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Numerical Simulation of Broadband Bi-Negative Elastic Metamaterials and Wave Transmission Properties

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Abstract

In this paper, we introduce an alternative model of elastic metamaterial by following the conceptual design of hybrid elastic solid reported by Lai and colleges [17]. The proposed model is comprised of build-in resonant microstructures which are made of three kinds of conventional materials. Under specific incident frequencies, it behaves seemingly as a medium with negative mass density and elastic modulus so that a few novel wave propagation properties can be observed. We utilize finite element simulation to analyze the effective material parameters as well as the wave transmission properties. Comparing to the literatures, the proposed model appears larger band of practical application, and furthermore the required material is reduced which may be more easy to fabricate.

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Keywords: elastic metamaterial, double negative material, effective medium, band structure

Nomenclature

u_α	displacement
F	resultant force
$\boldsymbol{k}$	wave vector
$c_{\alpha\beta}^{eff}$	effective elastic constants

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ω	radial frequency
μ^{eff}	effective shear modulus
κ^{eff}	effective bulk modulus
ρ^{eff}	effective mass density
$\sigma_{\alpha\beta}$	stress
$\varepsilon_{\alpha\beta}$	strain

1. Introduction

Metamaterial, a special type of artificial material, have attracted a great deal of research attention especially for the case with double negative parameters that can lead to unusual physical properties. Such bi-negative medium is also denoted as left-handed material or negative index material which was first introduced by Veselago [1] in electromagnetics and is now extended to acoustics and elastodynamics. In fabrication, the core concept is to construct microstructures with local resonance on a scale much less than the relevant wavelength. As a result, effective negative parameters can be achieved near resonant frequencies. For electromagnetics, the first metamaterial sample make use of metallic metal wires and spilt-ring resonators [2-5] to form the microstructure which can lead to electric and magnetic resonances respectively. For acoustics, negative bulk modulus and negative density has been realized by using an array of Helmholtz resonators [6, 7] and thin membranes [8, 9], respectively. Simultaneously negative in both parameters is also proposed [10, 11]. For elastodynamics, different locally resonant microstructures are demanded. Ding et al.[12] theoretically demonstrated a metamaterial which possess negative bulk modulus and mass density by combining two types of structural units with different built-in local resonances. Wu et al.[13] suggest a type of elastic metamaterial comprising fluid-solid composite inclusions which can possess a negative shear modulus and negative mass density over a large frequency region. In 2011, Liu et al. 2011 [14, 15] proposed composite models to approach double negativity by inserting a chiral microstructure. Huang and Sun [16] theoretically study a mass-in-mass mechanical system which can be effectively modeled as an elastic solid with simultaneously negative density and Young's modulus. Lai et al. introduce an anisotropic structure model called hybrid elastic solid which can achieve negative mass density together with negative shear modulus in lower resonant frequency or with negative bulk modulus in higher resonant frequency. This model provided richer applications than other model reported so far but the microstructure is more complex due to the lack of symmetry. In this letter, we follow the same concept [17] to propose an alternative design of anisotropic elastic metamaterials with simpler constituents but better functionality. Numerical method is performed to analyze the effective parameters and wave propagation characteristics through the text.

2. Elastic metamaterial model

In our study, a type of three-component elastic metamaterial is introduced. The geometric configuration is shown in Fig.(1), and the corresponding material parameter is listed in table 1. This model is expected to produce the local dipolar, quadrupolar and monopolar resonances which may lead to effective negative mass density, shear and bulk modulus under certain excitation frequencies, respectively. The proposed metamaterial model is basically a simplified version of Lai's model, since we fill the matrix material (foam) in the inner most core rather than hard silicon rubber used in their paper so that the required material is reduced (three in total). In addition, we change the size and shape of inclusions (soft silicon and steel) and then the volume of four steel resonators become larger. Using fewer kinds of material is easier and more economical to fabricate. Applying heavier inclusions could enhance the local resonance effect and thus it is anticipated that better functionality of such metamaterial can be achieved. We will show later the proposed simplified model not only yields bi-negative properties but also possess broader frequency range of practical application.