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Asymptotic analysis for composite laminated plate with periodically fillers in viscoelastic damping material core

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ABSTRACT

A novel functional structure which can generate large structural loss factor (LF) in low frequency is designed in this research. The free flexural dynamic characteristics of composite laminated plate (CLP) cored with viscoelastic damping material (VDM) are studied by considering its frequency- and temperature-dependent properties. The heavy-density-material-rods (HDMRs) are periodically embedded into CLP. CLP's in-plane variables are obtained by classic laminated plate theory (CLPT) first, and then substituted it into the equilibrium equations which are derived from the Hamilton's principle, the flexural and shearing deformation compatible equations according to the mechanism of a primitive cell. The analytical deformation equation of the CLP is solved by the second order "rapid" asymptotic method, and LF is obtained, subsequently. The parameters that affect the LF are thoroughly analyzed. The validity of the research is verified by FEM. The research show the advantages of the presented CLP which could be applied in engineering under low frequency zone, especially in 1–200 Hz.

1. Introduction

CLP is utilized extensively in mechanical, aviation and aerospace, marine and naval structure, and other engineering structures for its excellent mechanical characteristics, such as high bending resistance and strength with little weight penalty. Viscoelastic damping material (VDM) is not only low in weight and cost, highly reliable, and easy implementation, but also has a commendable feature in vibration absorbing and control ability on lightweight and flexible structures [1,2]. VDM cored CLP have been researched for a long time. At the beginning of 1960s, Mead [3,4] initiated studies on the vibration mechanical of the sandwich pate with VDM core. Since then, more and more researches have been conducted in the area of the dynamics of the composite structures with VDM core. Rao and his co-workers [3] researched the dynamics properties (Such as modal frequency and modal LFs) of VDM cored beam by finite-element-based modal strain energy method. Applying GHM method to describe the frequency-dependent properties of VDM, Wang et al. [4] presented modes analysis of CLP by Galerkin assumed modes method and experimental method. By applying the refined FEM and based on the layer-wise shell theory, Oh [5] developed and researched the viscoelastic damping model of the cylindrical hybrid panels with difference boundary conditions. By considering the frequency-dependent properties of VDM, applying Carrera's Unified Formulation, Ferreira et al. [6] presented a layerwise finite element model researched the CLP with VDM core. And, there has been a lot of established calculation theories and methods, for example, layerwise deformation theory [2,6], finite element method [7,8], asymptotic analysis [9,10] and shear deformation theory [11]. Zhou et al. [12] presented a comprehensive summary about the calculation theory and method of VDM formed structures. In general, FEM is a convenient, powerful and fast numerical method to calculate the dynamic characteristics of engineering structures, especially the complex structures, but the calculation accuracy usually decreases as the frequency increases if the mesh size of the structure could not satisfy the calculation requirement, especially in high-frequency zone. In order to achieve a highly accuracy results, refine the mesh size, guarantee that the mesh size should 10–20 times smaller than the wavelength of the highest research frequency [13,14], therefore the calculation will be time consuming. The other three previously listed methods are all analytical calculation methods, which can provide analytical solutions for the

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dynamic characteristics of the structure under defined assumptions with relatively high calculation accuracy that satisfies engineering requirement. In this research, the asymptotic analysis method (AAM) is applied due to the HMDRs distributed periodically in CLP; a primitive cell can be taken out and calculated by this method, therefore. The AAM can simplify the calculation and provide relatively accurate solutions, especially for periodical and quasi-periodical structures [15–18].

It is known that the damping ratio of the damping material is large in high frequency zone according to the mechanics theory of VDM in engineering structures. The vibration of engineering structures and facilities, such as aerospace equipment, aero crafts and vehicles, whose vibration and noise is concentrated in low and medium frequency, therefore, a relative large LF is needed in such frequency zone. After Liu et al. [19,20]constructed and found the low frequency energy band-gap in low frequency with locally resonant structure (LRS), many researches show that a large LF could be obtained if heavy density materials are filled in VDM, which is a practical way to deal with low and medium frequency vibration [21]. On the other hand, the physical properties of the CLP, such as stiffness and damping, are altered by the embedding structures or materials.

There have been many investigations developed to study the structures or materials embedded in a composite medium to change its physical properties, such as nanosprings and nanorods [22], nanotubes [23,24], shape memory alloy (SMA) [25], and heavy density material structures (such as lead or tungsten ball and rod, etc.) [19,26]. To actively control of the vibrations, Ganilova and Cartmell [27]applied hybrid WKB–Galerkin method to exam the novel composite plate periodically embedded with SMA. Focusing on the design, fabrication and testing, Zhang et al. [28] researched the energy absorption characteristics of SMA embedded composites, and concluded that the composite structures embedded with SMA increase in energy absorption as high as 600% compared to non-embedded composite structures. To restrict vibration of structures, carbon nanotubes are embedded in an elastic/plastic medium [29–32]. Natsuki et al. [30]presented analytical models of wave propagation in single- and double-walled carbon nanotubes embedded in an elastic matrix described by a Winkler model, and find the wave behaviors of single- and double-walled nanotubes differ significantly. Based on a multiple-elastic beam model, and considered inter-tube radial displacements and the related internal degrees of freedom, Yoon et al. [29]studied resonant frequencies and the vibration modes of an individual multiwall carbon nanotube embedded in an elastic medium, and compares them with those of the single beam modal under difference surrounding elastic medium.

The present analysis continue to the former research [10], the mathematic model in refer [10] is a CLP with periodically perforated VDM core. One important results of the former research is that a LF larger than 0.3 can be obtained in medium and high frequency (250–1000 Hz), but the LF still small in low frequency. Based on the mass effect of damp ratio in low frequency and the locally resonant theory [19], the HDMRs are embedded in the VDM core layer, and an analytical solution is obtained. The researches show that a large structure LF (>0.5) can be obtained in low frequency, especially in the range of 1–200 Hz. Therefore, the structure could be as a novel structure applied in aerospace and aviation where the vibration in low frequency that needs to be solved urgently. In general, the mainly differences between the two researches are: i) the model of [10] have periodically perforated VDM core, and the presented analysis model have a VDM core which embedded periodically by HDMRs; and ii) the relatively large LF of refer [10] concentrated upon 250–1000 Hz, but the presented analysis focus on 1–200 Hz.

2. Modeling and mathematical formulation of the sandwich plate

The mathematical model of the CLP embedded with HDMRs in VDM core is shown in Fig. 1, and the CLP contains four parts: two face layers, VDM cored layer and HDMRs.

The mathematical model of the CLP is shown in Fig. 2(*a*), and a unit cell of the CLP with boundary is shown in Fig. 2(*b*).

The material distribution and the dimensions of the thickness of a unit cell are showing in Fig. 3, where t_i indicates the thickness of *ith* layer.

The middle layer of the structure is constructed by VDM and HDMRs, and the physical properties of the two kinds of materials vary widely. Meanwhile, the top surface of the HDMRs does not reach the bottom face of the top face layer, and the bottom surface of HDMRs does not touch the top face of the bottom face layer in order to form a LRS in CLP, and obtain significant vibration reduction in low frequency. The core layer is divided into three layers, namely, the top-, middle-, and bottom-layer of the core (denoted as TLC, MLC and BLC respectively), as shown in Fig. 4, denote its thickness as t_{2t}, h and t_{2b}. The diameter and height of the HDMRs are denoted by R and h, respectively.

The derivations of this research relay on the following assumptions: (1) the laminate thickness is very small compare to its other two dimensions. (2) The layers of the sandwich are perfectly bonded. (3) Lines that perpendicular to the surface of the lamination remain straight and perpendicular to the surface after deformation. (4) The middle plane of the sandwich plate is half as thick as the CLP. (5) The shear strain and rotational inertia in the face plates are ignored. (6) The HDMRs and the VDM layer are perfectly bonded, the material will not slip appear while deform.

2.1. The in-plane variables calculation

The in-plane displacements and shear deformations of the unit cell are showed in Fig. 5.

Let u_i and v_i ($i = \{1,3\}$) denoted the in-plane displacements in x and y directions at the points of the top and bottom layers in the middle planes respectively as shown in Fig. 5, and then Eq. (1) could be obtained according to [2].

$$\begin{cases} u = u_0(x,y) + z\dfrac{\partial w(x,y)}{\partial x} \\ v = v_0(x,y) + z\dfrac{\partial w(x,y)}{\partial y} \\ w = w_0(x,y) \end{cases} \tag{1}$$

where, u_0, v_0 and w_0 are the displacement along x, y and z axis at middle face of the core layer.

Let u_{2t}, v_{2t}, $\gamma_{xz,2t}$ and $\gamma_{yz,2t}$ (u_{20}, v_{20}, $\gamma_{xz,20}$ and$\gamma_{yz,20}$; and u_{2b}, v_{2b}, $\gamma_{xy,2b}$ and $\gamma_{yz,2b}$ respectively) be the in-plane deformations and the shear deformations in xz and yz plane for TLC (MLC and BLC respectively). According to the symmetry property of the structure, it is easy to obtain that $u_{20} = u_0$, and the in-plane deformations of first and third layer can be written as in the forms in Eq. (2)

$$\begin{cases} u_i = u_0(x,y) + \dfrac{t_2 + 2t_i}{2}\dfrac{\partial w(x,y)}{\partial x} \\ v_i = v_0(x,y) + \dfrac{t_2 + 2t_i}{2}\dfrac{\partial w(x,y)}{\partial y}, i = 1,3 \\ w = w_0(x,y) \end{cases} \tag{2}$$