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Multiband wave filtering and waveguiding in bio-inspired hierarchical composites

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ABSTRACT

We investigate the elastic wave propagation in bio-inspired hierarchical composites with nacre-like and biocalcite-like architectures. These two types of architectures consist of hard mineral and soft organic phases, which are hierarchically assembled to develop multilevel of hierarchy. We numerically demonstrate that multiple band gaps and passbands, covering an ultrawide frequency range, arise in the proposed hierarchical composites with two levels of hierarchy. We further reveal that the multilevel structural hierarchy itself is responsible for this multiband characteristic. Specifically, the low frequency band gaps in the composites with two levels of hierarchy are attributed to Bragg scattering, which are intrinsically governed by the hierarchical and periodic modulation of constituent phases at the second hierarchical level. By contrast, the multiple band gaps and passbands in high frequency ranges correspond to waveguide modes, enabling the incident wave to be either trapped inside the waveguides or efficiently transmitted through the waveguides. The findings in this paper not only shed light on the mechanisms responsible for the multiband features of bio-inspired hierarchical composites, but also offer new opportunities towards the design of compact and mechanically robust phononic crystals with the capability to effectively manipulate wave propagation.

1. Introduction

Manipulating acoustic and elastic wave propagation using rationally designed architectures has attracted increasing research interests in recent years. The periodic architectures of phononic crystals, for example, can modify phonon dispersion relations, providing avenues to tailor group velocities and hence the flow of vibrational energy [1,2]. When the structural periodicities of phononic crystals have the same order of magnitude as the wavelengths of acoustic and elastic waves, multiple scatterings arise at the interfaces between constituent phases with contrast in elastic constants. This mechanism gives rise to complete wave band gaps, where propagation of phonons is prohibited, irrespective of incident angles. Interestingly, even if the structural periodicity of phononic crystals is interrupted by defects, it is still possible to effectively manipulate wave propagation, such as wave bending and wave splitting [3–8]. These capabilities make the perfect and defective phononic crystals particularly suitable for designing wave filters and waveguides [4,5,7,9–12].

Aside from the basic requirements of wave filtering and waveguiding capabilities, a few novel attributes, including multiple band gaps, subwavelength characteristic, compact size, and outstanding mechanical performance, are highly desirable in engineering practice. Conventional phononic crystals, however, become inefficient when these properties are simultaneously pursued. Inspired by the fractal design of their counterparts in electromagnetic waves [13–16], phononic crystals with periodic fractal architectures have been proposed recently [17–19]. The rationally designed fractal architectures can

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give rise to multiple band gaps as well as the shifting of band gaps towards lower frequency ranges for longitudinal waves [17]. Similar to the fractal design of phononic crystals, bio-inspired hierarchical composites with multilevel structural hierarchies have been reported, which exhibit a broadband wave filtering phenomenon [20]. In addition, a multiobjective optimization method has been proposed to achieve desired wave dispersion properties, including simultaneous multiple passbands and stopbands in one-dimensional layered systems [21,22]. These progresses indicate that the desired multiple and broad band gaps could be achieved by rationally designing the inherent architectures of phononic crystals.

This paper aims to explore the elastic wave propagation in bio-inspired hierarchical composites with nacre-like and biocalcite-like architectures. These two types of architectures consist of hard mineral and soft organic phases, which are hierarchically assembled to develop multilevel of structural hierarchy (Fig. 1). Guided by the finite element modelling, we show that multiple band gaps and passbands, covering an ultrawide frequency range, arise in the hierarchical composites with two levels of hierarchy. In particular, low frequency band gaps, akin to the subwavelength characteristic in acoustic metamaterials, exist in the hierarchical composites with two levels of hierarchy. We emphasize that the mechanisms responsible for the multiple band gaps and passbands are totally different, depending on the frequency ranges of the band gaps and passbands.

2. Numerical modelling

2.1. Characterization of the hierarchical composites

The proposed bio-inspired composites have a nacre-like architecture and a biocalcite-like architecture with two levels ($N = 2$) of structural hierarchy, where N is the total number of structural hierarchy level (Fig. 1(a) and (b)). In the nacre-like composite, the soft organic phase is continuous, with the hard mineral platelets dispersed in the soft organic matrix. In the biocalcite-like composite, however, the soft organic platelets are distributed in the continuous hard mineral phase. The two-dimensional periodicity at each level of the hierarchical architectures is characterized by a rhombic lattice with vectors $\mathbf{a}_{n1} = [(l_n + t_n)/2,\ \tan\alpha_n \cdot (l_n + t_n)/2]$, and $\mathbf{a}_{n2} = [(l_n + t_n)/2,\ -\tan\alpha_n \cdot (l_n + t_n)/2]$, where l_n is the length of the mineral platelet, t_n is the thickness of the matrix, α_n is the lattice angle (Fig. 1(c) and (d)), and the subscript n denotes the order of structural hierarchy level. In this regard, the volume fraction of the mineral phase can be defined as $v_{fn} = 2l_n h_n/[(l_n + t_n)^2 \cdot \tan\alpha_n]$ for level $n = 1$, 2 of nacre-like composite and level $n = 2$ of biocalcite-like composite; while for level $n = 1$ of biocalcite-like composites, the volume fraction of mineral phase is given by $v_{fn} = 1 - 2l_n h_n/[(l_n + t_n)^2 \cdot \tan\alpha_n]$, where h_n is the height of the organic platelets at level n.

We assume the overall volume fractions of mineral phase in the composites with $N = 1$ and $N = 2$ levels of hierarchy are equal to $V_{fn} = 0.80$. To ensure the self-similarity in each level of the composite with $N = 2$ levels of hierarchy, the volume fraction of mineral phase in each level is given by $v_{fn} = \sqrt{V_{fn}} = 0.894$. In addition, the lattice angle is taken as $\alpha_n = 30°$ in each level. We further assume that for level $n = 1$ of the nacre-like and biocalcite-like composites, $l_1 = 10\ \mu$m and $t_1 = l_1/50 = 0.2\ \mu$m. Considering the trade-off between accuracy and computational burden, we use four unit cells (nine layers of hard minerals) along vertical direction in each level of structural hierarchy. Then the parameters in level $n = 2$ can be calculated as $l_2 = 97.69\ \mu$m and $t_2 = l_2/50 = 1.95\ \mu$m accordingly.

2.2. Numerical modelling of wave propagation

The governing equation of elastic wave propagation in the hierarchical composites can be written as

$$-\rho\omega^2\mathbf{u} = \frac{E}{2(1+\nu)}\nabla^2\mathbf{u} + \frac{E}{2(1+\nu)(1-2\nu)}\nabla(\nabla\cdot\mathbf{u}) \tag{1}$$

where $\mathbf{u}$ is the displacement vector, and ω is the angular frequency. E, ν, and ρ are the Young's modulus, the Poisson's ratio, and the density of each constituent phase, respectively. Here we assume the constituent phases of the hierarchical composites are homogeneous, isotropic and linearly elastic. Their properties are characterized by, Young's modulus $E_m = 100$ GPa, Poisson's ratio $\nu_m = 0.30$, and density $\rho_m = 2950\ \mathrm{kg/m^3}$ for the mineral phase, and Young's modulus $E_o = 1$ GPa, Poisson's ratio $\nu_o = 0.30$, and density $\rho_o = 1350\ \mathrm{kg/m^3}$ for the organic phase [23–27].

The transmission spectra of the elastic wave propagation in the proposed composites are calculated by performing frequency domain analyses. To model the normally incident elastic wave propagating in the hierarchical composites, a harmonic vertical displacement with an amplitude of 0.01 μm is applied on the top surface of the composites with 1×4 supercells. Perfectly matched layers (PMLs) are applied at the two ends of the homogeneous parts to prevent reflections by the scattering waves from the domain boundaries [28]. In addition, periodic boundary conditions are applied on the two lateral sides of the composites to model the infinite periodicity of the supercells. The transmission coefficient is defined as $\phi = (u + v)/(u_0 + v_0)$, where u and v are the amplitudes of transmitted horizontal and vertical displacements, respectively, and u_0 and v_0 are the amplitudes of applied horizontal and vertical displacements, respectively. Since we only apply a small amplitude vertical displacement, then we have $u_0 = 0$, and $v_0 = 0.01\ \mu$m in this study.

The phononic dispersion relations are constructed by performing eigenfrequency analyses. To this end, Bloch's periodic boundary conditions are applied at the boundaries of the supercell such that

$$\mathbf{u}_i(\mathbf{r} + \mathbf{a}) = e^{i\mathbf{k}\cdot\mathbf{a}}\mathbf{u}_i(\mathbf{r}) \tag{2}$$

where $\mathbf{r}$ is the location vector, $\mathbf{a}$ is the lattice translation vector, and $\mathbf{k}$ is the wave vector.