Composite Structures 130 (2015) 124–142

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

A unified method for the vibration and damping analysis of constrained layer damping cylindrical shells with arbitrary boundary conditions

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ARTICLE INFO

Article history:
Available online 25 April 2015

Keywords:
PCLD
Sandwich shells
Loss factor
Elastic restraints
Damping

ABSTRACT

In this paper, an accurate solution is developed for the vibration and damping characteristics of a three-layered passive constrained layer damping (PCLD) cylindrical shell with general elastically restrained boundaries. In this formulation, characteristic equations of the system are derived by using the modified Fourier–Ritz method in conjunction with Donnell shell assumptions and linear viscoelastic theory. Regardless of boundary conditions, the displacements of each layer are expanded as the linear combination of a standard Fourier series and closed-form functions introduced to eliminate all the relevant discontinuities with the displacements and derivatives at the edges. This method can be universally applicable to all classical boundaries, elastic boundaries and their combinations without any special change in the solution procedure. It provides an effective way to investigate the influence of restraints from different directions on the vibration and damping performance of PCLD shells. New results for elastic restraints and intermediate ring supports are presented, which may serve as benchmark solutions. Furthermore, the detailed effects of thickness of layers and shear parameter on natural frequencies and loss factors are also illustrated.

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1. Introduction

The sandwich structures have many applications in industries such as vehicles, aerospace and submarines etc., especially where suppression of vibration and noises is required. The high damping capacity of these structures is usually expressed as the modal loss factor, which is mainly due to the shear deformations of viscoelastic materials. Sandwich structures such as beams, plates and shells have been studied by many researchers. The early studies on the vibration and damping characteristics of beam and plate structures with constrained damping layer (CLD) were done by Kerwin [1], Ross et al. [2], DiTaranto [3], and Mead and Markus [4]. In their works, a sixth order partial differential equation of motion governing the transverse displacement of a sandwich beam was developed and established a theoretical foundation for passive constrained damping layer (PLCD). Furthermore, loss factor was defined and has been considered as an indicator to measure damping property of a sandwich structure. The influence of shear deformation and rotational inertia in the case of short PCLD beam has been investigated by Rao [5], who also developed an analysis method to obtain loss factor and natural frequency under various boundary conditions [6]. The cylindrical shell with PCLD treatment is composed of a base shell, viscoelastic material (VEM) layer, and constrained layer. Pan [7] might be the first person who conducted vibration analysis of a cylindrical shell with a CLD treatment. He investigated axisymmetrical vibration of a finite-length cylindrical sandwich shell with a viscoelastic core layer.

The present studies mainly include analytical solution, finite element modeling, semi-analytical methods and experimental works. Alam and Asnani [8,9] considered the vibration and damping analysis of a general multilayered cylindrical shell having an arbitrary number of orthotropic material layers and viscoelastic layers. Zheng and Qiu [10] investigated the damping analysis of multilayer PCLD cylindrical shell using transfer function method. It showed the application of multilayer PCLD treatment results in a slight drop of natural frequency and a rapid increase in loss factor. The finite element method (FEM) has been widely applied due to its flexibility for arbitrary geometry and boundary conditions. Ramesh and Ganesan [11,12] developed a semi-analytical finite element modal based on the first order shear deformation theory (FSDT) for the vibration and damping analysis of a cylindrical shell with a viscoelastic core. They discussed the effect on the natural frequencies and loss factors with various parameters of isotropic and orthotropic cylindrical shells such as boundary conditions, shear parameters, and ratios of core to facing thickness and length to radius. The influence of a constrained damping layer on the

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http://dx.doi.org/10.1016/j.compstruct.2015.04.017
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resonant response of cylindrical shells to different types of loading is investigated [13]. The results showed that the damping layer was obviously effective in reducing the resonant displacement and the stress magnitudes in composite shells. Hu and Huang [14] have derived general differential equations of motion for a three-layer sandwich structure with the Hamilton principle and Donnell–Mushtari–Vlasov (DMV) assumption. The differential equations contain only three displacements, which greatly improve computational efficiency. Wang and Chen [15] discussed the vibrations of a cylindrical shell with partially constrained layer damping (CLD) treatment. Numerical results showed that thicker or stiffer constraining layer (CL) warrants better damping. Thicker VEM does not always give better damping than thinner ones when CL exceeds a certain thickness. Xiang et al. [16] developed a new matrix method for solving the governing equation of the sandwich cylindrical shell which could be written as a matrix differential equation of the first order. Cao et al. [17] used wave propagation approach to study the free vibration of circular cylindrical shell with constrained layer damping. Partially constrained layer damping shells based on a discrete layer theory are studied by Wang and Chen [18] by using a finite element method. Wang and Zheng [19] investigated the vibration and damping of a submerged CLD cylindrical shell in terms of power flow analysis using the wave propagation approach. Results showed that the constrained damping layer will restricts the exciting force inputting power flow into the shell, especially for a thicker viscoelastic layer, a thicker or stiffer constraining layer (CL), and a higher circumferential mode order. Farough and Ramin [20] studied the damping characteristics of a three-layered sandwich cylindrical shell for thin and thick core viscoelastic layers using semi-analytical finite element method. Nonlinear and linear models for displacement distribution through the thickness of the core layer were developed. According to their results, the nonlinear model exhibits more damping properties than the linear model. The effect of imperfect bonding between the layers has also been investigated in the modeling. Saravanan et al. [21] studied the vibration and damping characteristics of multilayered fluid-filled shells with viscoelastic layers. The effect of varying the number of viscoelastic layers and the fluid filled in shells on the vibration and damping characteristics is also discussed. Ferreira et al. [22] studied a laminated shell by radial basis functions collocation, according to a sinusoidal shear deformation theory (SSDT). The free vibration analysis of simply supported composite and sandwich doubly curved shells are investigated by Garg et al. [23]. Their formulation employed the Sander's theory and assumed a parabolic distribution of transverse shear strains through the thickness of the shell. Singh [24] studied the free vibration of open deep sandwich shells which consist of thin facings and a moderately thick core. The free damped vibrations of sandwich shells including cylindrical, conical and spherical sandwich shells were researched by Korjakin et al. [25] using a zig-zag model.

It can be seen from the above literature reviews that most of the previous studies on PCLD cylindrical shells were conducted under the classical boundary conditions. However, in practice, the boundary conditions of a cylindrical shell may not always be classical in nature. So the existing solutions are often only suitable for some classical boundary conditions, and typically require modifications of the trial functions and corresponding solution procedures to adapt to different boundary cases. Therefore, the use of the existing solution procedures will results in very complex calculations. It is necessary and of great significance to develop a unified method which is well capable of dealing with PCLD cylindrical shells with any boundary condition. A modified Fourier series method was developed to study the free vibrations of the composite laminated cylindrical shells with general boundary conditions [26,27].

This present paper extends this method to the vibration and damping analysis of a three-layered passive constrained layer damping cylindrical shell with general elastically restrained boundaries, aiming to provide a unified and reasonable accurate alternative to other analytical and numerical techniques. Regardless of boundary conditions, the displacements of each layer are expanded as the linear combination of a standard Fourier series supplemented with auxiliary functions introduced to ensure and accelerate the convergence of the series expansions. Since enough smooth displacement field is constructed throughout the entire solution domain, characteristic equations of the system are derived by using the Rayleigh–Ritz method in conjunction with Donnell shell assumptions and linear viscoelastic theory. In contrast to most existing methods applied in sandwich shells, the current method can be universally applicable to a variety of boundary conditions including all classic, elastic cases and their combinations. Some new results for the PCLD cylindrical shell with elastic restraints and intermediate ring supports are illustrated, and the effects of restraining stiffness, thickness and material property of the layers on frequency and loss factor parameters are investigated further.

2. Theoretical formulations

2.1. Description of the model

As shown in Fig. 1, an isotropic sandwich shell which is composed of the base shell, the viscoelastic core and the constraining layer is considered. In the present work, the viscoelastic material has frequency-independent complex shear modulus G_v which is able to dissipate energy. The symbols R_i, h_i, and $\rho_i (i = s, v, c)$ denote radius, thickness and density of the layers, and the subscripts or superscripts s, v, and c in the following derivation are designated for base shell, viscoelastic core and constraining layer, respectively. The length of cylindrical shells is L. Prior to developing the model, the following assumptions will be made for simplifying the computational effort:

(a) The base shell and constraining layer satisfy Donnel thin shell hypothesis. Moreover, these two layers are only allowed flexural and axial deformations but no shear deformation.
(b) The VEM layer undergoes only shear strains due to the fact that the Young's modulus of the viscoelastic layer is much smaller than that of the base shell and the CL.
(c) The displacements and rotary angles of the interfaces for three shells satisfy continuity condition. That is, for a given position x, the radial displacement in the z direction is same for the three layers.
(d) Due to the much lower density of VEM, only the radial inertia is considered for VEM layer.

With the assumptions above, the displacements of the sandwich cylindrical shell could be further defined. $w(x,\theta,t)$ is the radial displacement of the shell along the z-axis and is positive in the direction of the normal of the shell surface. $u_i(x,\theta,t)$ and $v_i(x,\theta,t)$ $(i = s, v, c)$ are the axial and circumferential displacements of the each layer along the x-axis, respectively, and is positive in the direction of increasing x and θ.

2.2. Kinematic relation

As shown in Fig. 2, according to the deformation compatibility between layers, the displacements at an arbitrary point of each layer can be written as:

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