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# Simulation-based conceptual design of an acoustic metamaterial with full band gap using an air-based 1-3 piezoelectric composite for ultrasonic noise control

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ABSTRACT

This paper aims at proposing a novel type of acoustic metamaterials with complete band gap composed of piezoelectric rods with square array as inclusions embedded in an air background (matrix). A modified plane wave expansion method accompanied with the principles of the Bloch–Floquet method with electromechanical coupling effect and also impedance spectra are used to get a band frequency and to investigate the passband for the selected cut of piezoelectric rods. We investigate both the electromechanical coupling coefficient and mechanical quality factor and their dependency to passband and bandwidth, which depends on both the density and the wave impedance of the matrix and the inclusions (rods). The ratio of the volume of inclusion to the matrix is used to define the fill factor or the so-called inclusion ratio, to introduce the bandwidth as a function of that. Furthermore, the fabrication method is presented in this paper. The results make a suitable foundation for design purposes and may develop an inherently passive ultrasonic noise control. In addition, the results provide the required guidance for a simulation-based design of elastic wave filters or wave guide that might be useful in high-precision mechanical systems operated in certain frequency ranges and switches made of piezoelectric materials; they also propose a novel type of elastic metamaterials, which is independent of the wave direction and has an equal sensitivity in all directions in which it reacts omnidirectionally and mitigates the occupational noise exposure.

## 1. Introduction

Having industrialized the modern world, the literature and private studies have confirmed the adverse effects of industrial noise in the working environment on human hearing. Indeed, in high-frequency audiometry, i.e. 8–20 kHz, significant changes occur in the hearing threshold level [1]. Many countries (e.g., France and Germany) are working on assessing the harmfulness of occupational noise exposure and on amending the admissible values in the ultrasonic range [1]. France determines admissible values of ultrasonic noise and recommends limiting noise exposure in the high-frequency audible range (8–20 kHz) and the low-frequency ultrasonic range (20–50 kHz) [1]. Phononic crystals have analogue properties to photonic

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## Nomenclature

| | |
|---|---|
| $\mathbf{G}$ | The vectors of reciprocal lattice |
| $\mathbf{k}$ | The "Bloch" wave vector |
| $f$ | Filling fraction ratio |
| $r$ | The radius of cylindrical scattering material |
| $\sigma_{ij}$ | Cauchy stress tensor |
| $e_{ijk}$ | The piezoelectric coefficients |
| $\rho$ | Material density |
| $\phi$ | Electric potential |
| $D_i$ | The electric displacement vector fields |
| $A_c$ | The Fourier component of arbitrary material constants |
| $\mathbf{A_G}$ | The amplitude vector of the partial waves |
| $E_i$ | The electric field |
| $2\pi/\Lambda_{x_2}$ | Normalized reciprocal lattice vector along $x_2$ |
| $\mathbf{U}(\mathbf{r}, t)$ | Generalized displacement or generalized stress vectors |
| $F(\mathbf{G})$ | The structure function |
| $c_{ijkl}$ | The elastic coefficients tensor |
| $\varepsilon_{ij}$ | Linear part of the elastic strain tensor |
| $\omega$ | Frequency |
| $\alpha(\mathbf{r})$ | The Fourier component of arbitrary material constants |
| $u_i$ | Displacement vector |
| $J_1$ | The first kind Bessel function of first order |
| $A_c$ | The area of the primitive unit cell |

crystals [2–4]. Hence, shortly after starting the research on photonic band gaps, where the band gaps or stop bands are observed for electron waves in semiconductors; the idea has been extended to both electromagnetic waves in photonic crystals and elastic waves in phononic crystals [5]. These types of meta-materials, constituted by a periodic repetition of two different materials, can either show absolute band gaps in their transmission spectra [6,7], where the elastic waves do not propagate at some frequencies, or dictate the modes that are allowed to be propagated in the material. Moreover, these types of materials can decrease the velocity of the elastic waves and even represent negative refraction [8]. This capability offers the idea of constructing new meta-materials with special performance for vibration control [9] or producing acoustic shield with applications in designing acoustic filters, wave guides, mirrors, and wave transducers. Similarly, several phenomena such as guiding [10–12], bending [13,14], filtering [15,12], demultiplexing [3], and super lenses for acoustic waves [16] have been predicted so far. On the other hand, phononic crystals can tailor the allowed modes and their wave speeds inside the material in such a way that the frequencies of various material losses subjected to different regimes is to be matched with the density of some states and frequencies of some modes in order to provide enhanced energy absorption [5]. Since mechanical waves propagate in a solid in the form of both longitudinal and transverse waves, a designated structure with complete phononic filters might have band gaps for both waves in the same frequency region [17].

The geometry and composition characteristics of phononic filters play essential roles in showing forbidden gaps of wave propagation in these filters, regardless of wave polarization and propagation directions. However, the larger the bandwidth for these forbidden zones, the more the applications for phononic filters. Actually, the bandwidth for this forbidden zone is a key factor for some purposes, e.g., for vibration control at specific frequencies. Some researchers have tried to enlarge the width of band gaps (e.g., see [18]). They showed that the width of band gaps may be determined by the contrast of elastic constants, the inclusion (filling) volume fraction, and the lattice of the constructed parts. Changing either the geometry or the elastic characteristics of the constitutive materials through external stimuli such as wave propagation causes the band structure of phononic crystal to be adjusted to a specific range of frequencies, and thus, represents either a partial or a full band gap.

Geometry design of phononic crystals with its inclusions and of matrices with tunable band gaps is an interesting but challenging issue. The ability to tune the band gaps leads to make both non-absorbing mirrors for elastic waves and vibration-free cavities, which might be useful in high-precision mechanical systems [19] operated in certain frequency ranges. Thus, a phononic crystal may be designated in such a way that it can be adjusted in a desired band gap configuration.

Some functional materials such as thermally activated shape memory alloys, electro-rheological materials, dielectric elastomeric layers, and either magneto-elastic or magneto-electro-elastic materials have been selected to be used to capture a tunable passband and stop band in phononic crystals with higher efficiency [20–24]. Representing a full band gap for phononic crystals could lead to improve the design of transducers and vibration controllers.

The high electromechanical coupling factor and low wave impedance at piezoelectric materials [25,26] stimulate the piezoelectric-based phononic crystal developments. Moreover, piezoelectric materials have some unique properties as compared with other tunable materials such as shape memory alloys and electro-rheological materials, which make the piezoelectric materials to be highly accurate in the control of displacement, quick response, and to reduce the device size strongly [27]. But, since the piezoelectric substrate is not isotropic, they allow bulk waves to travel with different speeds in different directions. These phenomena cause piezoelectric crystals to be configured in such a way that the full band gap will result. A key note is that the velocities of bulk wave propagation or the slowness of surfaces in anisotropic piezoelectric materials have directional dependency [28]. Since the band gap property depends on both geometry and wave impedance, there is a need to investigate the effect of these parameters accurately to catch suitable configurations for inclusions to reach the desired performance.

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