

Abstract

Elastic metamaterials exhibit mechanical properties unattainable in natural materials and demonstrate vast potential in vibration and noise reduction, acoustic functional devices, acoustic stealth, energy harvesting, and fault diagnosis. To fully leverage their advantages, a key challenge must be addressed: designing metamaterial structures with low-frequency and broadband bandgap characteristics. Currently, active control strategies for low-frequency elastic wave bandgaps remain limited, making large-range tunability within the low-frequency domain difficult. Therefore, widening the low-frequency bandgap, enhancing elastic wave attenuation, and achieving tunable control are critical for the practical application of elastic metamaterials. This dissertation investigates several novel helical metamaterial configurations, combining the finite element method (FEM), the Carrera Unified Formulation (CUF), and laser Doppler vibrometry experiments. Theoretical analysis and experimental validation are conducted to elucidate the mechanisms of bandgap formation and tunability, achieving effective low-frequency broadband control. The main research outcomes are summarized as follows:

(1) Antisymmetric dual-helix metamaterial beams, inspired by the nautilus shell, are proposed with and without attached mass spheres. The mechanisms of low-frequency flexural bandgap formation are analyzed using CUF, focusing on the effects of helix turns, mass sphere radius, and material composition. The results indicate that the low-frequency bandgaps originate from localized resonance, significantly enhanced by the coupling between the helical structure and the mass spheres. Adjusting the geometric parameters effectively tunes the bandgap range. Numerical and experimental results confirm the accuracy of CUF predictions.

(2) For two-dimensional dual-helix metamaterial plates, numerical simulations reveal the dependence of flexural wave bandgaps on geometric and material parameters. The geometric configuration of the unit cell critically affects bandgap formation. Increasing helix width shifts the bandgap to higher frequencies and broadens it, while increasing plate thickness raises both boundary frequencies with minimal effect on bandwidth. The bandgap frequency varies almost linearly with the mass sphere radius.

(3) A bandgap-tunable DNA dual-helix metamaterial is proposed to address the challenge of fixed bandgaps. FEM analyses show that rearranging mass blocks enables programmable longitudinal wave bandgap control without altering unit geometry. Further adjustment of geometric parameters refines the bandgap range. Experimental

results closely align with FEM predictions, particularly in the first longitudinal bandgap region.

(4) To achieve ultra-low and ultra-wide bandgaps, a DNA dual-helix metamaterial with node masses is developed. Analyses of configurations with different node mass disks (steel, aluminum, and copper) reveal broad and deep longitudinal bandgaps in the 0–2000 Hz range. By tuning the helix diameter, disk thickness, and axial pitch, longitudinal bandgaps below 50 Hz are obtained, which are verified experimentally.

In conclusion, the study demonstrates that helical metamaterial structures are effective for achieving broad, low-frequency tunable bandgaps. The coupling of dual-helix geometry and mass inclusions intensifies localized resonance, enabling ultra-low-frequency and wideband vibration attenuation. Adjusting geometric, material, and mass distribution parameters allows programmable bandgap control. Furthermore, the extended application of CUF in complex structural analyses has been validated through both COMSOL simulations and laser vibrometry experiments, confirming its precision and robustness. The findings provide a novel theoretical and experimental foundation for the design of wide, low-frequency tunable elastic metamaterials.

Key Words: Helix metamaterials, wide low-frequency bandgap, controllable design, laser vibration measurement, strong vibration attenuation, Carrera Unified Formulation