgap (*50.04*% width) due to the coupling of the Bragg scattering with resonances localized in the beams. The inclined-beam structures have the widest band-gaps (*161*% width) because of the activation of the additional inertial amplification in the inclined beams.

The found bandgaps were also observed in numerical and experimental transmission results, where average attenuation of 46 dB for inclined-beam structure was achieved even for two structural layers of unit cells. This proves high attenuation capability of the designs, promising for applications. More details about the discussed results can be found in Ref. [6].

The waveguiding functionality is implemented by replacing the inclined-beam unit cells with the thick-beam ones to create a free-form defect paths (Fig. 2 (a)). The excellent wave localization along the path was proven experimentally by exciting the 3D-printed waveguiding structures with a piezo-actuator (input) and measuring the wave transmission along (output) and outside (side output) the defect path. The transmission data along the path is seen to be at least one order of magnitude larger than the side output (Fig. 2 (b)). As shown in Fig. 2 (c), the waveguiding (shown as mechanical stress distribution) is achieved for straight, angled, 3D-curved configurations in the broadband range spanning from 5 kHz to 40 kHz and demonstrated below at respective selected frequencies.

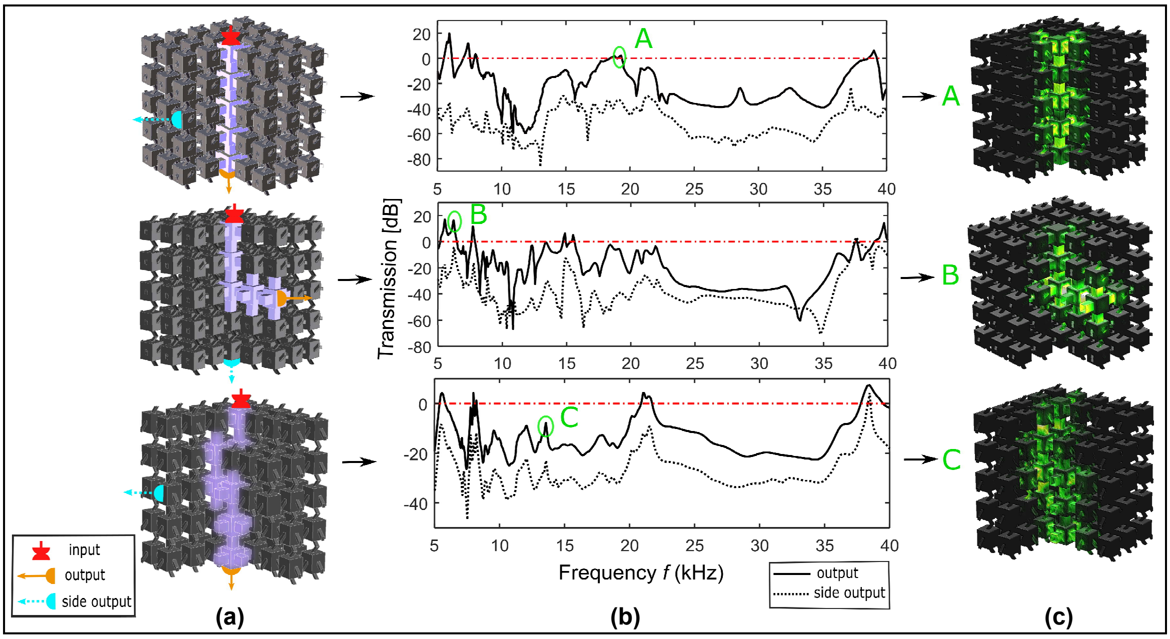

Fig. 2. Phononic waveguiding structures with (a) free-form defect paths, (b) respective transmission spectra (output and side output) and (c) mechanical stress distribution at selected frequencies.

IV. Conclusion

We demonstrated numerically and experimentally the feasibility to channel wave energy along predefined three-dimensional paths in an extremely broad frequency range. In addition, we validated the omnidirectional wave attenuation at broadband frequencies originated due to the coupling of the three known wave scattering mechanisms. These functionalities achieved in the proposed, simple but effective, designs can be useful for applications of phononic media in signal processing, non-destructive evaluation, vibration isolation and energy harvesting.

Acknowledgement

This research was supported by the start-up grants of the FSE at the University of Groningen. The authors acknowledge dr. T.C. Pijper (Philips Drachten, the Innovation Cluster, The Netherlands) for manufacturing the MJF samples and the Center for Information Technology of the University of Groningen for providing access to the Peregrine high performance computing cluster.

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