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Magnetorheological elastomer vibration isolation of tunable three-dimensional locally resonant acoustic metamaterial

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ABSTRACT

Magnetorheological elastomers (MREs) are used as cladding in three-dimensional locally resonant acoustic metamaterial (LRAM) cores. The metamaterial units are combined into a vibration isolator. Two types of LRAMs, namely, cubic and spherical kernels, are constructed. The finite element method is used to analyze the elastic band structures, transmittances, and vibration modes of the incident elastic waves. Results show that the central position and width of the LRAM elastic bandgap can be controlled by the application of an external magnetic field; furthermore, they can be adjusted by changing the MRE cladding thickness. These methods contribute to the design of metamaterial MRE vibration isolators.

1. Introduction

Phononic crystals and acoustic metamaterials have acoustic or elastic bandgaps (EBG), which cannot propagate in the forbidden bandgap [1–3]. The mechanism of phononic crystal EBG formation is Bragg scattering. The lattice size is the same order of magnitude as the acoustic wavelength. Thus, the use of phononic crystals to control low-frequency vibration and noise requires a large and bulky structure. Acoustic metamaterials are artificial microstructures with subwavelength sizes that can flexibly regulate and manipulate the propagation of elastic waves with wavelengths that are up to two orders of magnitude higher than the lattice size. Liu et al. [4] first demonstrated locally resonant acoustic metamaterials (LRAM), in which the EBG corresponding to the wavelength is considerably larger than the lattice size. The unit size can be small, making acoustic metamaterials feasible for low-frequency noise and vibration control components. Acoustic metamaterials can be processed and designed for microstructure units to achieve superior performance and many application prospects, such as negative refraction and superlensing [5], double negative refraction and reverse Doppler effect [6], zero refractive index and total reflection [7], subwavelength detection [8], seismic shielding [9], and omnidirectional acoustic cloak [10], and more.

LRAMs have a significant advantage in the field of vibration isolation, and researchers have undertaken considerable effort in this direction. Larabi et al. [11] designed a coaxial cylindrical LRAM with multiple layers of soft and hard materials to obtain a local resonant bandgap. Their results showed that if multiple alternating layers were used instead of individual alternating layers, the transmission spikes would be replaced by multiple spikes. Therefore, the multilayered structure was not conducive to the formation of a large bandgap. Bonnet et al. [12] designed cylindrical and spherical composite metamaterials composed of a hard core and cladding and calculated the resonant frequency in the form of analytical expressions. Their results showed that all resonant frequencies were independent under the ideal model. Additionally, a low resonance frequency could be obtained by optimizing the composition and shape. Wang et al. [13] designed an LRAM with a metal core and a matrix connected with an elastic beam. This LRAM was tunable over a wide frequency range and could use the deformation to open or close the EBGs, which opened the way for an adaptive switch. Yang et al. [14] used a topological optimization method with an effective mass density to maximize the first EBG of an LRAM. Chen et al. [15] proposed a dissipative LRAM composed of multiple layers of viscoelastic continuum. The dissipative LRAM was used to effectively attenuate transient shock waves. A wide range of shock waves could be nearly completely mitigated by sub-wavelength-scale metamaterials. Krushynska et al. [16] compared 2D and 3D double-local models. Their results showed that 3D double-local LRAMs could produce an absolute bandgap. Furthermore, a 3D finite structure was practical.

The study of metamaterials with intelligent materials is important [17–19], and the study of magnetorheological elastomer (MRE) meta-

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materials is also progressing. An MRE is composed of a matrix material (natural or silicone rubber) that contains dispersed magnetic particles. These magnetic particles form a chain-like aggregate structure under applied magnetic field conditions [20–22]. MREs focus on the advantages of magnetorheological fluids and elastomers, namely, fast response and reversibility, and overcome the shortcomings of magnetorheological fluid settling and poor stability. Wu et al. [23] calculated the band structure of phononic crystals with MREs embedded in epoxy. Their results showed a complete acoustic bandgap. Xu et al. [24] constructed phononic crystals with lead embedded in MREs. An external magnetic field could be used to adjust the shear bandgap. Xu et al. [25] designed 1D two- and three-component phononic crystal magnetorheological vibration isolators and found a complete elastic wave bandgap whose width and position could be adjusted by an applied external magnetic field. Alireza et al. [26] designed a porous magnetorheological LRAM, studied the band structure under varying degrees of deformation and external magnetic field strengths, and demonstrated that a large deformation and/or external magnetic field could change the position and width of the bandgap.

In this research, we propose an LRAM unit with an MRE cladding for the hard core to realize elastic modulus adjustment. We also construct a 3D cubic/spherical MRE LRAM unit in the vibration bearing. Results show that the width of the LRAM EBG can be adjusted by controlling the MRE cladding with an external magnetic field or adjusting the MRE cladding thickness. These features provide new ideas for the design of vibration isolation bearings.

The remaining parts of the paper are presented as follows. The second part presents the model and method of the system. The third part explains the results and the discussion. Finally, the fourth part summarizes the research.

2. The model and method

Fig. 1(a) shows a diagram of the LRAM MRE vibration isolator. The LRAM MRE units are periodically arranged, and the LRAM MRE units and the magnetized steel plate are integrated into the whole unit. The magnetic steel sheet is placed between the layers and plays a role in enhancing and uniformizing the magnetic field; thus, the thickness can be ignored. Conductive steel foil, magnetic steel plate, and a core coil form a closed magnetic circuit. The elastic modulus of the MRE cladding can be controlled by coil regulation. Fig. 1(b) and (c) show cubic and spherical kernel LRAM unit models, respectively. The periodic lattice constant $a = 0.025$ m. Fig. 1(d) shows the first Brillouin zone of the cubic lattice; the tetrahedron ΓXMR represents the irreducible Brillouin zone, and the band structure is scanned along ΓXMΓRXMR, which represents the edge of the irreducible Brillouin zone. We use the finite element method [27], which is widely utilized in band structure calculation and has significant advantages for working with complex structures.

The propagation equation of an elastic wave in a 3D solid isotropic medium is as follows:

$$\rho\frac{\partial^2 u_i}{\partial t^2}=\sum_{j=1}^{3}\frac{\partial}{\partial x_j}\left(\sum_{l=1}^{3}\sum_{k=1}^{3}C_{ijkl}\frac{\partial u_k}{\partial x_l}\right) \tag{1}$$

where ρ is the density, u_i denotes the displacement, t represents the time, C_{ijkl} stands for the elastic constant, and x_j indicates the coordinate variable.

In the calculation, the tungsten density is $\rho_t = 19300\ \mathrm{Kgm^{-3}}$, the longitudinal wave velocity is $C_{tl} = 5090\ \mathrm{ms^{-1}}$, and the shear wave velocity is $C_{tt} = 2800\ \mathrm{ms^{-1}}$. The epoxy density is $\rho_e = 1200\ \mathrm{Kgm^{-3}}$; the longitudinal and transverse wave velocities are $C_{el} = 2830\ \mathrm{ms^{-1}}$ and $C_{et} = 1160\ \mathrm{ms^{-1}}$, respectively.

For MREs, we use the magnetic dipole model. The Fe particle density is $\rho_{Fe} = 7890\ \mathrm{Kgm^{-3}}$, and the rubber density is $\rho_r = 1200\ \mathrm{Kgm^{-3}}$. The tensile properties of the MREs are similar to their shear properties, and the Poisson ratio is 0.47 [28]. The change in the shear modulus of the external magnetic field is as follows [29,30]:

$$\Delta G = 36\phi\mu_f\mu_0\beta^2H^2(R/d)^3\zeta \tag{2}$$

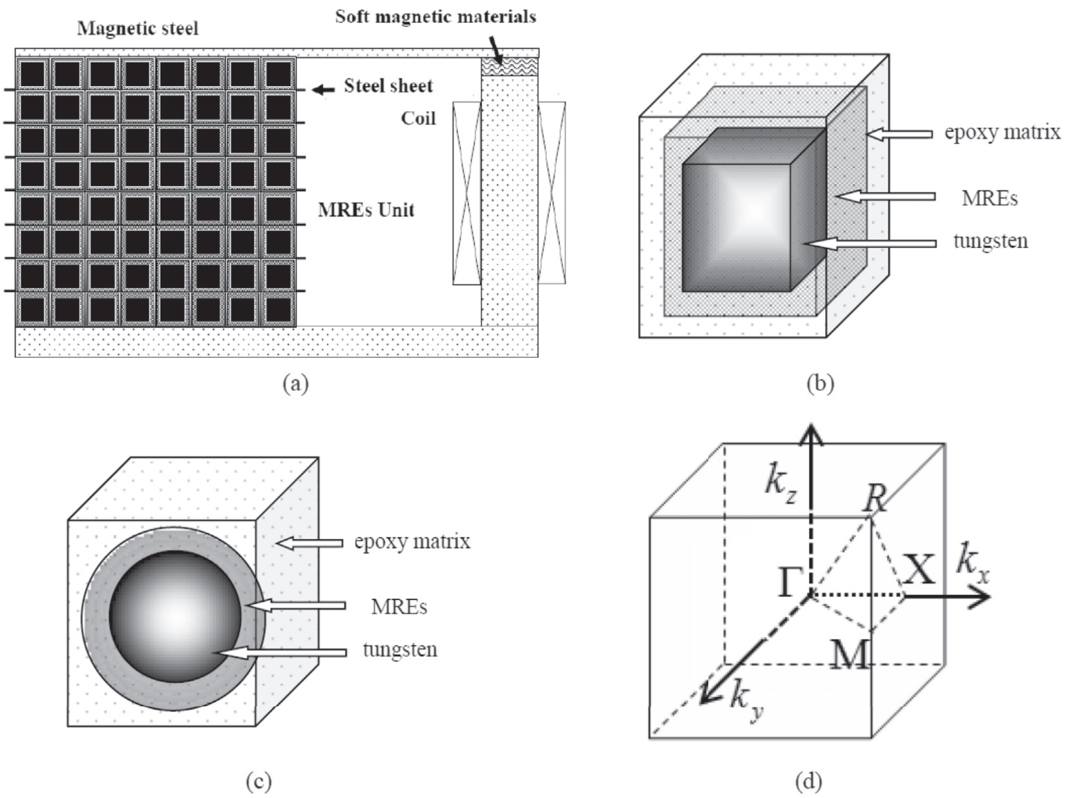

Fig. 1. (a) Locally resonant metamaterial MRE vibration isolator; (b) cubic core metamaterial unit; (c) spherical core metamaterial unit; (d) cubic structure irreducible Brillouin zone.