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Free vibration analysis of a hard-coating cantilever cylindrical shell with elastic constraints

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ABSTRACT

In this article, free vibration of the hard-coating cantilever cylindrical shell is investigated considering the elastic constraints at the clamped end. Love's first approximation theory and Rayleigh–Ritz method are applied to build the analytical model of hard-coating cylindrical shell. In the modeling process, orthogonal polynomials are used as admissible displacement functions to formulate the displacement field, and the elastic constraints are simulated by constrained springs whose stiffness values are determined using model updating technique. The developed model has been validated by the comparison between the natural frequencies obtained by analytical calculation and by experiment respectively. Finally, the influences of hard-coating parameters, including thickness, Young's modulus and loss factor, on the vibration characteristics of the cylindrical shell are studied.

1. Introduction

Due to high strength-to-weight ratio and other superior performance, cylindrical shell has been commonly used in a variety of engineering applications. Particularly, in the field of aircraft and aerospace, cylindrical shell always serves as supporting and bearing component. In the service process, however, the cylindrical shell is most likely subjected to combined interaction of many dynamic loads, such as mechanical load, inertia force, flow field, thermal field, etc. These broadband loads are prone to cause resonance phenomenon. The excessive vibration level would not only affect normal operation of the cylindrical shell, but also cause fatigue damage to cylindrical shell. Therefore, it is of great importance to develop corresponding method to suppress above destructive vibration.

At present, vibration control of the cylindrical shell has attracted extensive attention, and most methods were achieved by attaching viscoelastic damping material on the surface of the cylindrical shell. For example, Ramesh and Ganesan [1] studied the influence of viscoelastic constrained damping on the resonance response of orthotropic cylindrical shell, and it was concluded that the damping layer was very beneficial to reduce vibration of the composite shell. Chen and Huang [2] conducted an investigation about the effect of constrained layer damping treatment of strip type on the vibration characteristics of shells, and the results showed that thicker constrained layer could provide better damping. Masti and Sainsbury [3] explored the application of a standoff-layered viscoelastic damping treatment for vibration reduction of the cylindrical shell, and the conclusion showed that partial distribution of the treatment as damping patches could be more beneficial than the case using full coverage. Many cylindrical shell structures, such as aero-engine casing, drums, and so on, usually operate under the conditions of high temperature and high corrosion. In that case, the vibration reduction technology with viscoelastic damping material is no longer working because viscoelastic material cannot bear high temperature and its damping capability is impacted by temperature obviously [4], but the newly developed vibration reduction technology with hard coating [5–8] can offer a powerful solution to this problem.

Hard coating is a kind of coating materials prepared by the metal substrate, ceramic substrate or their mixtures, which are mainly used in structure parts for the purpose of thermal barrier, anti-friction, anti-corrosion, etc. Recent studies have found that hard coating also has damping effect and has become a kind of vibration reduction technology with considerable application prospect. The greatest advantage is that hard coating can maintain its original damping capacities in high temperature and high corrosion environment. In order to apply this vibration reduction technology, dynamic model and prediction of vibration characteristics of hard-coating cylindrical shell need to be investigated. As a new vibration reduction technology, to the authors' knowledge, relevant studies on the vibration analysis of cylindrical shell coated

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with hard coating are not carried out yet. Hard-coating cylindrical shell includes cylindrical shell substrate (which is usually metal) and hard coating, and then it can be thought a kind of special composite structure. Thus, some experimental, numerical and simulation studies on vibration analysis of composite plates and shells are discussed in the following lines.

Chen et al. [9] analyzed the vibration of cantilevered, thick, laminated, trapezoidal plates using the p−Ritz method and incorporating Reddy's third-order shear deformation theory. Kabir [10] applied the classical lamination theory to formulate the deformation and solved numerically the free vibration of arbitrarily laminated rectangular plates. Phan-Dao et al. [11] analyzed the static, free vibration and buckling of symmetric laminated composite using a generalized higher-order shear deformation theory and improved meshfree radial point interpolation method. Kiani [12] dealt with the free vibration analysis of skew plates made from functionally graded carbon nanotube reinforced composites using the first order shear deformation plate theory and Ritz method. Braga [13] obtained approximate numerical results of the high-frequency response by the layer-wise theory for isotropic-laminated cylindrical shells. Xiang et al. [14] used the Haar wavelet discretization method to conduct the numerical solution of the free vibration for composite laminated conical, cylindrical shells and annular plates with various boundary conditions. Panda and Katariya [15] analyzed numerically the free vibration and the buckling behavior of laminated composite flat and curved panels under the thermo-mechanical load using ANSYS Parametric design language code. Kar and Panda [16] computed numerically the free vibration of functionally graded curved panels using the higher order shear deformation theory under thermal environment. With further research, nonlinear vibrations of composite structure were investigated widely. Panda and Mahapatra [17] considered the nonlinearity in geometry produced by thermal load and analyzed nonlinear free vibration behavior of laminated composite shallow shell using Green-Lagrange based on higher order shear deformation theory. Katariya and Panda [18] developed a general mathematical model for laminated curved structure using higher-order shear deformation theory and Green–Lagrange-type nonlinearity under uniform temperature loading. Singh and Panda [19] analyzed large amplitude free vibration behavior of doubly curved composite shell panels using Green Lagrange type geometric nonlinearity in the framework of higher order shear deformation theory. Similarly, Mahapatra et al. [20–24] investigated numerically the nonlinear free vibration behavior of different composite structure under thermal or hygrothermal environment, including laminated composite single/doubly curved shell and spherical shell panels, etc. Nonlinear vibrations of composite structure with functionally graded (FG) or piezoelectric layer were also investigated. Kar and Panda [25–27] analyzed the nonlinear free vibration behaviors of FG single/doubly curved shell and spherical shell panels and the material properties of FG material were considered using Voigt micromechanical model. Mehar and Panda [28,29] developed a mathematical model of nonlinear free vibration for the FG carbon nanotube reinforced composite plate and the material properties of the FG plate were introduced in their model through a micromechanical model under temperature load. For laminated composite single/doubly curved shell and spherical shell panels embedded with the piezoelectric layer, Singh et al. [30–32] conducted the numerical analysis of nonlinear vibration behaviors of these composite structures. Because delamination is a most common type of damage mode, the vibration of laminated composite structure with delamination were also investigated recently. Hirwani et al. [33] investigated the effect of delamination on the free vibration behavior of the laminated composite curved panels of different geometries. Sahoo et al. [34] analyzed the free vibration, bending, and transient responses of laminated composite plates with delamination. Except for aforementioned numerical and simulation studies, some experimental investigations were also performed. Hemmatnezhad et al. [35] validate the analytical achievements of free vibration for GFRP-stiffened composite cylindrical shells by experimental modal analysis. Sahoo et al. [36] validated the numerical results of the static and the free vibration for the laminated woven glass/epoxy composite plate by unidirectional tensile test, bend test and modal test, and they [37] also applied three point bend test and modal analysis to validate the deflections and the natural frequencies of the laminated composite flat panels obtained by numerical method. From the aforementioned literature review, it can be found that the vibrations of composite plates and shells have been investigated extensively based on classical theory and various shear deformation theories, and governing equations of composite structure are obtained using Ritz method, Lagrangian equation and Hamilton's principle, etc. In addition, compared with numerical studies, the number of experimental investigation for composite structure is small. All of these contributions can be used for the reference of this study.

Furthermore, as this paper focuses on the analysis of cantilever cylindrical shell with hard coating, some important and selective literatures about the vibration analysis of cantilever laminated composite cylindrical shells were described emphatically in the following. Based on Love's first approximation theory, Lam and Loy [38] considered beam functions as axial modal functions to form the displacement field and Ritz procedure was used to investigate effects of different classical boundary conditions on natural frequencies of multi-layered cylindrical shell. For laminated composite cylindrical shells under cantilever and other classical boundary conditions, Shu and Du [39] also used Love's theory to derive the differential equations of motion and obtained natural frequencies by discretizing governing equations and boundary conditions using generalized differential quadrature (GDQ) method. Zhang [40] applied wave propagation approach to analyze natural frequencies of cross-ply laminated composite cylindrical shells under clamped–clamped, clamped-simply supported and other boundary conditions. Based on Sanders' thin shell theory, Hemmatnezhad et al. [41] used Stoke's transformation to obtain Fourier series, then formed the displacement field and calculated the natural frequencies of the composite cylindrical shells under clamped-free and other classical boundary conditions. It is clear from the above researches that general procedure of the vibration analysis of cantilever laminated composite cylindrical shells is: assuming the form of displacement field firstly, and then formulating motion equation by energy method, finally solving the equation by numerical algorithm. The above procedure can provide a comparatively solution for the composite cylindrical shell under classical cantilever boundary condition. However, cylindrical shell is often not under this classical cantilever status in practical engineering, and the fixed end is under the status of elastic constraints. Thus, the displacement field which is determined by ideal cantilever boundary condition is difficult to meet the requirements of the vibration analysis of cylindrical shell with elastic constraints.

Some scholars have investigated vibration analysis of cylindrical shells with elastic constraints. For example, based on Flügge's theory, Dai et al. [42] studied the vibration characteristics of the cylindrical shell with arbitrary boundary conditions and different boundary conditions of cylindrical shell can be simulated by changing stiffness values of the constrained springs. Similarly, Jin et al. [43] applied constrained springs on the each end of the shell to simulate elastic constraints and used Rayleigh–Ritz procedure to analyze free vibration of laminated composite cylindrical shells. Qu et al. [44] analyzed vibration characteristics of isotropic and composite cylindrical shells with various combinations of classical and non-classical boundary conditions by domain decomposition method. Song et al. [45] analyzed free vibration of symmetri-