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Vibration and damping analysis of thick sandwich cylindrical shells with a viscoelastic core under arbitrary boundary conditions

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An accurate solution approach based on the first-order shear deformation theory (FSDT) is developed for the free vibration and damping analysis of thick sandwich cylindrical shells with a viscoelastic core under arbitrary boundary conditions. Laminated and sandwich theories are employed to describe the laminated composite layers and viscoelastic material layer, respectively. The present solution is based on a set of new displacement field expression in which the displacements of the middle surface are expanded as a combination of a standard Fourier series and auxiliary functions. Due to the improved displacement expansions, rapid convergence and high accuracy can be easily obtained. The current method can be universally applicable to a variety of boundary conditions including all the classical cases, elastic restraints and their combinations. Natural frequencies and loss factors under various boundary conditions and lamination schemes are calculated, which may serve as benchmark solutions in the future. The effects of some key parameters including the boundary conditions, fiber orientation angle, and number and thickness of the layers on free vibration and damping characteristics of the shells are illustrated and analyzed.

1. Introduction

Sandwich cylindrical shells with transversely flexible core material which are able to effectively control the vibration and noises are widely used in many types of engineering structures such as aeroplanes, marine crafts and construction buildings. The damping capacity of sandwich structures is usually expressed as the modal loss factor, which is caused by the shear deformations of viscoelastic materials (VEM). Sandwich structures such as beams, plates and shells have been studied by many researchers.

The earlier theoretical analysis of constrained and unconstrained viscoelastic sandwich structure was conducted by Ross et al. [1]. In their work, loss factor was defined in terms of strain energy. The analysis of sandwich beams with a viscoelastic core could be traced to DiTaranto [2] and Mead and Markus [3] for bending vibrations of beams in the axial direction. Free vibration analysis of a cylindrical shell with a constraining layer damping (CLD) treatment might be first conducted by Pan [4], who investigated axisymmetrical vibration of a finite-length circular cylindrical shell with full passive constraining layer damping (PCLD) treatment. Ramesh and Ganesan [5–7] studied the free vibration and damping performance of three-layered cylindrical shells with the finite element method. Influence of boundary conditions, material and geometry parameters on the natural frequencies and loss factors were discussed. Ramasamy and Ganesan [8] developed a finite element code based on the displacement field proposed by Wilkins et al. to find out the natural frequencies and loss factors of fluid filled cylindrical shells with a constraining viscoelastic layer. In their work, the fluid effect on the natural frequencies and loss factors are taken into account by the added mass of the fluid on the structure. Yeh and Chen [9] investigated the influence of treatment location on the vibration characteristic of PCLD beams by using FEM and the transfer matrix method. Sainsbury and Masti [10] studied the partial coverage of cylindrical shells with a constrained viscoelastic damping layer, with emphasis on looking for the minimum area of coverage that would produce optimal damping. Farough and Ramin [11] studied the damping properties of a PCLD sandwich cylindrical shell for thin and thick core viscoelastic layers using semi-analytical finite element method. In their work, nonlinear and linear models for displacement distribution through the thickness of the core layer were developed. A multilayered PCLD cylindrical shell with several viscoelastic cores are investigated by Zheng and Qiu [12] using transfer function method. The results show that applied multilayer PCLD treatment results in a slight drop of natural frequency and a rapid increase in loss factor. A general method was proposed by Zhang et al. [13,14] to study the sound and vibration of a finite cylindrical shell with arbitrary thickness. This method was further applied in acoustic radiation of damped cylindrical shell with arbitrary thickness in the

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fluid field. The influence of thickness, mass density, dilatational wave loss factor and Young's modulus of damping material and circumferential mode number of the cylindrical shell on the insertion loss are studied.

Various kinds of laminated shell theories [15–21] have been proposed and developed. Among the numerous theories, the classical shell theory which is based on the Kirchhoff–Love assumption is widely used. Due to the mechanical complexity of the shell structures, various subcategory shell theories were developed with different assumptions and simplifications, such as the Reissner–Naghdi's linear shell theory, Donnel–Mushtari's theory, Sanders' theory. Related survey articles and monographs oriented to such contributions may be found in Leissa [15], Qatu [16] and Reddy [17]. Important and detailed works on the laminated structures such as beams, plates and shells have been given by Qatu in his published book [16]. A domain decomposition approach is developed by Qu et al. [22,23] for vibration analysis of isotropic and composite revolution shells with arbitrary boundaries. Jin and Ye [24,25] studied the free vibration of laminated composite cylindrical shell with using the Reissner–Naghdi's theory and first-order shear deformation theory in their work. The general boundary conditions including classic and elastic restraints are investigated in their studies. Carrera et al. [26,27] conducted an analysis of thickness locking (TL) mechanism about plates, shells and also multilayered shells. TL has been investigated for a large variety of shell theories in their work. A discrete singular convolution (DSC) algorithm for determining the frequencies of the free vibration of laminated conical and cylindrical shells is developed by Civalek [28–30]. By applying the DSC method, the free vibration equations of motion of the composite laminated conical shell are transformed to a set of algebraic equations. Recently, a meshless technique based on multiquadric radial basis function method for high order shell theories had been applied to static and free vibration analysis of laminated composite shells by Ferreira [31–33]

In general, the analytical models of the sandwich structures are mainly based on one of the following approaches: classical shell theory; equivalent single layer (ESL) [34]; layer-wise (LW) theory; shear deformation theories [35–38], and recently, the high-order sandwich panel theory (HSAPT) [39,40]. Khare et al. [35] investigated the free vibration and thermo-mechanical analysis of laminated sandwich thick shells using the higher order shear deformation theories (HSDT). The free vibration analysis of simply supported composite and sandwich doubly curved shells are investigated by Garg et al. [36]. Their formulation employed the Sander's theory and assumed a parabolic distribution of transverse shear strains through the thickness of the shell. Singh [37] 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 are researched by Korjakin et al. [38] using a zig–zag model. Frostig et al. [39,40] developed a high-order theory for sandwich beams and plates. The theory does not impose any restriction on the distribution of the deformation through the thickness.

According to the author's knowledge, this paper presents, for the first time, a thick sandwich cylindrical shell with a viscoelastic core under arbitrary boundary conditions. The first-order shear deformation shell theory is adopted to formulate the whole theoretical model. Lamination theory and sandwich theory are applied in laminated composite facings and viscoelastic material layer, respectively. Characteristic equations of the system are derived by using the modified Fourier–Ritz method based on energy functions of the laminated composite and sandwich cylindrical shell. In this procedure, without considering boundary conditions, the displacements and rotation components of the structure are expanded as a new form of trigonometric series expansions with several supplementary terms introduced to remove any potential discontinuities of the original displacements and their derivatives. Mathematically, such series expansions are capable of representing any functions (including the exact displacement solutions). Exteriorly, the size of the final system is increased, but the solution procedure is simplified significantly. The accuracy and convergence of the proposed Fourier series solution will be verified by several numerical examples.

The main purpose of the present work is to supplement the vibration studies of the laminated sandwich cylindrical shell with various kinds of boundaries including the elastic ones and develop a unified and sufficiently accurate method to provide some useful results of the titled problems. In this work, the effects of lamination schemes and geometric properties of the structure on natural frequencies and on loss factors are also illustrated.

2. Theoretical formulations

2.1. The model

Consider a laminated sandwich cylindrical shell as shown in Fig. 1. The whole structure consists of base laminated layers, viscoelastic core layer and constraining laminated layers. The symbols R_i, h_i and ρ_i (i=s, v, c) denote radius, thickness and density of layered shells, and the subscripts or superscripts s, v, and c in the following derivation are represented for the base part, viscoelastic core and the constraining part of the shell. There is a reference surface in each part of the laminated sandwich shell. The reference surfaces are taken to be at the middle surface of each part where an orthogonal co-ordinate system (x, θ, z) is fixed and x, θ and z axes are taken in the axial, circumferential and radial directions, respectively. Furthermore, the displacements of the three middle surface in the x, θ and z directions are denoted by u_0^i, v_0^i and w_0, respectively, and ϕ_x^i and ϕ_θ^i separately represent the rotations of transverse normal respect to θ- and x-axis

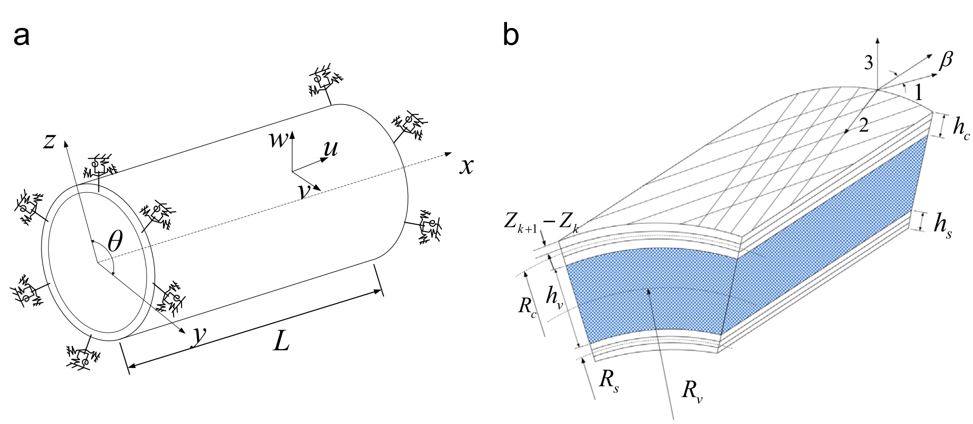

Fig. 1. Schematic diagram of the laminated sandwich cylindrical shell: (a) the whole shell and (b) the partial cross-sectional view of the shell.