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Asymptotic analysis on flexural dynamic characteristics for a sandwich plate with periodically perforated viscoelastic damping material core

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ABSTRACT

The flexural dynamic characteristics of the cored sandwich plate with periodically perforated viscoelastic damping material (VDM) are analyzed by considering the frequency and temperature relationship in this paper. First, the mechanism of the sandwich plates is developed by using the Saint–Venant principle and the flexural and shearing deformation compatible equations. Next, the deflection equation of the sandwich plate is established based on the principle of flexural deflection of isotropy plate, and then, it is expanded for easy solution by the second order "rapid" asymptotic method. The opening ratio and the thickness of the core layer which affects the loss factor of sandwich plate are thoroughly researched. Finally, the validity is performed and the advantage of the perforated structure in industrial application is presented.

1. Introduction

Viscoelastic damping material (VDM) is utilized widely in mechanical structure such as national defense, navigation, and aerospace industries for its good mechanical properties. VDM not only is low in weight and cost, high reliability, and easy implementation, but also has decent noise and vibration control ability especially on lightweight and flexible structures [1]. Theoretical analysis for the VDM mechanism can be traced to as early as 1950. Liénard [2], Oberst [3], and Mead [4,5] had done a thoroughly research on composite beam and plate. Subsequently, there are plenty of researchers who investigated VDM beam plate and shell structures. For example, Mead and Markus [6,7], Yan and Dowell [8], Rao et al. [9], Kristensen et al. [10], Kumara and Singh [11], and Sher and Moreira [12] are typical researchers in this area. Traditionally, VDM has four methods of application in industry, which is free layer damping, constrained layer damping [11,13] and partially constrained layer damping [14], and active constrained layer damping [15,16]. The free layer damping is the easiest method of application of VDM, which need only patch the VDM on the structure. However, the effect of this method is very limited. The constrained layer damping, also called hybrid damping, is an efficient way to utilize the VDM. Therefore, it is applied mostly in industry. The active constrained layer damping has the properties of self-controlling, self-monitoring capabilities, and high loss factor by using piezoelectric material. With deep analysis on mechanisms of VDM, it is found that partially constrained layer becomes a good format for application in dynamic mechanics engineering products.

The effects of VDM application are depended largely upon the frequency and temperature. Unfortunately, the frequency and temperature are two dependent parameters in VDM. When they have been introduced into structures, the dynamics analysis will be very difficult to deal with. There are three theoretic models which describe the frequency dependent parameters of VDM, as shown in Eqs. (1)–(3)

$$G^*(\omega) = G_0(\omega)\left[1 - \sum_{n=1}^{N} g_n + \sum_{n=1}^{N} \frac{j\omega g_n \tau_n}{1 + j\omega\tau_n}\right] \tag{1}$$

$$G^*(\omega, T) = G_0(\omega, T)(1 + j\zeta(\omega, T)) \tag{2}$$

$$G^*(\omega) = 0.142\left(\frac{\omega}{2\pi}\right)^{0.494}(1 + 1.46j) \tag{3}$$

where: $G^*(\omega,T)$ is complex shear modulus of VDM; $\zeta(\omega,T)$ is frequency and temperature dependent damping ratio; $\omega = 2\pi f$, f is the frequency; and $j = \sqrt{-1}$, is the imaginary part. The symbolic meaning in Eq. (1) can be checked in Ref. [13]. Model strain energy method is presented in Eq. (2) is applied in this paper to calculate the frequency dependent storage modulus and damping ratio which

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are adopted in Refs. [17,18]. The frequency dependent shear modulus of Eq. (3) is found in [14,19,20].

Recently, VDM core layer laminated sandwich structure (sandwich structure) is widely utilized in engineering by virtue of its distinctive advantages such as light mass, high strength/stiffness, seismic behavior, and vibration/sound insulation. Many researchers analyzed the dynamic characteristics of VDM core layered sandwich beam [6,7,21], plate [22,23], and shell [24–26]. Ferreira et al. [22] researched VDM core layered sandwich laminated plate through layer wise finite element model based on Carrera's Unified Formulation. Meanwhile, the frequency dependent coefficient of the core layer was considered, and the results revealed a good consistency with experiment. Oh [26] took the transverse shear and normal strains and the curved geometry into account. Applying the refined finite element method based on the layer wise shell theory, he researched cylindrical hybrid panels with co-cured and constrained layers of VDM. He also compared the different damping effects between partial and full layerwise shell. Li [27] applied Hamilton principle and derived the dynamic governing equations for a thin laminated circular plate. He concluded that the critical speeds of the rotating laminated plate with the visco-elastic core layer could be improved by a proper thickness ratio, Young's modulus ratio, and loss factor.

For analyzing composite materials and structures, asymptotic method is a powerful mathematically rigorous technique, which can explore the periodical structures with dimensions of a unit cell which is much smaller than the overall dimensions of the solid unit [28,29]. It is used especially in the periodical and quasi-periodic thin-plate or shell, and laminated and composite plate and structure [30–33]. Barbero et al. [30] used Koiter's asymptotic method on laminated composite structure, and presented a numerical example for buckling and post-critical analysis. They concluded that asymptotic method was a valid and less computation method which was an alternative for the Riks path-following method. Hao et al. [31] analyzed a cantilever functionally graded rectangular plate based on Reddy's third-order plate theory and Hamilton's principle with assuming the temperature dependent material. They obtained a nonlinear averaged equation by applying asymptotic method, and concluded that chaotic, periodic, and quasi-periodic motions of the plate were existed under certain conditions, and could change the form of motions for the rectangular plate. Based on the rigorous mathematical foundation of the asymptotic method, Cai et al. [32] developed and implemented finite element formulations for periodic composite plate and shell without any complicated mathematical derivation. Therefore, it could be applied easily by using commercial software.

The frequency and temperature dependent storage modulus and damping ratio of VDM applied in this research is measured by resonance method [34]. In which, the frequency ranges from 1 to 1000 Hz, and the temperature is 10 to 30 °C, which are listed in Table 1 below.

In this table, the polynomial interpolation is applied. Nine times polynomial interpolations is performed to achieve higher precision. Interpolation figures are shown in Fig. 1(a) and polynomial coefficients are shown in Table 2.

$$(\bullet)(f) = \chi \sum_{i=0}^{9} C_i O^i, \quad (\bullet) = E_{10}, \zeta_{10}, E_{20}, \zeta_{20}, E_{20}, \zeta_{20} \tag{4}$$

where $O = \log_{10}(f)$, C_i is the coefficient of 9 times polynomial interpolations. Substituting Eq. (4) into Eq. (2), the frequency and temperature dependent shear modulus is obtained, as shown in Fig. 1(b).

The rest of the paper is organized as follows. The modeling and mathematical formulation of the sandwich plate is described in Section 2, which contains establishment of strain energy and kinetic energy of a unit cell and its equilibrium equations based on the Saint–Venant principle. Asymptotic analysis and model reductions of the sandwich plate are presented in Section 3. Numerical analysis and result comparison are illustrated in Section 4. Finally, discussion and conclusion are given in Section 5.

2. Modeling and mathematical formulation of sandwich-plates

The periodically perforated VDM core layer sandwich plate model and a unit cell model are presented in Fig. 2. VDM layer is perforated. Material and geometry schematics of the unit cell are illustrated in Fig. 3. To model the structure, the following assumptions are made for deriving the equations of the motion.

(i) The lamination thickness is very small, compared to its other dimensions.
(ii) The layers of the sandwich are perfectly bonded.
(iii) Lines that are perpendicular to the surface of the lamination remain straight and are perpendicular to the surface after deformation.
(iv) The middle plane of the sandwich plate is half thickness of the plate.
(v) The shear strain and rotation inertia in the face pales are ignored.

Set the in-plane displacements of the points in the middle planes of the top and bottom layer in x and y direction, u_i and v_i,

Table 1
Frequency and temperature dependent storage modulus and damping ratio of VDM.

Frequency (Hz)	10 °C		20 °C		30 °C	
	$E'(\omega)$	$\zeta(\omega)$	$E'(\omega)$	$\zeta(\omega)$	$E'(\omega)$	$\zeta(\omega)$
1	6.24E+08	1.09083	54300000	1.08332	24400000	0.507772
2	8.25E+08	0.959036	71700000	1.23898	28300000	0.588709
5	1.35E+09	0.724428	1.16E+08	1.41153	35600000	0.743035
10	1.72E+09	0.60444	1.76E+08	1.43741	44100000	0.899954
25	2.33E+09	0.453899	2.34E+08	1.40918	61800000	1.13551
40	2.57E+09	0.411398	3.45E+08	1.31039	74800000	1.25689
60	2.78E+09	0.373665	4.63E+08	1.20307	89900000	1.36311
80	2.9E+09	0.343765	5.61E+08	1.12698	1.04E+08	1.41862
120	2.13E+09	0.346326	6.69E+08	1.09311	1.28E+08	1.48977
160	2.88E+09	0.374684	6.22E+08	1.12719	1.49E+08	1.51566
200	2.38E+09	0.483164	6.33E+08	1.12845	1.61E+08	1.54509
300	2.8E+09	0.406857	6.22E+08	1.16412	1.76E+08	1.65014
400	2.47E+09	0.504578	5.73E+08	1.28383	1.69E+08	2.03964
600	2.06E+09	0.668202	7.34E+08	1.0918	3.64E+08	1.23642
800	2.12E+09	0.436325	2.17E+09	0.402016	1.16E+09	0.264892
1000	4.26E+09	0.213601	1.03E+09	1.10629	0	0