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Sonic metamaterials: Reflection on the role of topology on dispersion surface morphology

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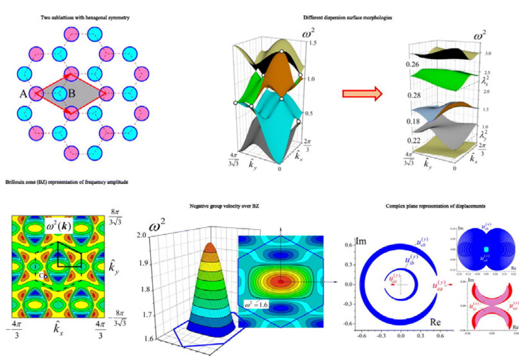
HIGHLIGHTS

- Dispersion surface morphology of 2D sonic metamaterials of $K_{3,3}$ and K_6 topologies is investigated.
- Effective methods for creating and manipulating band gaps are proposed based on anisotropic lattice acoustic properties.
- Separation of acoustic surfaces from optical surfaces is connected with negative effective mass in lattice unit shells.
- Effective vibration coupling requires internal masses to be of the same order as or higher order than external masses.
- Negative group velocity over a significant part of the Brillouin zone may be realised for an optical dispersion surface.

GRAPHICAL ABSTRACT



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ABSTRACT

Investigating dispersion surface morphology of sonic metamaterials is crucial in providing information on related phenomena as inertial coupling, acoustic transparency, polarisation, and absorption. In the present study, we look into frequency surface morphology of two-dimensional (2D) metamaterials of $K_{3,3}$ and K_6 topologies. The elastic structures under consideration consist of the same substratum lattice points and form a pair of sublattices with hexagonal symmetry. We show that, through introducing universal localised mass-in-mass phononic microstructures at lattice points, six single optical frequency-surfaces can be formed with required properties including negative group velocity. Splitting the frequency-surfaces is based on the classical analog of the quantum phenomenon of 'energy-level repulsion', which can be achieved only through internal anisotropy of the nodes and allows us to obtain different frequency band gaps.

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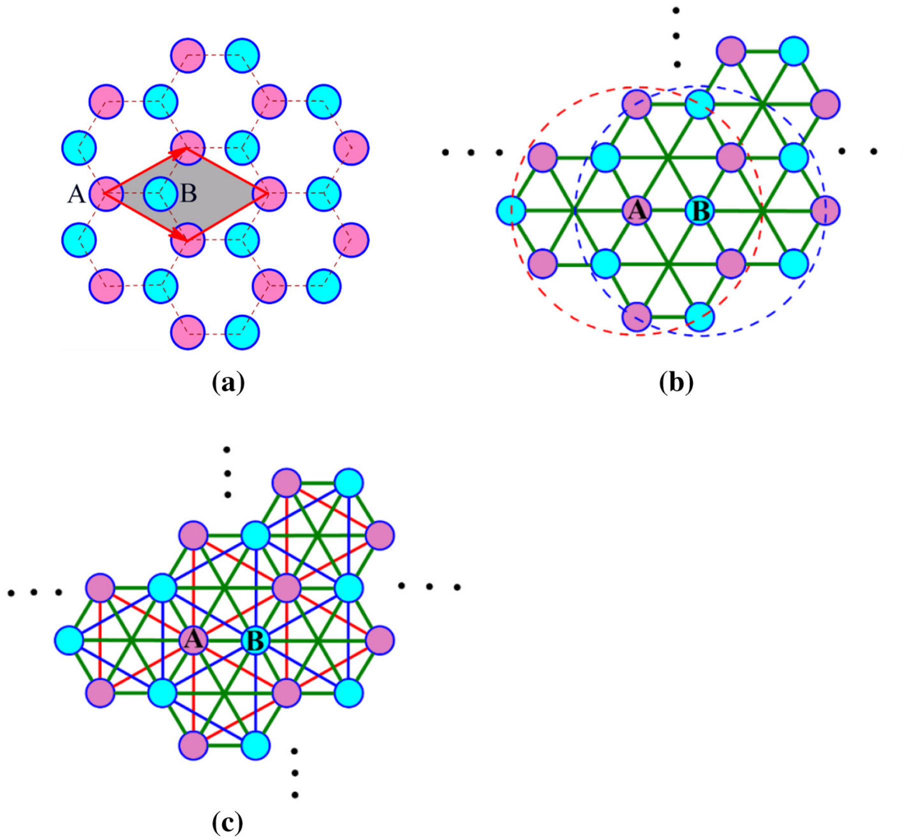

Fig. 1. a- Sublattices A (purple) and B (cyan), topologies of **b**- $K_{3,3}$ (left) and **c**- K_6 (right). Neighbourhoods of generic nodes of different sublattices are distinguished by different colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1. Introduction

Sonic metamaterials exhibit response characteristics not observed in natural materials, and signify certain elastodynamic features when considering vibration mitigation, wave manipulation, or sound attenuation. One important attribute of sonic metamaterials is their susceptibility to being tailored as acoustic filters. Associated properties such as negative effective mass density, negative effective elastic modulus, and the possibility of gap formation at certain frequencies allow sonic metamaterials to be used in acoustic imaging, sound wave control and vibration shielding, sonic cloaking, and impact and blast-wave mitigation.

Sonic metamaterials and lattices have been the subject of some contemporary research in order to investigate different aspects of these characteristics [1–12]. First sonic metamaterials appeared rather recently (in the year 2000). Since then, scientists have conducted a lot of research in order to explore the potentially beneficial properties of this class of metamaterials. Liu et al. [13] fabricated sonic crystals with negative elastic constants which acted as a wave reflector in the vicinity of resonance frequencies. In another study, Yao et al. [14] experimentally studied the 1D spring-mass model originally proposed by Milton and Willis [15]. As a result, the negative effective mass was attained which represented the situation when the internal sphere was not moving in phase with the outer bar. The effect of negative effective density can be presented by a lattice which consists of mass-in-mass units. Using this model, Huang and Sun [16] presented a metamaterial with negative effective mass density which created a band gap at a frequency close to local resonance. It was also shown that, by varying the internal parameters, one can easily shift the range of band gap frequencies which made this metamaterial efficient in blocking vibrations and low-frequency sound. Li and Chan [17] studied doubly negative acoustic metamaterials in which concurrent negative effective density and bulk modulus were obtained. Their double-negative acoustic system is an acoustic analogue of Veselago's medium in electromagnetism [18–20], and shares with it many principle features, as negative refractive index, as a consequence of its microstructural composition. In these applications metamaterials were used as filters and noise cancelling devices.

In a different vein, sonic metamaterials may be used as protective systems. It is evident that, for instance, blast waves are detrimental to critical systems and perilous for humans, causing severe damage to internal organs, especially to lungs (pulmonary contusion) and the hollow organs of the gastronomical tract. That is why it is crucial to design materials capable of strongly attenuating blast wave propagation. In a recent study, Tan et al. [21] looked into the effect of negative effective mass on blast-wave impact mitigation. In order to demonstrate blast-wave mitigation, they used a 1D system with single and double resonators and subjected it to a blast pulse. The results of their numerical analyses showed a large amount of reflection from the metamaterial. The waves which eventually passed through the metamaterial possessed much smaller amplitudes compared to the waves which pass through conventional structures. Dynamic load mitigation using negative effective mass structures was also discussed by Manimala et al. [22]. As a result, an isolator with the continuous bandwidth of isolation over a frequency range of approximately 4.5 Hz and a 98% isolation near the local resonance frequency was presented. The authors emphasised that adopting analogous negative effective density structures in the design of infrastructure building-blocks made them resilient to broadband impact-type loadings. Multi-band wave filtering in bio-inspired composites was discussed by Chen and Wang [23]. They investigated elastic wave propagation in two types of material architecture. They found out that low frequency band gaps were attributed to Bragg scattering while high frequency pass and stop bands were ascribed due to the manifestation of trapped and transmitted waveguides. The latter forms the foundation of the present study while the former falls beyond its scope.