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Simplified-super-element-method for analyzing free flexural vibration characteristics of periodically stiffened-thin-plate filled with viscoelastic damping material

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ABSTRACT

Flexural vibration characteristics of a periodically stiffened-thin-plate filled with viscoelastic damping material (VDM) are researched originally based on a simplified-super-element-method (SSEM) according to Floquet–Bloch's theorem and super-element-method (SEM). The density, damping ratio (the parameters of the VDM), and the lattice constant of the structure, which impact the frequency characteristics of periodically stiffened-thin-plate, are thoroughly analyzed. The SSEM developed in this research ensured the accuracy and simplified calculation work. It can be used in designing a periodic or quasi-periodic thin plate and shell structures for improving the mechanical property. The advantages of this method are verified by comparing the structures that is and is not filled with VDM.

1. Introduction

Viscoelastic damping material (VDM) is utilized widely in mechanical structures in national defense, navigation, and aerospace industries for its decent engineering properties such as light weight, high reliability, and easy noise and vibration control. The traditional roles of its application usually are free layer damping (FLD), constrained layer damping (CLD), and partial constrained layer damping (PCLD).

The simplest application of the passive VDM is free layer damping (FLD). Earliest research in this area began in the early 1950s, such as Liénard [1], Oberst [2], and Mead [3]. At the end of 1950s, more and more researchers had studied VDM. They found that the CLD was very efficient in vibration reduction in thin-walled engineering structure. Kerwin [4] may be the first researcher who presented a quantitative analysis on the damping effectiveness of CLD, and he found the loss factor and became fruitful research achievement in his series papers [5,6]. After their research works, there were many works done by Di Taranto [7], Mead and Markus [8,9], Yan and Dowell [10], Kristensen et al. [11], Kumar and Singh [12], Sher and Moreira [13], and Lei et al. [14]. These scholars studied the vibration and noise radiation for thin plate, beam, curved panel, cylindrical shell, and sandwiched structures tackled by CLD. Of cause, their research method was different with each other. For example, FEM was applied by Wang and Chen [15], the modal strain energy method was applied by Mead [3,16], and experimental examination was performed by Kumar and Singh [12]. By researching on the mechanics of VDM deeper and deeper, more profound findings had been achieved. All researchers agreed that the shear phenomenon was the original source with which the VDM dissipated energy. This is believed that it is the original idea of partial constrained layer damping (PCLD), which can enlarge the shear deformation and energy dissipation, and it is also the theory and idea of present research.

PCLD is utilized extensively in engineering structure, which saves not only the VDM but also diminishes the form of the structural system, especially in the aerospace industry's application. Di Taranto [7], and Mead and Markus [8] mentioned PCLD in their work when they studied CLD. The pioneer, Plunkett and Lee [17], who researched PCLD firstly, optimized the length of constrained viscoelastic layer damping. Subsequently, in this field, a more thorough analytical study was carried out by Lall et al. [18,19] and Marcelin et al. [20]. Recently, numerous scholars have done research on PCLD. Among them, Zheng et al. [21], based on energy approach, derived the governing equation of the PCLD covered beam. They

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presented an optimization study with the aim to minimize the vibration energy of the beams treated with PCLD. Khalfi and Ross [22,23] analyzed the transient response of a plate dealing with PCLD which was excited by an impact load thoroughly. Maoût et al. [24] researched the optimization of a hybrid composite/elastomeric sandwich plate structure using a periodical pattern of VEM.

Due to strong rigidity, better mechanical performance, good structural vibration and noise restraint, stiffened structure has been widely used in many mechanical products. For example, it has been used in bridge, ship deck, ribbed floor, aerospace structures, automotive structures [25–27], etc. However, very few researchers explored the VDM stiffened plates. Zhou et al. [28] researched the periodically stiffened plate based on the central difference finite method, and obtained dynamic characteristic of the structure in the frequency domain. Gupta et al. [29] studied free vibration of a damped stiffened and periodically damped and stiffened of thin panel with applied VDM just on the flanges of the stiffeners by using FEM. Mead and Yaman [30] presented a wave analysis on the three layers of sandwich rectangular plate with a VDM core and parallel stiffeners that stiffened one of the face layers. Blake et al. [31] investigated the static structural response of stiffer which was reinforced by a fiber reinforced plastic (FRP) and filled partly with VDM. In Blake's numerical example, VDM was just filled underneath the stiffeners. In present works, the VDM was filled between stiffeners which is different from Gupta et al. [29] who patched VDM just on the stringers of the stiffer. Then, the modal frequency and loss factor were obtained. Different from Mead and Yaman [30] who stiffened sandwich plate on one side, Blake et al. [31] researched the VDM which was filled under stiffer. Reinhall and Miles [32] performed research for the dynamic vibration properties of periodically thin plate. In his series researches, Jędrysiak [33–37] researched the periodical structure deeply, especially the periodically thin plate in one and two directions. In Ref. [34], Jędrysiak proposed a new research method which could take into account the effect of the periodicity cell size of the dynamics vibration of the plate with two dimensional periodic structures, investigated the vibrations and resonance frequencies of uniperiodic plates. By applying the tolerance averaging method, Jędrysiak [36] derived the length-scale plate model of thin periodic plate interacting with a periodic Winkler foundation, and analyzed the higher-order free vibrations of the periodic thin plate system. Later on, based on the Kirchhoff plate theory assumptions and additional hypothesis of tolerance averaging, took into account the effect of the periodicity cell size on the overall plate behavior, Jędrysiak [33] presented an analytical solution about the higher order vibrations of two dimensional thin periodic plates by a tolerance averaging technique. In the present research, the distance of stiffer was set periodically, so that the VDM and stiffer on plates or shells were distributed periodically.

The elements 'super elements method (SEM)' are termed since only a single element is required to model the basic response which is based largely upon the finite element method (FEM) [38]. FEM [39] is a powerful numeric method applied frequently in structure calculation, especially in complicated and arbitrary boundary condition structure. There have been abundant literatures, but the calculation work and cost are very large when the structure gets large. It is not very accurate in middle and high frequency, meanwhile. SEM ensured the accuracy and simplified calculation comparing with FEM, especially for large simple structures. It can reduce the calculation amount significantly. However, it has deficiencies. For examples, the dynamic mechanical characteristics (mainly the frequency characteristic) are difficult to bring in. Also, if the unit cell is complicated, SEM is not able to simplify it very much. In this case, the calculation amount is still large. Therefore, the SEM is not so accurate in high frequency. Only when the mesh size is very small, the calculation work will increase significantly according to [40]. SSEM can deal with the problems well, especially in periodic or quasi-periodical structure.

This research aims at the factors which affect the frequency characteristics of periodically stiffened-thin-plate filled with the VDM. This plate is systematically researched by analyzing the VDM parameters (damping ratio and density), and the lattice constant of structure.

The novelty of this research is focused on (i) constructing the calculation method: a method to calculate dynamic characteristics of the periodic or quasi-periodic structure with a complicated unit cell was developed. The goal is to reduce the calculation burden and bring frequency characteristics in calculating algorithm. (ii) Constructing a new structure: stiffened plates were allocated periodically, and then the void space between stiffer was filled with VDM, which formed a composite periodic structure. Flexural vibration characteristics analysis was presented. The damping ratio that affected the flexural vibration characteristics of stiffened plates was researched based on the dynamics analysis. The research is different from the mentioned papers in references which just obtain the natural frequency and the loss factor of structure by static analysis. The structure constructed in this paper is in a broadband frequency, especially for low and medium frequency (LMF) which is a critical problem need to be solved in noise and vibration control field.

The rest of the paper is organized as follows: the free flexural vibration model of periodically stiffened plate filled with VDM is outlined in Section 2. A solution procedure based on SSEM 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

The schematic diagram of the periodically stiffened plate filled with VDM is illustrated in Fig. 1. The black part between the stiffer is VDM. The dimensions of which are depended on the distance of neighboring stiffer.

Isolating one circular element and discreting it with the serendipity element (SE) into 6 parts, the structure is shown in Fig. 2. In the figure, parts I and III are stiffer. Part II indicates the VDM, and parts IV, V, VI stand for the thin steel plate. Assume the stiffer and the plates are of the same material. Both materials are 1045 steel in this paper. The geometric dimensions of the structure are provided in Fig. 3, where $h1$ is the thickness of the base plate, $h2$ and $b1$ denote the height and width of the stiffer, respectively, and $b2$ stands for the width of VDM.

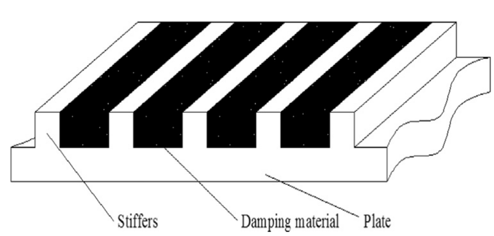

Fig. 1. Stiffened plate filled with viscoelastic damping material.