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Elastic Wave Propagation in Chiral Metamaterials

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ABSTRACT

Chiral metamaterials, defined by the absence of centrosymmetry at the unit cell level, exhibit acoustic activity during elastic wave propagation due to their shear-bending coupling characteristics. Acoustic activity, analogous to optical activity, refers to the rotation of the polarization plane or the splitting of circularly polarized wave modes in mechanical waves as they propagate through certain materials, with potential value in mechanical wave manipulation, sensing, and energy conversion. However, the complex microstructures of chiral metamaterials necessitate significant computational resources, rendering wave propagation simulations challenging. Classical homogenization methods based on the Cauchy continuum are insufficient for the analysis of these chiral materials, as they rely on even-order material property tensors that overlook intrinsic chirality and micro-rotations, both critical for enabling tailored acoustic responses. In this study, we present an augmented asymptotic homogenization approach based on couple-stress theory to address these limitations. The governing equations include second- and fourth-order spatial derivatives of displacements, effectively capturing the chiral nature of the material. Analytical solutions are derived in closed forms for the low-frequency regime, and numerical solutions are implemented using COMSOL Multiphysics via its equation-based module. The accuracy of the homogenized results is verified through comparisons with band diagrams and polarization rotation analyses obtained from computationally intensive detailed models. The excellent agreement observed in the low-frequency domain highlights the capability of the proposed method to efficiently and accurately predict the acoustic activity of chiral metamaterials. These findings advance the design and analysis of rationally engineered chiral systems for elastic wave manipulation applications, such as detecting the orientation of building cracks and altering the direction of seismic vibrations.