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Flexural wave suppression by an acoustic metamaterial plate

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ABSTRACT

A new acoustic metamaterial plate is presented for the purpose of suppressing flexural wave propagation. The metamaterial unit cell is made of a plate with a lateral local resonance (LLR) substructure which consists of a four-link mechanism, two lateral resonators and a vertical spring. The substructure presents negative Young's modulus property in certain frequency range. We show theoretically and numerically that two large low-frequency band gaps are obtained with different formation mechanisms. The first band gap is due to the elastic connection with the foundation while the second is induced by the lateral resonances. Besides, four-link mechanisms can transform the flexural wave into the longitudinal vibration which stimulates the lateral resonators to vibrate and to generate inertial forces for absorbing the energy and thus preventing the wave propagation. Frequency response function shows that damping from the vertical spring has little influence on the band gaps, although the damping can smooth the variation of frequency response (see the dotted line in Figs. 10 and 11). Increasing the damping of the lateral resonators may broaden the second band gap but deactivate its effect. This study provides guidance for flexibly tailoring the band characteristics of the metamaterial plate in noise and vibration controls.

1. Introduction

Continuum structures like beams, plates and shells are the most widely preferred elements in engineering applications such as the construction of the buildings, experimental tables and some large ships and submarines. Controlling the propagation of flexural waves in continuum structures is one of the most important issues in the safety and stability of such engineering structures [1]. An example is a submarine in service, which may radiate energy to the surroundings, thereby exposing its position and jeopardising safety. Since flexural wave is the main wave type for radiation, suppressing flexural waves is a vital safety issue. Moreover, in many experiments, vibration of the experimental table can influence the accuracy of results. In this situation, propagation of the flexural wave should be stopped. With the unique wave-blocking properties of metamaterial, studies have been devoting themselves to apply these novel properties for the control of wave propagation. Early studies [2] of wave propagation in metamaterial were mainly focused on dispersion analyses of longitudinal wave and band gaps of simple lattices. Huang et al. proposed different types of metamaterial lattices for blocking longitudinal wave propagation [3–6]. Zhang et al. disentangled longitudinal and shear elastic waves by neo-Hookean soft devices [7]. These studies are focusing on in-plane waves and still remote from engineering applications but provide guidance for metamaterial design.

In recent years, extensive investigations have been conducted on preventing flexural wave propagation within continuum structures in different structural configurations. It has been theoretically and numerically predicted that attaching absorbers to a beam or plate to construct a metamaterial could constrain flexural wave propagation [8–14], which is classified as 'Site-City Effect' in geophysics [15,16], and inserting absorbers into a sandwiched beam or plate [17–21] may also prevent such propagation. Further, beams and plates with perforated holes filled with a membrane and a mass in the centre exhibit novel properties for controlling flexural wave, but at the expense of decreasing strength [22–25], as with this method, the stiffness of the metamaterial has been dramatically decreased. The resonators mentioned above are all directly attached to continuum structures and vibrate in the perpendicular direction to the continuum structure. Only few researchers have investigated mechanisms for transforming the flexural wave into another direction and blocking the wave propagation in the new direction, e.g. Chesnais et al. [26,27] for reticulated structures.

The LLR substructure proposed by Huang and Sun [5,28] is composed of a four-link mechanism, two lateral resonators and a vertical spring. It exhibits an unusual frequency-dependent effective

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Young's modulus and transforms the vibration to another direction. Huang and Sun [20] showed that the periodic arrangement of the LLR substructure could attenuate the longitudinal wave propagation through the wave transformation mechanism. Recently, their group extended the lumped structure to a continuum structure based on beam elements [29]. However, investigation is still limited to longitudinal wave attenuation. Yet, as mentioned, the flexural wave is the main energy storage type. Controlling the flexural wave using the LLR substructure has great potential for engineering applications. To our knowledge, combination of the classical continuum structure with the lumped LLR substructure to form an acoustic metamaterial has not been discussed.

In this paper, we propose an acoustic metamaterial plate with LLR substructures for flexural wave suppression. To investigate the mechanism of the transformation of the waves, the dynamic characteristics of an LLR substructure are analysed in Section 2. The combination of the LLR and continuum plate is theoretically modelled in Section 3, including the analysis of dispersion surfaces and effective mass density. Finite element analysis is conducted in Section 4 to investigate the flexural wave propagation and damping effects. The outcome is expected to provide helpful guidance for generating multiple low frequency band gaps in flexural wave suppression and noise absorption.

2. Configuration of the negative Young's modulus substructure

The LLR substructure analysed here is different from that detailed by Huang and Sun [5]. As shown in Fig. 1, the LLR substructure consists of four-link mechanism, two lateral resonators and a vertical spring. The four-link mechanism is joined to the ground and a harmonic force $F = \tilde{F}e^{-j\omega t}$ is applied to the other end, which plays the role of transforming the vertical vibration into horizontal vibration. The lateral resonators with spring and mass constants of k_2 and m_2 vibrate only in the horizontal direction. The vertical spring k_1 moves vertically. The governing equation for this lumped system is

$$F = k_1 w + \frac{L}{D} k_2 (u - v) \tag{1}$$

$$m_2 \frac{\partial^2 u}{\partial t^2} = k_2 (v - u) \tag{2}$$

where w, u and v represent the displacement of the vertical point of the truss, the lateral mass and the horizontal point of the truss, respectively. L and D are the vertical and horizontal length of the four-link mechanism. Assuming the vibration is small, relationship of displacements v and w can be written as

$$v = -\frac{L}{2D} w \tag{3}$$

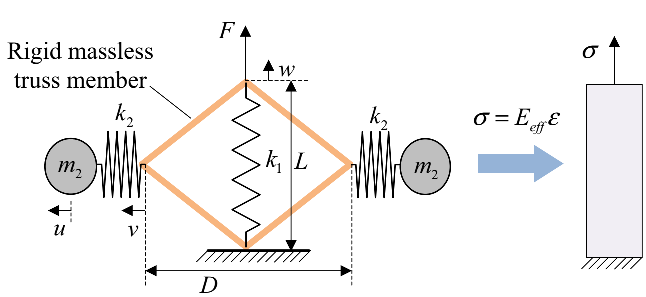

Fig. 1. Configuration of the negative Young's modulus inclusions and its effective continuum model.

In our analysis, the displacement fields are assumed in the harmonic form

$$w = \tilde{w}e^{-i\omega t}, u = \tilde{u}e^{-i\omega t} \tag{4}$$

Substitution of Eqs. (3) and (4) into Eqs. (1) and (2) yields the force-displacement relation as

$$\tilde{F} = \left(k_1 + \frac{1}{2} \left(\frac{L}{D} \right)^2 \frac{k_2 \omega^2}{\omega^2 - \omega_0^2} \right) \tilde{w} \tag{5}$$

where $\omega_0 = \sqrt{k_2/m_2}$. Using a continuum elastic solid to represent the lumped system with the cross section area A, the stress-strain relation is defined as

$$\sigma = E_{eff} \varepsilon \tag{6}$$

with $\sigma = F/A$ and $\varepsilon = w/L$ respectively. E_{eff} is the effective Young's modulus of the continuum system. Denoting that $E_0 = k_1 L/A$, the normalized effective Young's modulus is calculated by

$$\frac{E_{eff}}{E_0} = 1 + \frac{k_2}{2k_1} \frac{\omega^2}{\omega^2 - \omega_0^2} \left(\frac{L}{D} \right)^2 \tag{7}$$

in which $k_1 = 1 \times 10^4$ N/m, $m_2 = 0.003$ kg, $k_2 = 0.5 \times 10^4$ N/m, $L = 0.02$ m, and $D = 0.01$ m.

Fig. 2 shows the effective Young's modulus of LLR substructure as a function of frequency. It is obvious that from 145 Hz to 205 Hz, the effective Young's modulus is negative whereas in other ranges it remains positive. At the frequency of 205 Hz, the effective Young's modulus is unbounded because of the resonance of the lateral local resonators. Around the resonance frequency, waves can be effectively attenuated, according to the results of Huang and Sun [5].

With the above analysis of the LLR substructure, we can see that the vibration direction of the stimulus F and that of the LLR substructure u are different. The four-link mechanism can transform the vertical vibration into longitudinal vibration, thus controlling the wave in a unique way. This transformation can be used to design different absorbers and isolators for wave suppression. Considering that flexural waves in beams and plates are the main energy type, the LLR substructure is suitable for the design of acoustic metamaterials for wave attenuation.

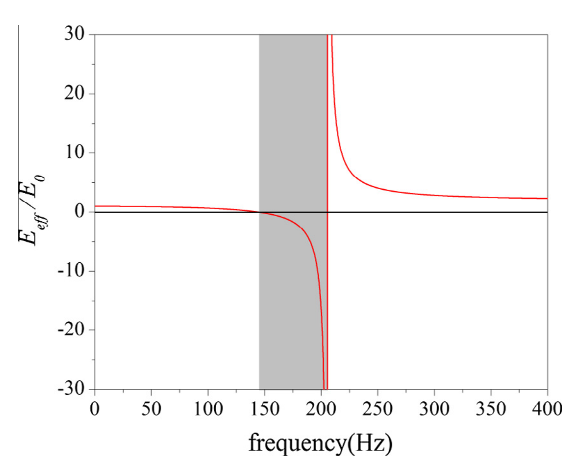

Fig. 2. The effective Young's modulus versus frequency.