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Vibration analysis of bolted joined cylindrical-cylindrical shell structure under general connection condition

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ABSTRACT

Modeling and free vibration analysis of bolted joined cylindrical-cylindrical shell were presented in this paper. First, a new analytical model was established for bolted joints. Second, based on Sanders' shell theory, the dynamic equation of substructure of the assembly structure was formed. Then, by using the connection condition, into which the coupling stiffness between the segments was considered, the vibration differential equation of the assembly structure was established. Finally, the vibration characteristics of bolted joined cylindrical-cylindrical shell were obtained. To test the accuracy of the present method, the frequencies and mode shapes under some special connecting condition were examined with the results obtained by ANSYS and a good agreement was shown. Further, the number of bolts, connecting stiffness and length ratio of the two segments have a significant influence on natural frequency parameters and mode shapes of symmetrical and unsymmetrical structures. The results reveal the vibration characteristics of bolted joined cylindrical-cylindrical shell and are presented to provide useful information for future research. Moreover, some new results would be of signification for assembly structure design and vibration control.

1. Introduction

Shell structures are widely used in aerospace, civil engineering, navigation fields and so on. Therefore, free vibration analysis of cylindrical shell has been deeply investigated by many researchers in past several decades. A literature review was presented by Qatu [1], in which many analytical methods were summarized such as the Ritz method, the Galerkin method, finite element method and so on. Different shell theories were developed and applied, such as Sanders' theory [2,3], Love's theory [4], Reissner's theory [5], Flügge's theory [6], Donnell's theory [7] and so on, and comparisons were made in Refs. [8,9].

For shell structure, boundary conditions are the popular topic for researchers in past few decade years. The simple homogeneous boundary condition, such as simply supported-simply supported (SS), free-free (FF), clamped-clamped (CC) edges, were employed in most of the works [10,11]. As the development of artificial spring technology, cylindrical shells with the elastically supported were investigated [12,13]. Based on this technology, non-uniformly supported cylindrical shells were studied [14,15], in which point supported and line supported were analyzed. For example, Xie et al. [15] used the wave based method to investigate free and forced vibration of cylindrical shells with point and line supports and the effects of location of supported points were studied.

However, in practice, cylindrical shell is not used alone. It is always combined with plates, conical shells or cylindrical shells [16]. The assembly structure of cylindrical-cylindrical shell, which is studied in this paper, is also widely used in engineering and they are usually combined by bolts. To the authors' best knowledge, there are little papers studying vibrations of bolted joined cylindrical-cylindrical shell structure. Zhang et al. [17] studied the vibration of circular cylindrical shells with stepwise thickness variations by the state-space technique and the domain decomposition method. Chen et al. [18] applied wave based method to analyze the free and forced vibration characteristics of cylindrical shells with the discontinuity in thickness. Qu et al. [19] presented a domain decomposition technique for solving vibration problems of uniform and stepped cylindrical shells with arbitrary boundary conditions. Poultangari et al. [20] utilized the extended vectorial wave method for free and forced vibration analysis of cylindrical shells with discontinuities in their thickness in the presence of several intermediate flexible supports.

Although the stepped cylindrical shell is a special kind of cylindrical-cylindrical shell structures, it cannot sufficiently express the connecting characteristic of two shell segments, especially with the same thickness. For coupled structure system, there are some papers about

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vibrations of cylindrical shells combined with plates and conical shells and the coupling effect of the junction was discussed. Ma et al. [21,22] presented vibration analysis of coupled conical-cylindrical shells and cylindrical-plate structures with general elastic boundary and coupling conditions through the modified Fourier series method as well as Rayleigh-Ritz method. Zhang et al. [23] studied the free and forced vibration analysis of circular cylindrical double-shell structures under arbitrary boundary conditions. Xie et al. [24,25] investigated free and forced vibrations of elastically coupled thin annular plate, cylindrical shell and spherical shells with arbitrary boundary conditions and the coupling effect was expressed by the artificial springs.

From the aforementioned references about vibration analysis of cylindrical shell and cylindrical shell combined with other shell or plate structures, it is worth noting that there are rare papers studying free vibration of bolted joined cylindrical shell structure, in which the joined part is discussed in detail. In this paper, Sanders' shell theory is applied to describe the motion of the shell segments. Orthogonal polynomials are used in this paper to express the vibration displacements of the shell segments. The nonlinear connection force are utilized to connect the shell segments, which are connected by bolts in practice. The emphasis of this paper focuses on the interesting, practically important but seldom reported free vibrations of bolted joined cylindrical-cylindrical shell. Boundary conditions are accounted for by using the artificial spring techniques by which complex boundary conditions can be also analyzed. Symmetrical and unsymmetrical assembly structures are considered. The natural frequencies and mode shapes under some special connection conditions are checked against the results obtained by ANSYS, and the good agreements observed the accuracy of the present results. Influences of the number of bolts, connecting stiffness and length ratio on natural frequencies and mode shapes were investigated.

2. Formulation

Fig. 1 shows the picture of an aero-engine casing. It is obvious the casing is consist of several segments though bolted joint. Based on this assembly structure, a bolted joined cylindrical-cylindrical shell is considered as the object of the study in this paper, and the schematic diagram is shown in Fig. 1 (b). The two shell segments were connected by forces of bolts. In the past research, the connect part was always assumed as clamp supported, elastic supported or simple continuity condition. However, contact state at locations of the connecting bolts may be complex when the shell is subjected to external excitations. To analyze the vibration characteristic of the bolted joined cylindrical-cylindrical shell, a coordinate is established. $O_1{-}x_1\theta_1 z_1$ and $O_2{-}x_2\theta_2 z_2$ are located at the geometric center of the left circle of Shell 1 and Shell 2, respectively. And (x_1, x_2), (θ_1, θ_2) and (z_1, z_2) represent the axial direction, the circumferential direction and the radial direction, respectively. The movements of P_1 and P_2 can be expressed by the movement of the points on the middle surface of the shell. u_1, v_1, w_1 and u_2, v_2, w_2 are the displacements in the x_1, θ_1, z_1 and x_2, θ_2, z_2 directions, respectively. The two shell components have the same thickness (h) and radius (R) but the different length (L_1 for Shell 1, L_2 for Shell 2). The material of the cylindrical shells is assumed to be isotropic with the mass density ρ, Poisson's ratio μ and Young's modulus E.

The boundary condition of the cylindrical-cylindrical shell can be represented by three linear springs and a rotational spring in axial, circumferential, radial and rotational directions, respectively [26]. The potential energy of the boundary conditions can be given as

$$U_{boundary1} = \frac{1}{2}\int_0^{2\pi}\left(k_1 u_1^2 + k_2 v_1^2 + k_3 w_1^2 + k_4\left(\frac{\partial w_1}{\partial x_1}\right)^2\right)Rd\theta_1 \quad (x_1 = 0) \tag{1}$$

$$U_{boundary2} = \frac{1}{2}\int_0^{2\pi}\left(k_5 u_2^2 + k_6 v_2^2 + k_7 w_2^2 + k_8\left(\frac{\partial w_2}{\partial x_2}\right)^2\right)Rd\theta_2 \quad (x_2 = 1) \tag{2}$$

where (k_1, k_5), (k_2, k_6), (k_3, k_7) and (k_4, k_8) are the axial, circumferential, radial and rotational stiffness for two ends. And the different boundary conditions can be obtained by setting the value of springs. For example, clamp boundary condition was obtained by setting the spring stiffness to be infinite value, which was represented by 10^{14} Therefore, the method used is also suitable for other complex boundary conditions. The total potential energy of the boundary condition are

$$U_{boundary} = U_{boundary1} + U_{boundary2} \tag{3}$$

As introduced above, the bolted joint is always considered by three methods such as clamped connection, elastic connection or displacement continuity condition. Actually, the mechanical condition at the position of bolts is complex and nonlinear. Because the contact state may be stick, slip and separation when the assembly structure suffers external loads. The deformations can be resolved into the displacements in three directions and a rotating angle, so there are three contacting forces and a bending moment at the bolted joint.

Considering the relative motion in the axial direction, the contact state may be compression or tension. Therefore, the connecting force in axial direction f_{u1} for Shell 1 can be obtained

$$f_{u1} = \begin{cases} k_T(u_1 - u_2) & F_{pre} < k_C(u_1 - u_2) \\ k_C(u_1 - u_2) & F_{pre} > k_C(u_1 - u_2) \end{cases} \tag{4}$$

where k_C and k_T are the compression and tension stiffness in the axial direction, respectively. F_{pre} is the preload of the bolts.

In the rotational direction, k_θ is the rotational stiffness and the bending moment M_1 can be written by:

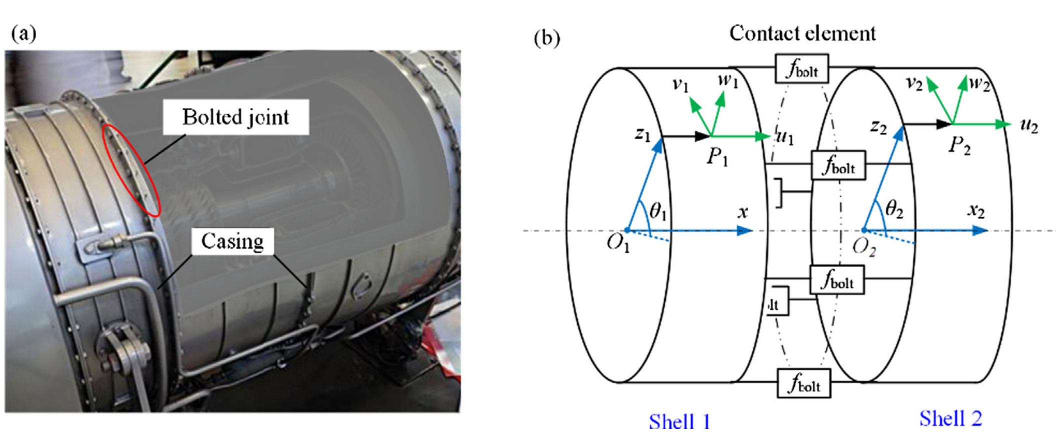

Fig. 1. Simplified model of system and coordinate establishment.