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Structural engineering of three-dimensional phononic crystals

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ABSTRACT

Artificially-structured materials are attracting the research interest of a growing community of scientists for the possibility to develop novel materials with advantageous properties that arise from the ability to tailor the propagation of elastic waves, and thus energy, through them. In this work, we propose a three-dimensional phononic crystal whose unit cell has been engineered to obtain a strong wave-attenuation band in the middle of the acoustic frequency range. The combination of its acoustic properties with the dimensions of the unit cell and its static mechanical properties makes it an interesting material for possibly several applications in civil and mechanical engineering, for instance as the core of an acoustically insulating sandwich panel. A sample of this crystal has been manufactured and experimentally tested with respect to its acoustic transmissibility. The performance of the phononic crystal core is remarkable both in terms of amplitude reduction in the transmissibility and width of the attenuation band. A parametric study has been finally conducted on selected geometrical parameters of the unit cell and on their effect on the macroscopic properties of the crystal. This work represents an application-oriented example of how the macroscopic properties of an artificially-structured material can be designed, according to specific needs, by a conventional engineering of its unit cell.

1. Introduction

The capability of carrying quasi-static loads, while preventing the rise of structural vibrations is a desirable combination of properties that is not usually found in a single material. In typical structural applications, these two tasks are accomplished by different elements, where the stiffer and stronger element carries the loads, while a damping element is generally responsible for dissipating the energy of the vibration and, thus, for reducing its amplitude. The attenuation of sound and vibration, especially at low-frequency, is usually associated with materials in which the mechanical energy is dissipated by means of internal loss. The conflict arises from the fact that materials with large values of loss factor are typically characterized by a low value of Young's modulus, as shown in [1].

In the last decades, the concept of metamaterials and artificially-structured materials has been introduced to develop novel materials with advantageous properties that arise from the macroscopic arrangement of their building blocks [2]. While it has been originally proposed in the fields of electromagnetism and optics, the concept of metamaterials has been

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recently extended to rather different areas of classical mechanics such as elastostatics, elastodynamics, acoustics and fluid dynamics [3]. Indeed, the introduction of an additional level of structure above the atomic scale may lead to the development of macroscopically-structured materials that exceed the typical relations between static, dynamic and mass properties of bulk materials. Compared to conventional damping solutions where the energy of the vibrations is firstly admitted into the structure and then dissipated, the metamaterials approach aims at hindering the propagation of waves in prescribed frequency ranges, so that structural vibrations are prevented from arising.

The strong interest in this field is demonstrated by the increasing number of published works on periodic structures, phononic crystals, and acoustic/elastic metamaterials. A number of recently-published review papers [3–6] demonstrate the effectiveness of using macroscopically-structured materials for tailoring the propagation of elastic waves, and thus their effective properties, for diverse purposes, such as acoustic cloaking [7–10], negative effective mass and modulus [11,12], or for controlling heat transport [13,14].

A large portion of the published works investigates the presence of band gaps in the dispersion properties of periodic systems. Indeed, metamaterials and phononic crystals are artificial media that exhibit some form of periodicity, and their overall dynamical characteristics can be compactly described by a frequency band structure. Band gaps represent forbidden frequency ranges in which no waves can propagate and may have substantial impacts on the development of structures free from vibrations in specific frequency ranges. Since structural vibrations are the result of the interaction of traveling waves with the boundary conditions, in the absence of energy transport no structural vibrations can occur in the band gap frequency ranges [15].

In phononic crystals, acoustic bandgaps result from the destructive interference of scattered acoustic waves and are usually referred to as Bragg-type band gaps. Most of the presented works are limited to two-dimensional phononic crystals and have investigated different topologies of unit cell in order to maximize the width of the forbidden frequency range [16–19]. Plate lattices have been also investigated with respect to the propagation of Lamb waves in thin plates with stubbed surfaces [20–22]. However, only few examples of completely three-dimensional crystals have been investigated, so far [23–26]. In metamaterials, attenuation bands can be obtained by exploiting micro-scale resonators that seemingly absorb energy on the macro-scale [12]. While the actual frequency at which Bragg-type band gaps occur is related to the characteristic size of the unit cell, an advantage of local resonators is the possibility to obtain low frequency attenuation bands using sub-wavelength unit cells. After the pioneering work of Liu [27], a number of studies have focused on reducing the frequency [28,29] or increasing the width of these bands by either using multi-degree resonators [30–32] or some mechanisms related to the geometry of the unit cell of the artificial medium (inertia amplification [33,34] and auxetic honeycomb [35,36], for instance).

Besides the aforementioned works on the dynamic properties of artificially-structured materials, they have been also investigated regarding their quasi-static properties. The largest portion of the published works has focused on modeling and investigating new periodic lattice structures with the goal of enhancing the specific load carrying capacity [37–41]. Auxetic materials, i.e. materials with negative Poisson's ratio, have been also proposed and manufactured with direct laser lithography [42,43]. Additionally, materials with out-of-the-ordinary ratios of bulk to shear modulus [3] have been reported, as well as composite materials with negative stiffness inclusions (i.e., statically unstable) have been shown to exhibit extreme damping [44] or an effective Young's modulus greater than that of either constituent [45].

Despite the considerable deal of fundamental research recently done in the field of acoustic metamaterials, a challenge that still remains open is how to combine in a single artificially-structured materials the ability of preventing the propagation of waves at very low frequency regimes with load-carrying capability and practical qualities, such as being small and lightweight. Such demands call for a targeted, possibly conflicting, modification of multiple specific properties of the material. Such modification of the properties is best performed at the level of the unit cell of the structured material, using engineering methods.

In this work, we propose a three-dimensional phononic crystal whose unit cell has been engineered in order to tune the macroscopic effective properties of the crystal. The main idea is to apply the engineering knowledge of structural dynamics in the design of the unit cell of a structured material with the ultimate goal of tailoring its effective properties at the macroscopic level. In the first part of this work, the dispersion properties of a phononic crystal are numerically investigated and its basis is designed in order to obtain a complete, wide band gap in the middle of the acoustic frequency range. While the dispersion properties refer to an infinitely periodic arrangement of unit cells, the footprint of the band structure on the acoustic transmissibility is experimentally verified on a sample of this crystal and compared to the acoustic transmissibility of a structural foam with the same overall size and mass density. Finally, a parametric study is conducted on the effect of selected geometrical parameters of the unit cell on the macroscopic properties of the crystal, such as the frequency range of the band gap, the quasi-static stiffness and mass density.

Even though the dynamic properties of the actual phononic crystal investigated in this work are remarkable, we believe that the importance of this work lies rather in the engineering approach to the design of its unit cell. For a given wavenumber, the band structure of a crystal is determined by the eigenvalues of its unit cell with the appropriate boundary conditions. The design of a phononic crystal with desired macroscopic properties can thus be obtained by exploiting the engineering knowledge of structural dynamics for tailoring the eigenvalues of its unit cell.