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Tailoring concurrent shear and translational vibration control mechanisms in elastomeric metamaterials for cylindrical structures

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The implementation of engineered metamaterials in practical engineering structures for vibration control purposes is challenged by a lack of understanding on the specific interaction mechanisms present among finite-sized metamaterials and the greater host structures. This research begins to address such knowledge gap by establishing an analytical framework to study the dynamic response and coupling mechanisms between elastomeric metamaterial inclusions embedded within a cylindrical host structure, representative of a variety of engineering systems. The analysis is formulated based on energy methods, and approximately solved by the Ritz method. Following experimental validation, the analysis is leveraged to reveal deep understanding on the precise mechanisms of coupling between such elastomeric metamaterial inclusions and the host structure. Several non-intuitive roles of parameter changes are conclusively revealed. For instance, while the decrease in open angle ratio of the inclusion cross-section geometry and the increase in the central core radius both appear to increase the significance of the core mass, the analysis reveals that the primary inclusion characteristic tuned by such parameter changes is the dynamic stiffness of the inclusions. Together, the dynamic mass and dynamic stiffness work to induce two tuned-mass-damper-like behaviors that lead to broadband vibration attenuation capabilities. The results of this research encourage attention to the study of specific problems whereby metamaterials directly interact with host structures to accurately understand the working mechanisms of vibration control for sake of optimal practical implementation.

1. Introduction

A long-standing demand remains for exceptional vibration attenuation in many engineering applications. Lightweight materials that deliver high vibration attenuation capabilities extend the life of engineering systems and improve working quality. With these aims in mind, previous researchers have investigated structural and material systems capable of attenuating broadband vibration by using the concepts of tuned mass dampers, bandgap behavior, and constrained layered dampers.

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Tuned mass dampers (TMDs) are mass-spring-damper resonators capable of transferring the local vibration energy from the host structure to the mass-spring-damper. With this additional degree-of-freedom available, the vibration of the host structure may be suppressed by out-of-phase reaction force of the TMD with respect to the phase of the excitation force. Researchers have investigated tailoring this mechanism of vibration absorption via a variety of approaches. For example, Pai [1] proposed an elastic metamaterial with one-dimensional TMD subsystems to realize broadband vibration absorption for a one-dimensional host structure. The TMDs supply inertial forces that attenuate longitudinal wave propagation, including when the longitudinal wavelengths are much greater than the size of the periodic TMD subsystem, or unit cell. Similarly, Sun et al. [2] designed an elastic metamaterial beam with an array of TMD subsystems that exert shear forces and bending moments to absorb transverse wave propagation. Pai et al. [3] reported that using dual-mass TMD subsystems may enhance vibration absorption in two-dimensional structures while also broadening the range of frequencies of wave attenuation. Nonetheless, for each TMD the attenuation is only effective for a relatively narrow frequency range of resonance inherent to the TMDs or array of TMDs.

In a similar spirit to the resonant behavior of TMDs, bandgaps are a promising property of metamaterials for vibration absorption since waves are prohibited from propagating through the host structure at frequencies within the bandgap. The center frequency, bandwidth, and number of the bandgaps are related to the interrelationships among geometry, stiffness, and filling fraction of the metamaterials within the media. For example, Wang et al. [4] reported that the number of bandgaps increases as the metamaterial is subjected to increasing compressive strain while the center frequency and bandwidth simultaneously reduce. With the aim to combine local resonance and bandgap behaviors, Matlack et al. [5] adopted resonant elements embedded in a polycarbonate lattice to realize a broad Bragg bandgap. The bandgap breadth and center frequency were thus shown to be controlled by the local resonances. Indeed, the breadth of metamaterial concepts that exhibit bandgap behaviors are diverse and are inspiring for new approaches via their combination. For instance, Nouh et al. [6] presented a metamaterial plate composed of periodic cells with a small mass on a viscoelastic membrane, while Oh et al. [7] developed an elastic metamaterial insulator capable of creating a broad bandgap at low frequency by combined shear stiffening and rotation softening. Furthermore, for the chiral elastic metamaterial inclusions, Liu et al. [8] and Zhu et al. [9] investigated chiral metamaterials with inclusions comprised of a core with coating layer. Also using a multi-material concept, Baravelli and Ruzzene [10] found that reduction of the filling fraction of the periodic elements caused the number of bandgaps to increase and the center frequency to decrease. Abdeljaber et al. [11] reported that the use of segmented, non-continuous, and non-periodic metamaterials may be advantageous for vibration and wave control in engineering structures. Although locally resonant bandgap mechanisms may provide useful means to suppress target bandwidths of elastic waves in host structures, the bandwidth effected by such phenomena may be limited. Such limitation is inevitable when utilizing a parameter sensitive resonant behavior. Furthermore, designing these metamaterials to attenuate low frequency waves requires large size and often more material mass, which are undesirable aspects in practice.

Constrained layer damping (CLD) materials introduce an alternative strategy for vibration attenuation and typically use small added mass. The attenuation mechanism of CLD is attributed to the shear deformation in the thin and soft viscoelastic layer between the host structure and the constraining layer. As a result, CLD provides vibration control most effectively at wavelengths on the order or shorter than the size of the applied CLD materials. This bounds the effective working range of the CLD to mid to high frequencies in practical applications. Using these principles, Aumjaud [12] developed a double shear lap-joint damper to yield high modal loss factor and amplitude reduction for a minimum of added mass. Additionally, previous researchers discussed influences of the length, elastic modulus, thickness, structural damping, and interfacial damping of the viscoelastic layer that is central to the CLD approach [13–20]. Douglas and Yang [21] concluded that the thin viscoelastic material provides broadband vibration attention by way of enhanced shear transfer to the viscoelastic layer, which agrees with findings by Kerwin [22]. For thicker viscoelastic layers, the broadband attenuation of vibration is less apparent whereas transverse compressional damping phenomena may occur. Although conventional CLD may provide broadband attenuation at mid to high frequencies, the CLD must cover a large proportion of the host structure, which is challenging in practice and may have side-effects, such as introducing a thermally insulating layer.

The survey above identifies promise and shortcomings for the variety of techniques for vibration attenuation: TMD, bandgap, and CLD. Recent work has sought to advance beyond these techniques by utilizing compression constraint on lightweight, elastomeric metamaterials. In this spirit, Bishop et al. [23] reported a lightweight hyperdamping metamaterial inclusion capable of attenuating more impact energy than the bulk material from which the metamaterial was derived. The concept was extended by Harne et al. [24] who utilized such inclusions to enhance noise control capabilities of poroelastic media. Yet, to date, the working mechanisms by which metamaterials enhancing vibration attenuation in host structures has not been illuminated. Consequently, this research aims to build up an analytical framework to study the lightweight metamaterial inclusions, originally proposed in [23,24], as the inclusions interact with a host structure.

The metamaterial inclusions considered here are cylindrical so as to conform for a host structure that is a circular hollow tubular beam, a common component in automotive and aerospace structures as well as in mechanical equipment. The bottom left image of Fig. 1(a) illustrates the concept, where an elastomeric inclusion is embedded within a greater host structure (e.g. a long cylindrical tube). Several components to the cross-section may be identified using the general schematic at the top of Fig. 1(a) shown by the four distinct layers. In Fig. 1(b), the annular metamaterial layer (labeled 2 in Fig. 1(a)) is the thin outer-most component of the metamaterial that is between the host structure (labeled 1) and the porous metamaterial layer (labeled 3). The core bulk metamaterial layer (labeled 4) at the center of the metamaterial is a mass. All together, the radially arrayed beams are analogous to a soft elastic layer.