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Dynamic analysis of periodic vibration suppressors with multiple secondary oscillators

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A periodic vibration suppressor with multiple secondary oscillators is examined in this paper to reduce the low-frequency vibration. The band-gap properties of infinite periodic structure and vibration transmission properties of finite periodic structure attached with secondary oscillators with arbitrary degree of freedom are thoroughly analyzed by the plane-wave-expansion method. A simply supported plate with a periodic rectangular array of vibration suppressors is considered. The dynamic model of this periodic structure is established and the equation of harmonic vibration response is theoretically derived and numerically examined. Compared with the simply supported plate without attached suppressors, the proposed plate can obtain better vibration control, and the vibration response can be effectively reduced in several frequency bands owing to the multiple band-gap property. By analyzing the modal properties of the periodic vibration suppressors, the relationship between modal frequencies and the parameters of spring stiffness and mass is established. With the numerical results, the design guidance of the locally resonant structure with multiple secondary oscillators is proposed to provide practical guidance for application. Finally, a practical periodic specimen is designed and fabricated, and then an experiment is carried out to validate the effectiveness of periodic suppressors in the reality. The results show that the experimental band gaps have a good coincidence with those in the theoretical model, and the low-frequency vibration of the plate with periodic suppressors can be effectively reduced in the tuned band gaps. Both the theoretical results and experimental results prove that the design method is effective and the structure with periodic suppressors has a promising application in engineering.

1. Introduction

Enhancing structure stiffness [1–4] and utilizing dynamic vibration absorbers [5–9] are two general measures to control structure vibration response to low frequencies in practical engineering. Increasing the thickness of [10] and adding stiffener [1,3] to the plate structures can enhance the stiffness. However, compared with the band gap effect of phononic crystals (PCs), the method of increasing thickness or adding stiffener causes a cost of larger mass. Dynamic vibration absorbers with single

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degree of freedom can only reduce vibration transmission in a specific narrow frequency band [5]. To overcome the difficulties in controlling low-frequency vibration response, plenty of related research has been conducted on the topic of phononic crystals (PCs) [11–19] over the past decades. The band-gap property in PC helps reduce vibration and attenuate wave propagation in the band gaps (BGs). Two main mechanisms of PCs in existing literature are Bragg scattering mechanism [11] and locally resonant (LR) mechanism. The Bragg-scattering band gap is caused by structure periodicity in space, and the locally resonant band gap is mainly formed by resonant modes of resonators. In 2000, Liu et al. [14] first proposed the concept of LR mechanism by fabricating a type of LR PC containing an array of LR units. A resonance-type band gap in low-frequency range was achieved in his research. It has also been proved that LR PC can generate novel physical properties, such as negative mass density [14,20,21], negative modulus [22–24], and both [25–27] negative parameters. In general, the periodic structure with these negative properties is considered as acoustic metamaterials.

Arranging an array of periodic resonant elements on the surface of structure is of great importance to control vibration in LR PC research [28–31]. In 2012, Xiao et al. [30] studied a locally resonant plate with periodically attached spring-mass resonators. In his study, the resonator was considered with single degree of freedom, so there existed only single band gap. In order to improve the deficiency in previous study, Xiao et al. [32] proposed a new type of LR PC composed of multiple double-cantilevered thin beams in 2014. By attaching periodic elements to a thin homogeneous plate, multiple low-frequency band gaps were formed. Currently, researchers are focusing on obtaining more band gaps, broader band-gap widths and some other properties. They have made great achievements in researches on multiple frequencies [32–35], adjustable frequency [36–38], and nonlinear vibration control [39,40] in recent years.

In this paper, a periodic vibration suppressor with multiple secondary oscillators based on the locally resonant band-gap mechanism is examined. In previous research, the number of degrees of freedom for the locally resonant unit in the structure was set as one [34] or two [19], so there only formed one or two band gaps. In this paper, the number of degrees of freedom for the locally resonant unit is extended to be arbitrary by proposing the structure with multiple secondary oscillators. By using the proposed structure, more band gaps can be obtained, and thus this locally resonant structure can reduce vibration in broader band-gap widths. Besides, a generic theoretical model is established to solve the problem related to arbitrary number of degrees of freedom for the locally resonant unit. Thus, the structures in previous researches related to single and double degrees of freedom for the locally resonant structure become two special cases in the theoretical model proposed in this paper. In addition, the determination algorithm of suppressor parameters at given frequencies is also given in this paper to obtain multiple band gaps of the vibration-suppression structure and also to provide practical guidance for the design of the locally resonant structure with multiple secondary oscillators. According to the band-gap theory and parameter designing algorithm, a practical periodic specimen is designed and fabricated. In order to verify the theoretical model, the corresponding experiments are carried out. The experimental result shows that the low-frequency vibration of the structure with periodically attached suppressors can be significantly reduced when the band gaps are tuned to low-frequency range.

2. Structural dynamics model

A thin homogeneous plate periodically attached with an array of composite vibration suppressors is shown in Fig. 1(a), and a unit cell of the periodic structure is shown in Fig. 1(b). The model consists of a bottom spring-mass oscillator ($k_1 - m_1$) and $g-1$ secondary spring-mass oscillators ($k_2 - m_2$, …, $k_g - m_g$). In order to facilitate the theoretical derivation, complex stiffness is used. The term $k_j = k_{rj} + \mathrm{i}\cdot\omega c_j = k_{rj}(1+\mathrm{i}\cdot\eta_j)$ is the complex stiffness of the $j-\mathrm{th}(j=1,\cdots,g)$ spring, where k_{rj} is the stiffness of the spring, $c_j = \omega\eta_j k_{rj}$ the damping factor of the spring damper, ω the angular frequency and η_j the loss factor. In Fig. 1(a), each vibration suppressor is attached at the position of $\mathbf{R} = \overline{m}\mathbf{a}_1 + \overline{n}\mathbf{a}_2$, where $\mathbf{a}_1 = (a_1, 0)$ and $\mathbf{a}_2 = (0, a_2)$ are the basis vectors of a lattice. The terms $\overline{m}$ and $\overline{n}$ are the array numbers in x direction and y direction respectively.

2.1. Band gap calculation

The vibrational governing equation of the coupling system shown in Fig. 1(a) is given by

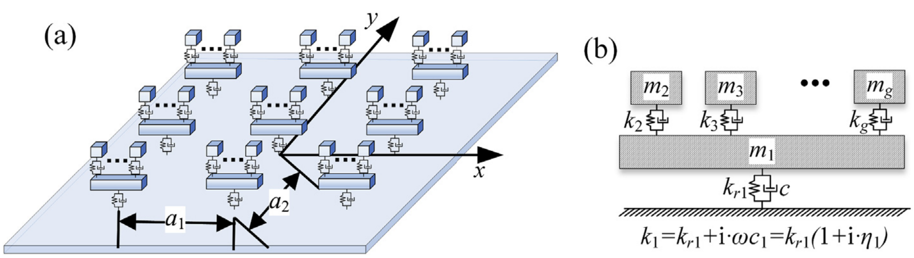

Fig. 1. (a) Schematic diagram of a thin plate with a two-dimensional periodic array of attached composite vibration suppressors. (b) A unit cell of simplified physical model of a composite vibration suppressor.