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Asymptotic analysis on flexural dynamic characteristics for a laminated composite plate with embedded and perforated periodically viscoelastic damping material core

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ABSTRACT

In this paper, the flexural dynamic characteristics of a laminated composite plate (LCP) with fillers and perforated periodically viscoelastic damping material (VDM) core is researched, which is the succession research of refer (Zhou et al. 2015) that could obtain highly effects of vibration energy absorption and dissipation in medium and high frequency, and refer (Zhou et al. 2016), in low frequency. By considering the frequency and temperature properties of VDM, applying the zig-zag theory (ZZT), the equilibrium equations are built by the extended Hamilton's principle (EHP), and the flexural and shearing deformation compatible equations, and then solved the equations by "rapid" second-order asymptotic expansion method (SAEM) according to the geometry characteristic of the constructed structures, and the opening ratio (OR), filling ratio (FR), the density of embedded material and the height of viscoelastic damping layer which affected the flexural dynamic characteristics of the composite structures are researched thoroughly, and the validity of the calculation is verified by finite element method and the advantages of the composite structures are demonstrated meanwhile.

1. Introduction

Due to its low mass, high stiffness and modulus and long fatigue life, laminated composite plate (LCP) and laminated composite shell (LCS) constructed by difference material are applied extensively in engineering structures, such as aeronautics, astronautics, navigation, civil engineering, mechanical and transportation equipment, especially the fields that required the structures with high stiffness-to-weight and strength-to-weight ratios, for thus of the low density and light in mass of the original laminated composite plate, its vibration dynamics properties should be considered, which could effected the stability, security, fatigue properties of the equipment. Meanwhile, taking consider the dynamics vibration energy absorption and dissipation, the VDM is considered as an effective method to isolate and reduce the vibration energy of laminated composite plate, to reserve its properties of high stiffness and modulus, the VDM is formed as core layers of laminated composite plate, and the composite structures with VDM core layer has researched by extensively scholars and researchers [3–11], and utilized extensively in the engineering structures where the vibration level should be in a safety and comfortable range, which could convert and transmit the mechanical dynamics vibration energy into the other type, such as electric energy that could be stored, and heat energy, which could be dissipated, and the dynamics vibration will be reduced or controlled eventually. By applying Hamilton's principle and Donnell-Mashtari-Vlasov simplification, Hu and Huang [3] presented a mathematic model and derived the general differential equations of a three layers laminated composite shell have with VDM core, the model of which just contains three displacements variable, and the traditionally existing model contains 5 variables. By assuming the core layer of LCP which could not be compressible, and the described the extension and shear modulus by complex qualities, Wang and Chen [4]researched the natural frequencies and modal loss factors of the three-layered annular plate with a VDM core layer, and concluded that there have three regions and a relatively large damping region exist by the increase of the modulus of VDM.

Based on the linear and nonlinear variations of the displacement distribution through the thickness of the core layer, Mohammadi and Sedaghati [9] analyzed the damping characteristics of

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three-layered sandwich cylindrical shell for thin and thick core viscoelastic by applying semi-analytical finite element method layers, and they pointed out that the imperfect bonding between the layers of the LCP could affect the loss factor (LF) of the majority of modes. In view of this point, in the analytical solve, all layers of the composite structures are assumed perfected and this did not slippage between the interfaces, as refer [1,2].

There have been several calculation theories to solve the dynamics characteristic of laminated composite plate, named laminated theory, which could be classified as three types: equivalent single layer theory (ESLT), layer-wise theory (LWT) [12–17]and Zig–Zag theories (ZZT). And furthermore, ESLT could be categories as classical laminated plate theory (CLPT) [18], first-order shear deformation theory (FSDT) [19–21], and higher-order shear deformation theories (HSDTs) [22–24]. By considering the working mechanical of the cored layers of the present laminated composite structures, the applicability of each theory and to improve the calculation accuracy, LWT is applied in this research, and compared it by the CLPT.

In generally, according to the wave transition and propagation, and the periodic of shear deformation, the energy absorption and transition of vibration energy of the laminated composite structures which embedded with VDM layers shows highly effective in medium and high frequency, but its effect in low frequency is very limited. To change the properties of VDM structures, such as damping ratio, friction coefficient, modulus and strength, other material or structure are embedded in VDM, such as for example, carbon nanotubes [25–29], carbon nanofiber [30–32], nanosprings [33] and heavy density materials [2]. Guedes et al. [25] prepared the multi-walled carbon nanotubes reinforced viscoelastic material with volume fractions ranges from 0.2 to 1%, and researched the dynamic mechanical properties of the composite structures by experiment in difference frequency (0.1–100 Hz) and difference temperature (22–82 degrees), and pointed out that the multi-walled carbon nanotubes could not seem affected the nature frequency of the nanotubes filled composite structure, but its storage modulus will increase with an increase of temperature when the volume fraction are 1 wt.%. As all of the researchers known that the storage modulus affected the energy storage and dissipation of viscoelastic material strongly, therefore, the changes of storage modulus could finally change the structural loss factor (SLF) of the VDM composite, meanwhile, in order to widen the working temperature of VDM, the nanotubes are also filled into the VDM, such as [34], the glass transition temperature and storage modulus are increased at a small volume fractions (1 wt.%). In the points of the storage modulus changes by the multi-walled carbon nanotubes, the results obtained by [34] and [25] shows high consistency. Montazeri [26]researched dynamics properties of the VDM and the multi-walled carbon nanotubes composite material, concluded that the existing of fillers could increase the loss modulus and the damping of the composite. Same as the nanotubes filled VDM, the research of the nanofibers is focus on the damping and storage values, but the fiber orientation and fiber aspect ratios should be taken into considering at the same time of fiber volume fractions, such as Finegan et al. [30] presented an analytical and experimental investigations of the dynamic mechanical properties of carbon nanofiber and VDM composites, and the research shown that the damping of the composite decreased by increasing of fiber volume fraction, and the LF decreases as the fiber aspect ratio decreases, if the aspect ratio reaches a proper value, there will be yields the highest LF. Continue to refer [35], Zhou et al. [36] researched vibration energy transition properties about the structures which filled VDM material periodically in stiffened plate structure, based on and improved the super element method, by changing the propagation characteristic of the composite structure, and finally obtained the vibration energy transition properties in lower frequency zone. Therefore, changing dynamics properties of VDM composite by fillers and then obtain a desired value of the composite structures in a reasonable scope is a feasible and implementable method. More information about the calculation methods and theories of VDM contained structures and its composite could be checked in [37].

By taking account the frequency- and temperature-dependent properties of VDM, the present paper is a series and further research of the refer [1] and [2], the research of [1] shows that the LCP with periodically perforated VDM core layer could obtain a relatively large SLF in medium and high frequency, especially in ranges of $250 \sim 1000$ Hz, and the value is $3 \sim 5$ times larger than the non-perforated VDM core layer composite plate, even if the OP is small(12.57%), however, the SLF in low frequency are still small, which is smaller than no-perforated composite plate, especially in $1 \sim 250$ Hz, by considering the vibration of most equipment and structures are focus in low frequency, and based on the locally resonant theory, the laminated composite structure which has a VDM core layer that embedded periodically by heavy density material [2], and the research shown that there did existence a relatively large SLF in low frequency, especially in ranges of $1 \sim 200$ Hz, and the SLF could reach to 0.7 in defined frequency and temperature, but, it is dissatisfied that the SLF in the frequency large than 200 Hz is very small, and even smaller than 0.1 in most considered frequency in all considered temperature, so, it could not satisfy the structures that working in medium and high frequency. Then, the presented paper formed a novel laminated composite structure whose core layer are coupled the perforated and embedded heavy density material based on VDM, and the research shows that the SLF in the considered frequency and temperature could achieve a desired value.

The rest of the paper is organized as follows. The modeling and mathematical formulation of the sandwich plate are described in Section 2, which contains establishment of strain energy and kinetic energy of a unit cell and its equilibrium equations based on the EHP. In terms of research theory, method and differential equilibrium equations are same as the research of [1,2], the process of the equation derivation and reduction in detail will be not shown in this paper, therefore, numerical analysis and result comparison as the following section, are illustrated in Section 4. Finally, discussion and conclusion are given in Section 5.

2. Modeling and mathematical formulation of sandwich-plates

The schematic diagram of LCP with periodically perforated and embedded with heavy-density-material-rods (HDMRs) is shown in Fig. 1(a), and its geometry dimensions and boundary of the perforated and embedded structures is shown on Fig. 1(b), the red parts are HDMRs, according to the periodically properties the perforated parts are constituted by four quarter circles.

The material distributes in the height of a primitive cell is shown in Fig. 2, which contains four types material in this research, the top and bottom layer are the traditionally engineering material, such as aluminum and 1045 steel, and the black part is the heavy density material, and the value defined here is large than 10 g/cm^3, such as the tungsten and plumbum, whose density are 19.36 g/cm^3 and 11.34 g/cm^3. The HDMRs is embedded in perforated VDM layer, and which formed as the core layer of the researched structure together.

The LCP is divided into 5 layers in the calculation as shown in Fig. 3, and the second and fourth layer are named top core layer (TCL) and bottom core layer (BCL), and the third layer is called middle core layer (MCL).