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Nonlinear travelling wave vibrations of a rotating thin cylindrical shell

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ABSTRACT

Nonlinear travelling wave vibrations of a rotating thin cylindrical shell are studied in the paper. Taking into account the effects of centrifugal and Coriolis forces as well as the initial hoop tension due to rotation, governing equations of the nonlinear rotating cylindrical shell with simply supported conditions are derived by using Lagrange equations. The model described by the governing equations is exact, which means no simplification procedures like neglecting all inertia terms on in-plane directions are carried out. Based on the exact model, numerical simulations are carried out to reveal some complex dynamic characteristics of nonlinear travelling wave vibrations, which are different from nonlinear (standing wave) vibrations in generic stationary shells. These results are presented in detail, including amplitude-frequency curves, bifurcation diagrams, time histories, phase portraits, poincaré maps and frequency spectrums.

1. Introduction

As one kind of thin-walled structures, thin cylindrical shells are widely used in many engineering applications and their large amplitude vibration can be excited in certain circumstance, thus nonlinear vibrations of thin cylindrical shells have been of great interest to many researchers [1]. However, for a rotating cylindrical shell concerned in this paper, vibrations are in the form of travelling wave, which is different from standing wave in generic stationary shells, as literature reveals [2–5]. This may lead to complex vibration characteristics of rotating thin cylindrical shells. Hence, nonlinear travelling wave vibrations of the rotating thin cylindrical shell are investigated in this paper.

Based on linear elastic theory, travelling wave vibrations of rotating cylindrical shells have been studied for a long time. Early studies on rotating cylindrical shells were reported by Zohar et al. [3], Saito et al. [4] and Huang et al. [5], in which the travelling-modes phenomenon was discovered and the effects of Coriolis and centrifugal forces were systematically investigated. After that, some numerical and analytical approaches have been developed to analyze the vibration of rotating shells, such as harmonic reproducing kernel particle method [6], finite element method [7], discrete singular convolution technique [8,9]. In recent years, composite materials have been widely used in many fields of engineering. As a result, the study on vibration of rotating composite cylindrical shells attracts many researchers' attention, and numerous articles have been published. In particular, the following studies are noted: a discussion on influence of boundary conditions for rotating

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laminated cylindrical shells by Lam and Loy [10], investigation on the effect of boundary conditions for rotating composite cylinders with orthogonal stiffeners by Lee and Kim [11], studies on vibration characteristics of a spinning cylindrical shell made of functional graded material by Mehrparvar et al. [12] and Malekzadeh et al. [13], analysis on vibration characteristics of rotating ring-stiffened cylindrical shells by Liu et al. [14], investigation on rotating cross-ply laminated cylindrical shells by Song et al. [15]. These articles have steadily improved our knowledge of rotating cylindrical shells.

In addition to the aforementioned studies, the author and his cooperators have also conducted some research, following the pioneering work of previous studies. A series of approaches are proposed to investigate vibration characteristics of thin rotating cylindrical shells with various boundary conditions, such as Fourier series expansion method [16], Rayleigh–Ritz method [17] and wave propagation approach [18]. Dynamic responses of rotating cylindrical shell are also investigated for a thin rotating cylindrical shell subjected to harmonic loads [19]. These investigations by the author and his cooperators have laid a good foundation for the present study of nonlinear travelling wave vibrations.

The literature on nonlinear vibration of cylindrical shells is abundant as Amabili et al. [1] summarized in their monograph. The early studies on the large amplitude vibration of cylindrical shells were presented by Chu [20] and Evensen [21]. After more than half a century, general theories of classic thin cylindrical shells have been extensively studied. Nowadays, many scholars' research interests turn to the theories and approaches dealing with some new problems. For example, various studies have been performed on the nonlinear vibration of cylindrical shells made of laminated material [22–27], functionally graded material [28–34], and nanotube-reinforced composite material [35]. While much research has been undertaken on generic stationary shells, less work has addressed the nonlinear vibration of rotating cylindrical shells:

Wang et al. [36,37] investigated nonlinear dynamic responses of rotating cylindrical shells using numerical integration method and approximate analytical approach. Nonlinear vibrations of a rotating laminated composite cylindrical shell were also studied in their following work [38]. It should be noticed that inertia terms on in-plane directions of cylindrical shells were neglected in their research to derive the simplified governing equations for analytical or numerical studies. To the author's knowledge, although vibrations of thin cylindrical shells are predominated by the flexural direction (i.e., out-plane direction), some key dynamic behaviors may be lost if the inertia terms on in-plane directions are neglected directly, due to the coupling of three deformation directions. Liu et al. [39] investigated the effects of nonlinearity, excitation and damping on frequency responses of a rotating cylindrical shell using perturbation method. However, from the expressions of displacement fields, one can see that the characteristics of travelling wave are not taken into account in their paper. Han et al. [40] studied parametric instability of a thin cylindrical shell with periodically time-varying rotating speeds using multiple scales method. In their study, geometric nonlinearity of the cylindrical shells is not considered.

In this paper, governing equations of the nonlinear travelling wave vibrations for a rotating thin cylindrical shell with simply supported conditions are derived by using Lagrange equations. The model described by the governing equations is exact, which means no simplification procedures like neglecting all inertia terms on in-plane directions are carried out. Based on this model, numerical simulations are conducted to investigate some complex dynamic characteristics of nonlinear travelling wave vibrations, which are different from nonlinear (standing wave) vibrations in generic stationary shells. These results are presented in detail, including amplitude-frequency curves, bifurcation diagrams, time histories, phase portraits, poincaré maps and frequency spectrums.

2. Theoretical formulation

2.1. Expressions of the cylindrical shell's energy

Consider a simply supported thin cylindrical shell rotating about its symmetrical and horizontal axis at an angular velocity Ω as shown in Fig. 1. In the figure, the thickness, the length and the mean radius of the cylindrical shell are denoted by H, L and R, respectively. An orthogonal coordinate system (x, θ, z) is fixed on the middle surface of the shell. The components of the deformation of the cylindrical shell with references to this coordinate system are denoted by u, v and w in the x, θ and z

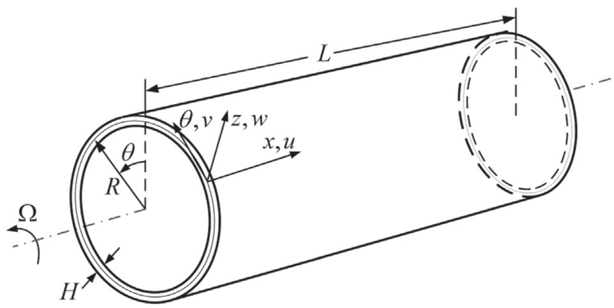

Fig. 1. Coordinate system and geometrical relations of a thin rotating cylindrical shell.