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Discrete singular convolution method for the free vibration analysis of rotating shells with different material properties

Ömer Civalek

Akdeniz University, Faculty of Engineering, Civil Engineering Dept., Division of Mechanics, 07200 Antalya, Turkiye

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ABSTRACT

Using the discrete singular convolution (DSC) method, this paper presents the free vibration analysis of rotating truncated conical shells, circular shells and panels. Isotropic, orthotropic, functionally graded materials (FGM) and laminated material cases are considered. The influences of centrifugal and Coriolis accelerations and the effects of initial hoop tension have been taken into account. The present analysis is based on Love's first approximation shell theory. Frequency values are obtained for different types of boundary conditions, rotating velocity, circumferential wave number, geometric and material parameters. To verify the accuracy of this method, comparisons of the present results are made with results available in the literature. Some results related to rotating annular plates are also presented via conical shell equations. It is shown that the present method is reliable and applicable for vibration analysis of rotating shells and plates.

1. Introduction

Laminated composite materials are increasingly used in aerospace, mechanical and civil engineering structures. With the increasing use of fiber-reinforced composites as structural elements, studies including the linear and nonlinear vibration of composite material shell are receiving considerable attention. The advantage of its anisotropic material properties and light weight with high strength, these materials can be used very efficiently in many disciplines. Rotating structural components such as shells and shafts are the important parts of some mechanical systems in different engineering applications. Advanced gas turbines, electric motors, rotor systems, drilling pipe, drive shafts for helicopters and wind turbines, high-speed centrifugal separator, aircraft jet engines and locomotive engines are the important examples of such systems. Conical and circular cylindrical shells have been widely used mechanical forms for such a rotating systems. So, the vibrational behavior and noise control of such systems are an important task for designer. Research on the subject of rotating shell structures has been reported by many researchers over the years. The studies presented by Aron [1], Bryan [2], and Ferderhofer [3] are the first important documents on this area. Travelling waves in rotating cylindrical shells have been investigated by Srinivasan and Lauterbach [4]. Zinberg and Symonds [5] give a brief history of rotating members. Critical speed analysis of laminated composite cylindrical tubes has been investigated by dos Reis et al. [6], Padovan et al. [7] give a finite element based solution for vibrations and the buckling of rotating anisotropic shells. Kim and Bert [8] used various shell theories for analyzing the first critical speed of a composite cylindrical shell and shaft. The method of reproducing kernel particle is proposed for free vibration analysis of a rotating isotropic cylindrical shell by Liew et al. [9]. By using the a few shell theories, Lam and Loy [10] studied the vibration behavior of thin rotating cylindrical shells. By using the Love's shell theory, Lam and Li [11] developed the formulation of rotating conical shells with orthotropic material case. Zhang [12,13] presented the vibratory behavior and some results for rotating cross-ply and general laminated composite cylindrical shells. Free vibration analysis of rotating composite cylindrical shells via some different thin shell theories has been given by Chun and Bert [14]. With consideration of Coriolis accelerations and large deformations, Chen et al. [15] applied the nine nodes curvilinear superparametric finite element method for rotating shells. A detailed analysis for rotating truncated conical shell is studied by Hua [16,17] and Hua and Lam [18]. Investigation of the effects of boundary types on the free vibration behavior of a rotating truncated conical shell were given by Lam and Hua [19,20]. Free vibration of rotating cross-ply laminated cylindrical shells with or without an axially load have been discussed via Ritz and meshless methods by Liew et al. [21,22]. Malekzadeh and Heydarpour [23,24] give numerical solution for vibration problem of functionally graded cylindrical shells in thermal environment. Three-dimensional elasticity analysis of

E-mail address: civalek@yahoo.com

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functionally graded rotating cylinders with variable thickness has been given by Ghafoori and Asghari [25]. Heydarpour et al. [26,27] investigate the thermo elastic analysis of rotating laminated functionally graded cylindrical shells and truncated conical shells with nanotube-reinforced composite via layer-wise differential quadrature method. Frequency response of thin rotating cylindrical shells has been studied by Sun et al. [28–31] with different methods. A few studies concerning free vibration modeling of conical shells have been carried out, namely by Naeem and Sharma [32], Dai et al.[33], Loy and Lam [34], Liu et al. [35], Ganesan and Sivadas [36], and Zenkour [37]. Frequency response of rotating conical panels has been analyzed via GDQ by Ng et al. [38]. 3D finite element method is proposed by Liu et al. [39] for vibration analysis of rotating annular plates. An analytical procedure is used for determination of the natural frequencies and critical speeds of a rotating functionally graded moderately thick cylindrical shell by Hoseini-Hashemi et al. [40]. Natural frequencies of delaminated composite rotating conical shells have been detailed reported by Day and Karmakar [41] using the FEM. Effect of rotation on free vibration response of a truncated conical Shell is concluded by Qinkai and Fulei [42]. Daneshjou and Talebitooti [43] and Talebitooti [44] proposed a layerwise-differential quadrature (LW-DQ) method for free vibration problem of rotating stiffened composite cylindrical shells and rotating laminated conical shells.

The main aim of this study is on the application of the method of discrete singular convolution (DSC) to the problem of free vibration analysis of rotating conical shells with different material properties. The governing differential equations of motion of the shell have been obtained via Love's first approximation classical thin shell theory for title problem. These equations can also be used for rotating analysis of circular cylindrical shell and annular plate vibrations. To the authors' knowledge, it is the first time the discrete singular convolution methodology has been successfully applied to rotating laminated composite conical and circular cylindrical shell problem with different material properties for free vibration analysis.

2. Formulations

In this section, the derivation of the related governing equations is not given. It is possible to find these equations and derivations in literature [11–23]. A typical rotating truncated conical shell figured in Fig. 1. The thin conical shell rotating about its symmetrical and horizontal axis is depicted. The angular velocity is depicted via λ. The cone semivertex angle, thickness of the shell, and cone length

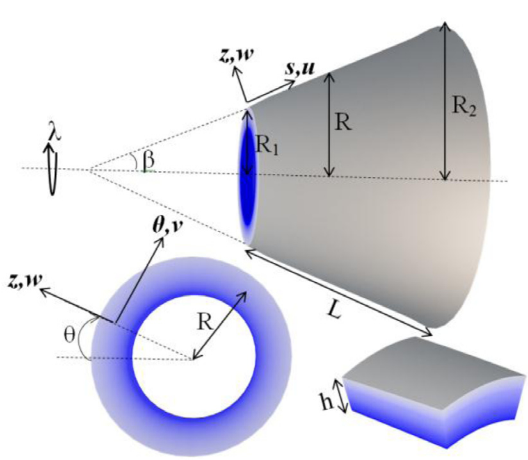

Fig. 1. Geometry and notation of rotating conical shell.

are denoted by α, h and L, respectively. R_1 and R_2 are the radii of the cone at its small and large edges. The conical shell is referred to a coordinate system (x, θ, z) as shown in Fig. 1. The components of the deformation of the conical shell with references to this coordinate system are denoted by u, v, w in the x, θ and z directions, respectively. The equilibrium equation of motion in terms of the force and moment resultants can be written as

$$L_x(u, v, w) - \rho_t \frac{\partial^2 u}{\partial t^2} = 0, \quad (1)$$

$$L_\theta(u, v, w) - \rho_t \frac{\partial^2 v}{\partial t^2} = 0, \quad (2)$$

$$L_z(u, v, w) - \rho_t \frac{\partial^2 w}{\partial t^2} = 0. \quad (3)$$

where

$$L_x = \frac{\partial N_x}{\partial x} + \frac{\sin\alpha}{R(x)}(N_x - N_\theta) + \frac{1}{R(x)}\frac{\partial N_{x\theta}}{\partial \theta} + \rho h \lambda^2\left[\frac{\partial^2 u}{\partial \theta^2} - r\cos\alpha\frac{\partial w}{\partial x}\right] + 2\rho h\lambda\sin\alpha\frac{\partial v}{\partial t} \quad (4)$$

$$L_\theta = \frac{\partial N_{x\theta}}{\partial x} + \frac{1}{R(x)}\frac{\partial N_\theta}{\partial \theta} + \frac{2\sin\alpha}{R(x)}N_{x\theta} + \frac{\cos\alpha}{R(x)}\frac{\partial M_{x\theta}}{\partial x} + \frac{\cos\alpha}{R^2(x)}\frac{\partial M_\theta}{\partial \theta} + \rho h\lambda^2\left[R(x)\frac{\partial^2 u}{\partial x\partial\theta} + R(x)\sin\alpha\frac{\partial v}{\partial x} + \sin\alpha\frac{\partial u}{\partial \theta}\right] - 2\rho h\lambda\left[\sin\alpha\frac{\partial u}{\partial t} + \cos\alpha\frac{\partial w}{\partial t}\right] \quad (5)$$

$$L_z = \frac{\partial^2 M_x}{\partial x^2} + \frac{2}{R(x)}\frac{\partial^2 M_{x\theta}}{\partial x\partial\theta} + \frac{1}{R^2(x)}\frac{\partial^2 M_\theta}{\partial \theta^2} + \frac{2\sin\alpha}{R(x)}\frac{\partial M_x}{\partial x} - \frac{\sin\alpha}{R(x)}\frac{\partial M_\theta}{\partial x} + \frac{\cos\alpha}{R(x)}N_\theta + \rho h\lambda^2\left[R(x)\frac{\partial^2 w}{\partial \theta^2} - R(x)\cos\alpha\frac{\partial u}{\partial x} + w\cos^2\alpha + u\sin\alpha\cos\alpha\right] + 2\rho h\lambda\left[\cos\alpha\frac{\partial v}{\partial t}\right] \quad (6)$$

where

$$R(x) = R_1 + x\sin\alpha \quad (7)$$

$$\rho_t(x, \theta) = \frac{1}{h}\int_{-h/2}^{h/2}\rho(x, \theta, z)dz \quad (8)$$

For conical shell, the reference surface are given as

$$\{\varepsilon\}^T = \{\varepsilon_1, \varepsilon_2, \gamma\} \text{ and } \{\kappa\}^T = \{\kappa_1, \kappa_2, 2\tau\}. \quad (9,10)$$

The components of the strain and curvature vectors listed below:

$$\varepsilon_1 = \frac{\partial u}{\partial x},$$

$$\varepsilon_2 = \frac{1}{R(x)}\frac{\partial v}{\partial \theta} + \frac{u\sin\alpha}{R(x)} + \frac{w\cos\alpha}{R(x)},$$

$$\gamma = \frac{1}{R(x)}\frac{\partial u}{\partial \theta} + \frac{\partial v}{\partial x} - \frac{v\sin\alpha}{R(x)}$$

$$\kappa_1 = -\frac{\partial^2 w}{\partial x^2},$$