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Research on the low frequency band gap properties of periodically composite stiffened thin-plate with fillers

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ABSTRACT

In this paper, a new composite stiffened thin-plate (CSTP) is developed, the filler is distributed periodically in the viscoelastic damping material (VDM), and the simplified-super-finite-element (SSFM) is employed in the analysis. According to the periodical properties of the CSTP, a primitive cell is extracted, which is divided into six parts according to *n*-order Lagrangian element (LgE). After each parts' mass, stiffness and damping matrices are obtained, the global matrices are assembled by standard direct stiffness method (SDSM). The filler's mass is considered as lump mass loaded on the defined LgE's nodes, and the filler's number is determined by the LgE's order. Then, the element matrices are simplified and compressed by Bloch's theorem. Finally, the band gap properties of the CSTP are determined according to the eigenvalues problems, and the parameters of the structures (such as the filler's mass, the VDM's damping ratio and the lattice constant, etc.) which affect the band gaps are examined thoroughly. The results show the existence of full band gap (FBG) in low frequency. Meanwhile, the results are validated by the finite element method (FEM), which show good consistency.

1. Introduction

Thin-plate is applied extensively in engineering structures and equipment due to its prior mechanical and manufacture properties, easy form and construct to a close environments and spaces, such as the automobile body-in-white, aerospace and aviation structures (such as aircraft fuselages, and ship hulls), and even the liquid tankers, etc. Therefore, the thin-plate is considered as a fundamental parts and structures in the engineering, but due to its large width-height ratio (could be consider also the length-height ratio), its mechanical vibration and sound radiation should be taken into consider, especially in the modern equipment and structures. Therefore, the stiffened plate (SP) is applied to increase the thin-plate's stiffness and strength, resist the deformation and vibration finally. There have so many researchers and scholars researched the statics and dynamics properties of the stiffened-thin-plate, Thorkildsen and Hoppmann [1] may be the pioneer researcher on the SP. Based on the FEM, Koko and Olson [2] developed the super-element-method and researched the non-linear large deflection elastic-plastic properties of SPs. By applying FEM, considering the contact and transverse shear deformation between the thin-plate and stiffeners, Gong and Lam [3] analyzed the transient response of a CSTP subjected to low velocity impact thoroughly. Rikards et al. [4] researched the modal frequency of a CSTP by the first-order shear deformation, and validated the results by experiment. By applying Fourier transform method, Ji et al. [5] approximated the equilibrium and continuity conditions along the interface between the beam and the plate, estimated the vibrations of beam-stiffened plate systems. In refers [6–8], Loughlan et al. researched the buckling and post-buckling behavior of the SP structures deeply.

By considering it reinforced functions, the stiffeners applied in the engineering structures are distributed periodically in most case, therefore, the periodical theories are introduced into the analysis, to research the dynamics properties of the SP, especially its wave propagation characteristics in frequency fields. In his series researches, Jędrysiak [9–11] researched the periodically thin-plate structures, especially the periodically SP. By applying the virtual energy method, Lee and Kim [12] developed an analysis research method, studying the sound transmission characteristics of a periodically SP. By considering the force and moment coupling between the stiffeners and the base plate, basis of flexural-torsion coupling equations, Shen et al. [13] analyzed the sound radiation of the periodically orthogonal CSTP based on layer-wise shear deformable theory. By applying central-finite-difference-method, Zhou et al. [14] analysis the transverse transmit wave propagation

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properties of periodically stiffened thin-plate, and discussed the factors which affected the band gap of the stiffened thin-plate. In order to dissipation more vibration energy in the SP, the VDM is applied between the stiffeners on the thin-plate [15], the research illustrated that the damping ratio of VDM affected the band gap of SP, especially in middle frequency. It should be noticed that Gupta and his coworkers [16–18] may be the original researchers who applied VDM in SP and they researched the periodically stiffened thin-plate with damped stringers thoroughly. For example, they studied the free vibration properties of SP with VDM is patched on the flanges of the stiffeners by FEM [16], and researched the periodically SP and CSTP which contain VDM on the stiffeners [17,18]. After then, there have more and more scholars investigated the CSTP with VDM. By applying strip FEM, Loughlan [8] studied the buckling performance of the CSTP with carbon-epoxy composite material. Considering the energy dissipation properties of VDM, Blake et al. [19] developed a new type of stiffened thin-plate structure, they filled the VDM in the base of the close form stiffeners. Neglecting the coupling effects between the direct and the converse piezoelectric, Mukherjee et al. [20] presented active vibration control of SPs by piezoelectric material, in their research, the stiffener is not needed pass the node of mesh line, therefore, it could be applied to research any shape of stiffener.

As is known that the vibration and sound radiation of thin-plate focuses on low frequency, but the vibration energy dissipation by VDM is not so efficient in low frequency. By considering the locally resonant theory [21] and taking account the mass effect in the vibration reduction, we embed the fillers in the VDM. Three reasons are given as follows: (1) Modifying the VDM's physical parameters(such damping ratio and the shear modulus) by embedding the nano-particle or nano-structures in VDM [22,23], more detail could be found in [24]. (2) Building a special periodically structure that could generate more shear deformation, and dissipate more wave transition energy [25]. (3) Developing a locally resonant structures, and obtaining low frequency band gap as refer [21], or getting a large structural loss factor in low frequency [26,27]. The current analysis is based on the periodically SP theory, the application of VDM and its embedded structures, to develop a novel structure. The analysis results show that the fillings of filler could provide low frequency band gap, and the band gap could be determined by changes of the CSTP's parameters, which provided a new method to deal with the low frequency elastic wave vibration in thin- and flexural-walled structures.

The rest of the paper is organized as follows: the model of periodically CSTP filled with fillers is outlined in Section 2. A solution procedure based on SSFM for the structure is described in Section 3. Then, results and analysis are presented in Section 4. Finally, conclusions and prospects are provided in Section 5.

2. Dynamics model of periodically stiffened plate filled with VDM

This current paper is the sequence researches about [14,15]. in the ref.[14], the authors researched the energy transitions properties of periodically SP by central-finite-element-method, obtained the parameters which affected the band-gap properties. By applying SSEM [15], the author analyzed the band-gap of the CSTP, which is developed based on the refer [14], the VDM is filled between two stiffeners, the dynamic vibration energy transition properties affected the CSTP's parameters are researched. The schematic diagram of the current analysis is shown in Fig. 1, and the primitive cell is shown in Fig. 2. It should be noticed that the filler's material applied in current research is a large density material, such as lead, tungsten and gold etc.

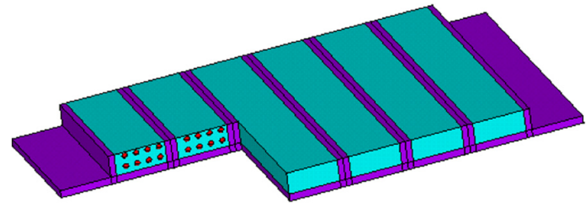

Fig. 1. schematic diagram.

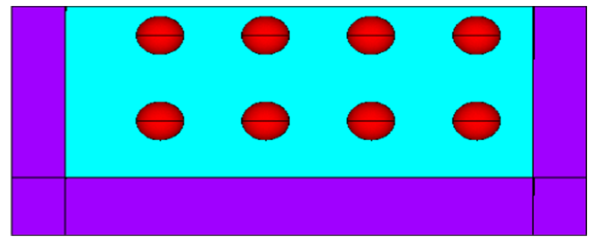

Fig. 2. Schematic of the primitive cell.

3. The model of CSTP with periodically fillers

3.1. Analysis assumptions

In calculation, the dynamics properties of the CSTP based on the FEM, the following assumptions are made: (i) The VDM is bonded perfect with the stiffener and the base plate; (ii) the filler's mass is (are) loaded on the internal nodes, and the fillers is distributed uniform in the VDM part; (iii) the filler's radius is far smaller than half of stiffener's height, the fillers and VDM contact well with each other; (iv) each node of LgE have two degree-of-freedoms (DOF), and which is denoted as $U = U(u, v)$; (v) due to the materials of base plate and stiffener are steel or aluminum, their damping ratio are neglected in the analysis; (vi) the existence of fillers will affect the element's mass matrix of the filler contains section, while the element's stiffness matrix affected by fillers will be ignored.

3.2. Shape functions of 2nd-order 9-nodes Lagrangian element

Different from the serendipity element which is applied in the ref [15], the Lagrangian element (LgE) is applied in this paper to show the location of the fillers distributed in the VDM and obtain a higher calculate accuracy. The LgE's order is determined by the number of the fillers in the VDM as shown in Fig. 2, and which finally defined the matrix's dimensions in the calculation. At the beginning of the research, 2nd -order 9-noded quadratic LgE is applied, which indicated that there only has one filler is embedded in the VDM in one period. The 2nd -order 9-nodes quadratic LgE is shown in Fig. 3(a). One filler embedded CSTP discrete by 9-nodes quadratic LgE is shown in Fig. 4.

Shape function (SF) of 9-node quadratic LgE

$$N_1(\zeta, \eta) = \frac{\zeta\eta(a + \zeta)(b + \eta)}{4a^2b^2} \tag{1a}$$

$$N_2(\zeta, \eta) = -\frac{\zeta\eta(a - \zeta)(b + \eta)}{4a^2b^2} \tag{1b}$$

$$N_3(\zeta, \eta) = -\frac{\zeta\eta(a - \zeta)(b - \eta)}{4a^2b^2} \tag{1c}$$

$$N_4(\zeta, \eta) = \frac{\zeta\eta(a + \zeta)(b - \eta)}{4a^2b^2} \tag{1d}$$