Extreme Mechanics Letters 4 (2015) 111–117

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Wide band-gap seismic metastructures

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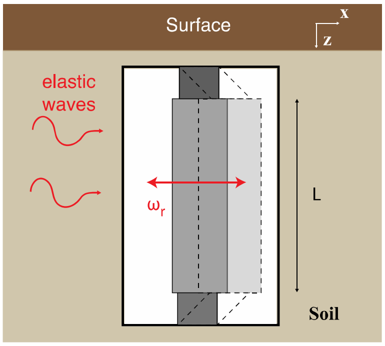
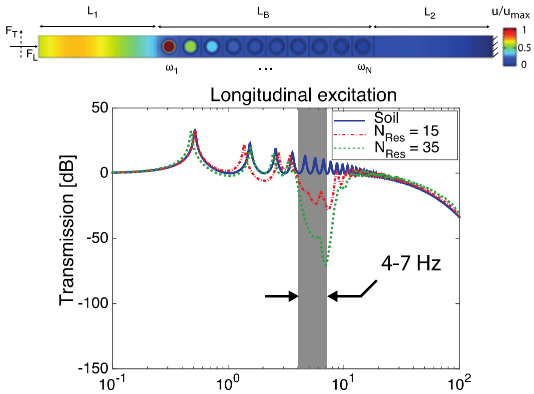
GRAPHICAL ABSTRACT





ARTICLE INFO

Article history:
Received 6 April 2015
Received in revised form 27 May 2015
Accepted 27 May 2015
Available online 1 June 2015

Keywords:
Mechanics
Wave-propagation
Metamaterials
Seismic protection
Earthquakes

ABSTRACT

Metamaterials exploit local resonances to reflect acoustic signals with wavelengths well above the characteristic size of the material's structure. This has allowed obtaining materials that present low-frequency (albeit narrow) band gaps or devices for optical and acoustic cloaking. In this work, we propose to use an array of resonating structures (herein termed a "*metastructure*") buried around sensitive buildings to control the propagation of seismic waves. These seismic metastructures consist of arrays of cylindrical tubes containing a resonator suspended by soft bearings. To obtain broadband attenuation characteristics, each resonator in the array is designed to exhibit a different eigenfrequency. We study the response of these systems using numerical analysis and scaled (1:30) experiments. We target wave mitigation in the infrasound regime (1–10 Hz), a range of frequencies relevant for the protection of large buildings.

1. Introduction

The ability to direct the propagation of mechanical waves and to control the transmission spectrum of materials is essential in many engineering applications, ranging

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http://dx.doi.org/10.1016/j.eml.2015.05.004
2352-4316/

from thermoelectrics [1] to sound absorption [2]. Phononic crystals and metamaterials are engineered materials that derive their fundamental properties from the geometry of their structural building blocks, rather than their constituting materials. Phononic crystals rely on the presence of periodicity in their structure, to induce Bragg scattering effects and create band gaps that yield reflections at selected frequency ranges [3]. The first experimental realization of phononic crystals demonstrated the attenuation of sound waves in the audible frequency range by a sculpture [4]. Metamaterials exploit the coupling between propagating waves and local resonances to prevent the propagation of waves at frequencies near resonances. The first realization of metamaterials demonstrated the ability to control electromagnetic waves below the materials' fundamental diffraction limit [5,6]. More recently, research on metamaterials was extended to the design of materials able to control elastic waves, targeting ultrasonic applications in acoustic imaging [7] and acoustic cloaking devices [8,9]. At smaller scales, advances in micro/nanofabrication techniques have allowed the use of metamaterials to control heat by altering high frequency (THz) phonons [10–13]. At very large scales, phononic crystals and metamaterials have been suggested for protecting civil infrastructures from impacts and seismic threats [14–16].

One of the advantages of metamaterials, as compared to phononic crystals, is that metamaterials do not rely on structural periodicity to reflect acoustic waves, and their characteristic sizes can be below the wavelengths of interest. This is particularly relevant for structures that target the reflection of very low frequency waves, for which the use of phononic crystals would require unpractical, large structures. This makes metamaterials particularly interesting in civil engineering application, for example, to shield buildings and civil infrastructures from natural or man-made earthquakes. In these problems, protective materials should be scaled to respond to bulk and surface waves at very low frequencies (1–10 Hz) and large amplitude [17] These low frequencies (i.e., large wavelengths) cannot be controlled by phononic crystals because their size being directly proportional to the wavelength. Being able to design protective structures with characteristic sizes below the natural wavelength makes their fabrication and use accessible with existing construction technologies. Most studies on seismic metamaterials have been theoretical and numerical, and focused on shielding surface waves. Brulé et al. [18] conducted real-size experiments on a seismic phononic crystal consisting of an array of cylindrical holes in the ground. They demonstrated the presence of a phononic band gap around 50 Hz, which is still above the most damaging excitations in a common earthquake spectrum.

Helmholtz-like resonators were also suggested as possible elements to create a seismic shadow zone [19] and as possible solutions to transform elastic wave energy into sound and heat. More recently, an approach that consists of cycloidal resonators that decrease the amplitude of the surface response function has been proposed and analyzed numerically [20]. Metaconcrete, i.e., concrete reinforced with mm-sized coated heavy inclusions, has been proposed to increase the blast mitigation capacity of concrete [21]. Coated heavy inclusions have also been analyzed for vibration isolation of building foundations [22].

2. Materials and methods

In this paper, we propose the use of metastructures to shield sensitive buildings from waves generated by an earthquake. The metastructures consist of arrays of cylindrical, locally resonant units, distributed in the soil surrounding the buildings (Fig. 1(a)). We choose cylindrically shaped resonators due to the widespread use of cylindrical structures in civil engineering (i.e., columns, pipes). This allows a direct translation of the proposed concept in engineering applications. In our proposed systems, the main attenuation of ground excitations arises primarily from the reflection of elastic energy due to the resonant modes of the suspended, rigid cylindrical structures. The metastructures discussed target the mitigation of waves close to the ground surface, however the approach could be extended to protect against bulk waves by placing similar resonating units below the buildings foundations. The resonant units in our proposed metastructures consist of an outer hollow cylinder (for example, a large steel tube, an aluminum hollow cylinder or a concrete pipe, of radius $r_c = 60$ cm with a thickness, $t = 3$ cm) containing a heavy steel mass (a bulk steel cylinder of radius $r_r = 22.5$ cm, length $L = 1.8$ m Young's module $E_r = 210$ GPa, Poisson's ratio $\nu_r = 0.3$ and density $\rho_r = 7850$ kg/m^3 with an overall mass of approximately 2000 kg) suspended between two polymeric springs or bearings (Fig. 1(b)). Variations in the mass of the resonators and/or the stiffness of the suspending springs allow varying the resonator's characteristic eigenfrequency. This particular geometry was selected because it can be constructed with existing building materials and easily adapted to size constraints of different applications. For example, in a full-scale realization of the metastructures, different commercial rubber bearings could be used as soft springs, being already available in variable sizes and stiffness grades [23]. The equivalent spring stiffness k_{RB} of a rubber bearing can be approximated by [23]

$$k_{RB} = G\frac{A}{H}, \tag{1}$$

where G is the shear modulus of the rubber material, A is the area and H is the height of the bearing. The resonance frequency of the resonators can be tuned changing one or more of these three parameters. The resonant mode of interest is depicted in Fig. 1(c), and shows the vibration of the inner rod suspended by the two polymeric springs. Each resonator is envisioned to be buried underground close to or at the ground surface, around the buildings to be protected. In most configurations, the bending frequencies of the inner rod and the structural frequencies of the outer cylinder are much higher than the resonance of the inner mass suspended by the soft springs and play no significant role in the protection of the buildings. Each resonator can be modeled as an equivalent, two-dimensional (2-D), plain strain element in the frequency domain (see Fig. 1(d)). In