

Composite 3D-printed metastructures for low-frequency and broadband vibration absorption

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Architected materials that control elastic wave propagation are essential in vibration mitigation and sound attenuation. Phononic crystals and acoustic metamaterials use band-gap engineering to forbid certain frequencies from propagating through a material. However, existing solutions are limited in the low-frequency regimes and in their bandwidth of operation because they require impractical sizes and masses. Here, we present a class of materials (labeled elastic metastructures) that supports the formation of wide and low-frequency band gaps, while simultaneously reducing their global mass. To achieve these properties, the metastructures combine local resonances with structural modes of a periodic architected lattice. Whereas the band gaps in these metastructures are induced by Bragg scattering mechanisms, their key feature is that the band-gap size and frequency range can be controlled and broadened through local resonances, which are linked to changes in the lattice geometry. We demonstrate these principles experimentally, using advanced additive manufacturing methods, and inform our designs using finite-element simulations. This design strategy has a broad range of applications, including control of structural vibrations, noise, and shock mitigation.

metamaterials | phononic crystals | band gaps | 3D printing | vibration absorption

Architected materials exploit the geometry of their structure, which can be directly designed, to attain properties not common in bulk, continuum media. The underlying principles that determine the dynamic properties of architected materials are applicable across several length scales, and can be used to control phonons or elastic and acoustic waves, as in phononic crystals and acoustic metamaterials. In the linear regime, decreasing the size of the geometrical feature designed in the structure increases the operational frequency. This opens opportunities to control elastic/acoustic waves ranging from seismic excitations (hertz), structural vibrations (kilohertz), ultrasonic waves in microelectromechanical systems (MEMS) devices (megahertz), and thermal phonons in, e.g., thermoelectric materials (terahertz) (1–3).

Advanced manufacturing techniques, such as 3D printing, have progressed over size scales, ranging from meters down to nanometers. With these techniques, complex structures can be realized in many materials such as polymers, metals, and ceramics. Here, we design and test 3D-printed, composite materials, which combine a polymeric matrix with metallic components, and present a previously unidentified type of architected materials for broadband vibration mitigation.

Phononic crystals (PCs) consist of periodic arrangements of materials or components with controlled spatial sizes and elastic properties. When excited by an acoustic or elastic wave, PCs exhibit band gaps, or ranges of frequencies that cannot propagate through their bulk and decay exponentially. The band gaps in PCs arise from Bragg scattering mechanisms, and can be quite wide, making them desirable in sound mitigation and vibration absorption applications (4–8). However, the periodicity dimension and the material properties of the crystal's components limit the

frequency range of band gaps found in PCs. These constraints limit the use of PCs in applications targeting low frequencies, because PCs would require impractically large geometries. To induce low-frequency band gaps, it is possible to design “meta-materials” that exploit locally resonant masses to absorb energy around their resonant frequency (9–12). However, band gaps in metamaterials are typically narrow-band in both acoustic (9, 13) and elastic wave attenuation applications (10, 14–16). Previous works have used concepts such as rainbow trapping effects (17), inertial amplification (8, 18), and combinations of phononic and locally resonant band gaps (19) to achieve wide and low-frequency band gaps.

Here, we introduce a different solution for opening low-frequency and wide band gaps: the coupling of local resonances with structural modes of an architected lattice, in what we refer to as “elastic metastructures.” These metastructures are fundamentally different from metamaterials that incorporate resonators surrounded by a soft coating to induce low-frequency band gaps (9, 19), because our metastructures exploit the geometry of the structure instead of material properties to selectively alter different locally resonant modes. Further, these metastructures are not typical of traditional PCs because their band gaps can be tuned through local resonances. For concept validation, we design a 3D-printable elastic metastructure that combines characteristics of both metamaterials (i.e., local resonances) and PCs (i.e., periodicity), to achieve wide and low band gaps.

Unit Cell Design and Fabrication

The metastructures consist of a polycarbonate lattice, with embedded steel cubes acting as local resonators. The fundamental

Significance

Architected material used to control elastic wave propagation has thus far relied on two mechanisms for forming band gaps, or frequency ranges that cannot propagate: (i) Phononic crystals rely on their structural periodicity to form Bragg band gaps, but are limited in the low-frequency ranges because their unit cell size scales with wavelength; and (ii) Metamaterials overcome this size dependence because they rely on local resonances, but the resulting band gaps are very narrow. Here, we introduce a class of materials, elastic metastructures, that exploit resonating elements to broaden and lower Bragg gaps while reducing the mass of the system. This approach to band-gap engineering can be used for low-frequency vibration absorption and wave guiding across length scales.

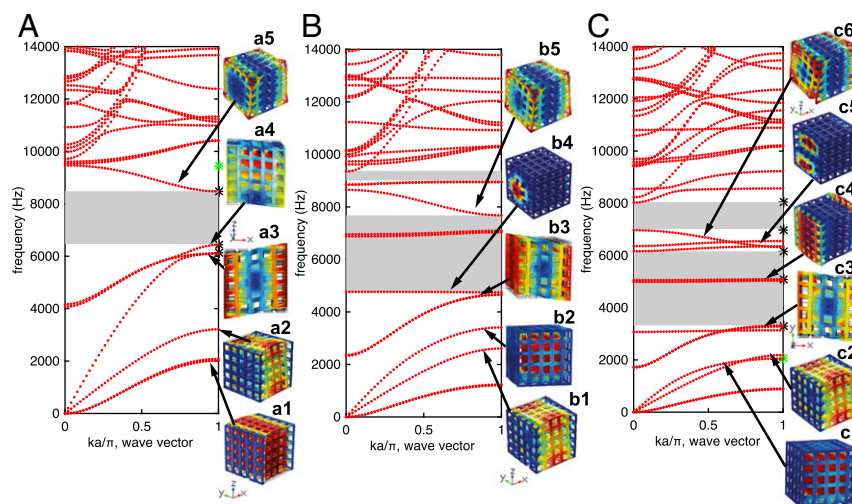
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structures using the relation $c = \omega/\kappa$ as κ approaches 0, for the lowest flexural, torsional, and longitudinal mode. This approximation, and the resulting flexural, torsional, and longitudinal band gaps, are shown in Figs. S4 and S5 for the high- and low-stiffness metastructures. It is shown that the Bragg scattering frequencies for each wave mode fall within the band gap calculated with FE simulations.

However, the resulting full band gaps observed in the metastructures are a superposition of the flexural, torsional, and longitudinal band gaps (Figs. S4–S6). By controlling the different wave modes independently, we can tune the full band gap to wider and lower frequency ranges, which we demonstrate by small manipulations of the lattice geometry to specifically control the band-gap edge modes.

Both FE simulations and experimental results of these proposed metastructures clearly show the ability to engineer low-frequency and wide band gaps by using the lattice geometry to selectively control the locally resonant modes. In addition, flexibility in the geometric design enables a variety of band-gap frequencies, distributions, and widths by varying the beam's thickness, the resonator and lattice dimensions, and filling fractions. With advanced 3D printing techniques, these metastructures could be fabricated on many different length scales to address a wide range of vibration isolation and wave-guiding applications, ranging from structural vibrations to MEMS devices.

Materials and Methods

FE Simulations. FE simulations (COMSOL) in 3D are used to analyze the infinite and finite metastructures. For the infinite metastructure simulations, a single unit cell was modeled and periodic Bloch boundary conditions were imposed. An eigenfrequency analysis was performed by sweeping the wave vector over the reduced Brillouin zone. We used tetrahedral elements, and mesh convergence was confirmed.

For the finite metastructure simulations, the elastic wave transmission was calculated by imposing a fixed boundary on one end of the six-unit cell chain, and measuring the reaction force on the opposite end. The transmission was defined as the ratio of output to input force amplitudes, and was calculated over a range of frequencies from 100 to 10,000 Hz (Fig. 4). The results shown are based on a harmonic x -direction displacement input. Band-gap edge frequencies calculated for the infinite system are indicated as dashed vertical lines in the same plots.

Parameters of 3D-Printed Materials. The material properties and key geometrical parameters used in the simulations are given in Tables S1 and S2. The Young's modulus used for the 3D-printed polycarbonate was measured

through tensile testing on 3D-printed standard tensile testing samples with different printing orientations, to account for anisotropy in the 3D-printed polycarbonate. Because 3D-printed material is known to be highly dependent on specific printing parameters, the measured Young's modulus was further tuned such that the low-frequency mode in the finite FE simulations aligned with the low-frequency mode in the dynamic experiments presented in Fig. 4. The shear modulus was calculated based on a Poisson's ratio of 0.4 (27).

It is well known that 3D-printed materials can have anisotropic mechanical properties that are dependent on the printing geometry, orientation, and ambient conditions (26). Our FE model assumes the lattice materials to be homogeneous and slightly anisotropic. As such, parameter-dependent deviations between experiments and simulations are also to be expected.

Experiments. To experimentally measure the elastic wave transmission through the metastructures, we fix the 3D-printed samples between a piezo actuator and a force sensor, which respectively excite and measure x -direction motion of the structure. A lock-in amplifier drives the piezo actuator and measures the response of the structure. A static load cell continuously monitors the precompression of the structure during experiments (due to the sample's supports) to ensure consistent boundary conditions when mounting different samples. The experiments presented in Fig. 4 *A* and *B* measured output force. The setup is shown in Fig. S2, consisting of a fixed static load cell mounted against a dynamic force sensor on a frictionless support, and a piezo actuator mounted on movable support to control precompression of the sample. To confirm a flat response of the system over the frequency range of interest (1–10 kHz), the response of the system without a sample was measured by pressing the force sensor against the piezo actuator, with the same precompression as in the transmission experiments. The noise floor in the experimental setup can be seen in the band gaps of both structures (Fig. 4).

For the experiments shown in Movie S1, accelerometers were glued to the exterior of the high- and low-stiffness metastructures, at heights corresponding to the second, fourth, and sixth resonator. The accelerometers measured the acceleration in the vertical direction, which is the direction of periodicity. The metastructures were mounted on a piezo actuator, which was swept in frequency from 1 to 6.5 kHz over about 25 s. The waveforms shown are the responses of the top (purple), middle (blue), and bottom (yellow) accelerometers. The transmission spectrum at the bottom of the screen shows the finite simulation results for both high- and low-stiffness metastructures, and the solid vertical line shows the swept frequency corresponding to the experimental sweep. The waveforms are recorded directly from a Tektronix DPO 3034 oscilloscope and are recorded at the same scale such that the amplitudes of the high- and low-stiffness metastructure responses are directly comparable.

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