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Flexural wave attenuation in a sandwich beam with viscoelastic periodic cores

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ABSTRACT

The flexural-wave attenuation performance of traditional constraint-layer damping in a sandwich beam is improved by using periodic constrained-layer damping (PCLD), where the monolithic viscoelastic core is replaced with two periodically alternating viscoelastic cores. Closed-form solutions of the wave propagation constants of the infinite periodic sandwich beam and the forced response of the corresponding finite sandwich structure are theoretically derived, providing computational support on the analysis of attenuation characteristics. In a sandwich beam with PCLD, the flexural waves can be attenuated by both Bragg scattering effect and damping effect, where the attenuation level is mainly dominated by Bragg scattering in the band-gaps and by damping in the pass-bands. Affected by these two effects, when the parameters of periodic cores are properly selected, a sandwich beam with PCLD can effectively reduce vibrations of much lower frequencies than that with traditional constrained-layer damping. The effects of the parameters of viscoelastic periodic cores on band-gap properties are also discussed, showing that the average attenuation in the desired frequency band can be maximized by tuning the length ratio and core thickness to proper values. The research in this paper could possibly provide useful information for the researches and engineers to design damping structures.

1. Introduction

The sandwich structure has been widely used in the last half century, and numerous papers about its dynamic behavior, structural types, and industrial applications can be found in the available literature, which has been reviewed by Herakovich [1], Caliri et al. [2], and Mouritz et al. [3]. In most cases, the sandwich structure is composed of two face sheets with high strength and a middle core with low strength and low density. The stiffness and strength of this configuration is much greater than that of a single plate made of the face material with the same weight. This is because the two faces are set a certain distance apart by the middle core, which will significantly increase the moment of inertia and the flexural rigidity of the sandwich structure. As a result, this type of configuration provides a simple but efficient way for designers to obtain a high stiffness/strength to weight ratio, which is a crucial factor in some industrial fields where reducing weight is a major concern.

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The dynamics of a sandwich structure have been examined theoretically, including equivalent single-layer theory [4], layerwise theory [5], and zig-zag theory [6], which has been reviewed by Hajianmaleki and Qatu [7]. Apart from these new theories, there is also research into new sandwich configurations to meet the requirements of various engineering applications. The differences between these new configurations mainly lie in the material and topology of the core, including but not limited to a honeycomb core [8], auxetic core [9], porous core [10], viscoelastic core [11], fiber-reinforced core [12], and, more recently, the electrorheological and magnetorheological cores [13,14]. These different configurations are designed to solve problems encountered in various engineering fields.

As lightweight sandwich panels vibrate easily and thereby cause noise problems when subjected to random excitations, some mechanical structures made of light sandwich panels may suffer fatigue from excessive vibration. In order to solve the associated vibrational and acoustical problems, efforts have been made to embed viscoelastic material (VEM) into the sandwich structure, based on the concepts of constrained-layer damping (CLD) treatment [15–17] and free-layer damping treatment [18–20]. As the VEM typically possesses heavy damping—providing an energy dissipation mechanism for reducing noise and vibration [21]—the dynamic and acoustical performance of this sandwich structure can be significantly improved by the large shear deformation of the VEM core. Because of its great potential in vibration and noise control, this damping treatment technology has been successfully applied to aircraft skins, submarine hulls, and automobile panels [22–24].

However, the wave attenuation performance of CLD caused by VEM core damping varies with frequency [25]. In General, the performance improves with increasing frequency, with more attenuation in the relative higher frequency and less attenuation in the relative lower frequency for the same damping parameter. This is partly because the lower frequency wave has a longer wavelength and the shear strain energy dissipated per unit length is less than that at higher frequency. Generally in the practical engineering, the CLD treatment may be ineffective in vibration control in the lower frequency range below several hundred hertz, where the attenuation could be less than 3 dB in unit length. Efforts have been made to improve the corresponding lower-frequency attenuation performance by using active or smart CLD treatments [26–28], where the constraint layer is made of piezoelectric or smart material instead of elastic material. As a result, passive control from the VEM damping and active control from the piezoelectric layer are combined to improve the CLD performance. However, the hybrid control system is quite complicated and expensive, and it is difficult to apply this control strategy to complex structures, which has limited the application of active and smart CLD. Hence, CLD requires further improvement by using some new and simple methods.

In recent decades, studies of phononic crystals and metamaterials have generated significant interest in the fields of vibration and noise control [29–35] because of their band-gap properties. Phononic crystals and metamaterials are generally constituted by periodic cells. Due to the spatial periodicity, a “filtering” phenomenon arises in the periodic structure, where the waves propagate freely in the pass-bands and attenuate in the band-gaps. Owing to the development of theory, design, and application of periodic structures and widely use of sandwich structures in the practical engineering, the research of periodic sandwich beam or sandwich plate has gradually been studied. In 2002 and 2003, Ruzzene et al. studied the wave propagation of a periodic sandwich beam [36] and plate [37,38] with a specific focus on the effect of periodic auxetic cores on the band-gap properties, where the auxetic core had a negative Poisson's ratio and thereby provided increased shear modulus and compressive strength. Then, this work is extended by Wen et al. [39] in 2007 where the effect of anxetic core parameters on band-gap was further studied. Also in 2007, an experimental study of a sandwich beam with periodical and graded cores was studied by Lyckegaard et al. [40] where a graded stiffness was obtained due to the variation of the beam diameter. In his study, the focus was not on the band-gap property but on improving the transverse stiffness. In 2008, Badran et al. [41] studied the vibration characteristics of a periodic sandwich beam by finite element method, which shows better performance in the band-gap when the core was designed with a very hard core (harder than the face sheet) and a soft core. More recently in 2014, Chen et al. [42] studied a sandwich structure with periodic assemblies, and examined the effect of elastic foundation and moving load on the propagation characteristic.

The above researches studied the periodic sandwich beams or sandwich plates in various views and help to improve the understanding of periodicity in sandwich structures. However, in these above researches of periodic sandwich structures, the core was considered as purely elastic where the Bragg scattering effect caused by periodicity was examined, while the damping of core material was neglected which also had attenuation of contribution in and out of the band-gap in phononic crystals and metamaterials [43–46]. Apart from these studies, Yeh [47] has also studied the wave propagation in a homogeneous beam periodically covered by partially constrained layers, where a unit cell is constituted by a sandwich beam element and a homogeneous single layer beam element. In this structure, the core was used by viscoelastic material where damping was considered. However, only longitudinal wave propagation was considered and the band-gap frequencies were located in ultrasonic domain. As in the vibro-acoustic practical engineering, the flexural wave propagation in the sandwich structures is most concerned owing to its strong radiation property, thus studying the attenuation of flexural wave has practical meaning.

Inspired by the attenuation ability of periodic structure, phononic crystal, and metamaterial, the CLD treatment could be possibility improved when periodicity is introduced in the damping layer. Currently, the attenuation of flexural wave in a sandwich beam where the cores are constituted by a hard VEM core and a soft VEM core alternated along the axial direction has not been well addressed, where the overall attenuation are caused by both Bragg scattering and material damping. This type of configuration can be considered as a periodic constrained-layer damping (PCLD) treatment, which can be used to improve the performance of a CLD treatment in vibration suppression. As the vibration in the band-gap could be reduced by