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Nonlinear vibrations analysis of rotating drum-disk coupling structure

Li Chaofeng [a, b, *], Miao Boqing [a], Tang Qiansheng [a], Xi Chenyang [a], Wen Bangchun [a, b]

[a] School of Mechanical Engineering & Automation, Northeastern University, Shenyang 110819, China
[b] Key Laboratory of Vibration and Control of Aero-Propulsion System Ministry of Education, Northeastern University, Shenyang, 110819, China

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ABSTRACT

A dynamic model of a coupled rotating drum-disk system with elastic support is developed in this paper. By considering the effects of centrifugal and Coriolis forces as well as rotation-induced hoop stress, the governing differential equation of the drum-disk is derived by Donnell's shell theory. The nonlinear amplitude-frequency characteristics of coupled structure are studied. The results indicate that the natural characteristics of the coupling structure are sensitive to the supporting stiffness of the disk, and the sensitive range is affected by rotating speeds. The circumferential wave numbers can affect the characteristics of the drum-disk structure. If the circumferential wave number$n = 1$, the vibration response of the drum keeps a stable value under an unbalanced load of the disk, there is no coupling effect if $n \neq 1$. Under the excitation, the nonlinear hardening characteristics of the forward traveling wave are more evident than that of the backward traveling wave. Moreover, because of the coupling effect of the drum and the disk, the supporting stiffness of the disk has certain effect on the nonlinear characteristics of the forward and backward traveling waves. In addition, small length-radius and thickness-radius ratios have a significant effect on the nonlinear characteristics of the coupled structure, which means nonlinear shell theory should be adopted to design rotating drum's parameter for its specific structural parameters.

1. Introduction

Drum-disk rotor structures are widely used in many engineering fields because of their great bending rigidity and ability to withstand large centrifugal loads, especially in the high-pressure compressor of turbofan engines. In aero-engines, the drum is often subject to significant inertia forces, gas forces, and other loads. The unreasonable design may lead to violent vibration of specific parts, which in turn can cause local damage and then affect the normal operation of the engine. Therefore, research on vibration characteristics of the drum-disk system is important in sensible design and stability of aircraft engines.

In the literature, the disk was often considered as a rigid object, and the drum was considered as a cylindrical shell. Love is the first scholar to put forward thin shell theory based on the classical linear elastic theory and in the following years, many

* Corresponding author. School of Mechanical Engineering & Automation, Northeastern University, Shenyang 110819, China.
E-mail address: chfli@mail.neu.edu.cn (L. Chaofeng).

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other linear shell theories were developed and widely used in static and dynamic responses of cylindrical shells [1]. The generalized differential quadrature (GDQ) method was used by Li and Lam [2] to study the effects of boundary conditions on the frequency characteristics of a thin rotating cylindrical shell. The frequency characteristics and mode shapes of the rotating cylindrical shells were studied by Lee [3] with the beam function method under the clamped as well as simple boundary conditions. The harmonic reproducing kernel particle method is proposed by Liew [4] for the free vibration analysis of rotating cylindrical shells. By Sanders' thin shell theory and Ritz method, Jafari [5] studied on the free vibration analysis of simply supported rotating cylindrical shells with rings of non-uniform stiffener eccentricity and non-uniform stiffener spacing distribution. In his numerical model, the stretching and bending characteristics were considered. Pellicano [6] conducted experiments on non-linear dynamics of circular cylindrical shells connected to a top mass under base excitation, the comparison result shows that this technique is computationally efficient and accurate in modeling linear vibrations of shells with different boundary conditions. Lam and Loy [7] used a straightforward method of analysis involving Love's first approximation theory and Ritz's procedure to study the influence of boundary conditions and fiber orientation on the natural frequencies of thin orthotropic laminated cylindrical shells. Sun [8] studied the vibration characteristics of cylindrical shells with arbitrary boundary conditions with Fourier series expansion method based on Sanders' shell theory. Then, the wave propagation approach was presented by Sun [9] to study the free vibration of rotating cylindrical shells and the influence of geometric parameters on the natural characteristics and frequencies at different circumferential wave numbers. Based on the several shell theories mentioned above, scholars around the world carried on a great deal of research about the forced vibration of cylindrical shells under different loads. The transient and steady-state instability of an axially loaded cylindrical shell are analyzed by Goncalves [10], Donnell's shallow shell theory was used and the shell spatial discretization is obtained by the Galerkin method. Lee and Kwak [11] constructed a dynamic model for the free vibration analysis of a circular cylindrical shell by using the Rayleigh-Ritz method and compared the results based on different theories such as Donnell-Mushtari theory, Sanders theory, Flügge theory, Vlasov theory, Love-Timoshenko theory, and Reissner theory and the results under different boundary conditions.

Based on the Flügge thin shell theory, Xiang [12] studied the vibration of circular cylindrical shells with step-wise thickness variations by the state-space technique and the domain decomposition method. Considering the effects of initial hoop tension and the centrifugal and Coriolis forces, Ng and Lam [13] conducted some research on the vibration and critical speed of a rotating cylinder shells subjected to constant axial loads and developed some numerical approaches to analyze the vibration of cylinders effectively. Jafari et al. [14] studied free and forced vibrations of cross-ply laminated circular cylindrical shells with clamped-free boundary subjected to lateral impacts and axial pressures. According to an elastic impact model and Coulomb's friction law, Liu and Cao [15] established a dynamic model of a disk–drum–shaft rotor system with the disk–stator and the drum–stator rubbing, in their paper, they adopted the finite element simulation to validate the disk–drum–shaft coupling structure, and got a good consistency. Unlike from others, Qin [16] used the Finite element method to analyze the vibration characteristics of the bolted disk-drum structure. In his work, the linear shell theory also was adopted for the drum's finite element model.

Rotational drums are often subjected to enormous external physical loads in the working conditions, thus an appropriate theory is necessary to be used to analyze and calculate the simplified models because classical cylindrical shell theories are no longer accurate when the vibration amplitude is close to the thickness [17]. There are a large number of studies on the nonlinear dynamic response of cylindrical shell structures introduced in Ref. [17]. Using a single-mode approach, Lee and Kim [18] studied the nonlinear free vibration of rotating composite cylindrical shells with simple-supported boundary condition. The nonlinear vibration and dynamic instability of axially loaded circular cylindrical shells under both static and harmonic forces are theoretically analyzed by Gonçalves [19] based on Donnell's shallow shell equations. Karagiozis [20] approximated axial bending vibration modal function of cylindrical shells with that of the beam under the clamped-clamped boundary conditions, and then he studied the nonlinear dynamic characteristics of thin-walled circular cylindrical shells under the same boundary conditions. With the Donnell-type nonlinear imperfect shell theory (neglecting in-plane inertia), Jansen [21] analyzed the nonlinear free vibration of laminated circular cylindrical shells, and a multi-mode solution is obtained for simply supported circular cylindrical shells. With a Lagrangian approach and the method of harmonic balance, Rougui [22] investigated the nonlinear free and forced vibration of simply supported circular cylindrical shells. In this paper, a simple approximate transverse displacement expansion including the driven mode and the axisymmetric modes were used for the minimization of the energy function, and it was found that the shell exhibits a softening behavior. Using Donnel's shallow-shell theory and von Karman-type of nonlinearity, Darabi [23] investigated large-amplitude nonlinear instability factor of laminated cylindrical shells under cyclical radial harmonic excitation in the spectral neighborhood of the lowest resonances. Non-linear vibrations of circular cylindrical shells subjected to radial harmonic excitation in the spectral neighborhood of the lowest resonances are investigated by Amabili [24] with four different nonlinear thin shell theories, namely Donnell's, Sanders–Koiter, Flügge-Lur'e-Byrne and Novozhilov's theories. Using Donnell's non-linear shallow-shell theory and considering the effect of viscous structural damping, Pellicano and Païdoussis [25] analyzed the influences of the geometric parameters such as radius, length, and thickness on the nonlinear characteristics of cylindrical shells. Several years later, Pellicano [26] analyzed the linear and nonlinear vibrations of cylindrical shells which connected with rigid disks. In his paper, comparisons were carried out on linear dynamics with experiments and with a finite element model by commercial software. By considering clamped-clamped boundary conditions and uniform temperature change, Zhang and Hao [27] studied on the nonlinear dynamic characteristics of FGM cylindrical shells subjected to an external excitation. Wang and Guo [28] used a numerical method to