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Mechanical characteristics of deployable composite thin-walled lenticular tubes

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ABSTRACT

In this paper, modal behaviors of composite thin-walled lenticular tubes (CTLTs) in free vibration and cantilever vibration are performed by comparing experimental with numerical outcome. Then, a linear and nonlinear buckling analysis of CTLTs subjected to axial compression are proposed to compare their numerical critical buckling loads with corresponding experimental results. The numerical method to simulate buckling behaviors of CTLTs under axial compressions is also verified. As the flattened and wrapped CTLTs need to be deployed completely in space engineering application, the flattening and wrapping process of CTLTs should be studied by using numerical simulation method due to complexity of composite materials. To explore the change rules of mechanical characteristics of CTLTs and facilitate design of CTLTs, the design parameters of CTLTs in vibration analysis, buckling analysis and flattening and wrapping process are all evaluated.

1. Introduction

Composite materials have been extensively applied in aviation and aerospace due to their high strength, stiffness and stability and ultra-low coefficient of thermal expansion. The composite thin-walled lenticular tubes (CTLTs) can be employed as basic component of deployable space structures. As deployment process of CTLTs is repeatability and highly accurate, it can be used as supporting backbone of cable-net of space deployable parabolic antenna or supporting frames of space planar array [1,2]. Currently, NASA Langley, JPL and Harris have developed various space deployable structures like radial ribs and wrapping ribs and coilable mast [3]. JAXA have studied space flight unit, Muses-V, variable geometry truss and fan-shaped membrane solar sails, deployable antennas in three and six prism components [4]. ESA also manufactured a large amount of space deployable structures like space masts [5]. An agreement was achieved between DLR and ESA, they launched a three-step plan to develop solar sailing technology for space mission and conducted first step of the project at ESA and DLR [6]. Chen et al. [1] proposed the conceptions, three dimensional models and prototypes of space deployable structures. Shen et al. [7–9] performed buckling and post buckling behaviors of carbon fiber tube and cylindrical shell by using analytical solutions. The operation procedure of CTLTs can be described as three steps: package, deployment and transition. The flattening and wrapping process of CTLTs starts from the fully deployed configuration to the flattened and packaged circulation. On the contrary, the wrapped CTLTs can be completely deployed and its shape can be recovered by releasing the elastic energy due to packaged deformation. These two reverse process could be called as CTLT configuration transition, as involves large deformation and potential large strain and complicated mechanism motion and control, and should be paid close attention. The common dynamic response and stability behaviors of CTLTs at fully deployed configuration should also be concerned as a foundation of the CTLTs composite structures.

As the deployable CTLTs is lightweight and low stiffness, CTLTs as thin-shelled structure, applied cycling thermal load in-orbit, control impulse, etc. one CTLT could be assumed in free flight or used as appendage of platform, as cantilever components. Shells are susceptible to dynamic loads causing vibration. The aim of vibration investigation is to identify natural frequencies and mode shapes of structures. Thus, the dynamic response of CTLTs should

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be performed to avoid resonance of structures as an essential requirement for design of these structures. Hemmatnezhad et al. [10] conducted free vibration behaviors of GFRP-stiffened composite cylindrical shells by using experimental, analytical and numerical methods. They obtained a good agreement in the three types of methods. Assaee and Hasani [11] presented forced vibration behavior of thin-walled composite circular cylindrical shells by using spline finite strip method. It is found that the spline finite strip method is effective to be used in transient and harmonic analysis of composite cylindrical shells. Lopatin [12] obtained fundamental frequency of a cantilever composite cylindrical shell by using analytical methods and verified the analytical solutions by comparing with numerical results. Li and Qiao [13] investigated nonlinear vibration behavior of anisotropic laminated composite cylindrical shells and effect of initial stress, geometric parameters on the nonlinear vibration behaviors. ESA and DLR just performed parabolic flight test of expendable deployment mechanism and ground demonstration test of sailing and incomplete in-orbit demonstration [14–16], but they have not reported any further study in the next two steps and detailed experiments and simulation of the CTLTs. Currently, most researches mainly focused on numerical simulation and experiments of cylindrical shell tubes, but lacked the relevant investigation in shell tubes of lenticular cross section with different geometry constraint. As composite material structures are multi-layers and composite structures, their analytical solutions in deformation of cross section could not be obtained by classic Bernoulli or Timoshenko beam assumption. Thus, it is essential to implement numerical simulation and experiments for composite thin-walled lenticular tubes.

The CTLTs subjected to external loads probably buckle after deployment of CTLTs. Geometric characteristics and material property of CTLTs can not only decide their buckling capacity, but structural parameters like single ply, lay-up angle, lay-up thickness, component proportion and characteristics can also have significant effect on stability of composite structures. Buckling process and corresponding critical loading can also affect the design and performance of space deployable structures. As the expected engineering optimization is to obtain optimum equilibrium between local and global stability and lightest weight for composite structures and axial compression is considered as a type of loading to explore their stability behaviors, buckling behaviors of CTLTs under axial compression should be performed to guide the design of CTLTs. A structure system are assumed to be a perfect structure system without any geometric and manufacturing imperfection in classic linear buckling analysis, whereas it could not achieve the perfection in practical application. Therefore, the critical buckling load from linear buckling analysis is greater than realistic critical buckling load. Due to the existence of geometric imperfection in manufacture, the buckling analysis of CTLTs should be considered as a nonlinear buckling analysis. Friedrich et al. [17] considered effect of three types of geometrical imperfections on the load carrying capacity of un-stiffened isotropic thin walled cylindrical shell structures under axial compression. It is found that imperfection pattern in non-rotational-symmetric imperfection and the single perturbation load approach can affect the buckling loads. Ismail et al. [18] analyzed the effect of initial imperfection on the critical buckling load of various composite materials including glass fiber reinforced polymer, carbon fiber reinforced polymer and aluminum by using numerical simulation methods. White et al. [19] assessed the linear and nonlinear buckling analysis of two variable stiffness cylindrical shells under axial compression and compared their results with existing experimental results. A better prediction can be obtained from nonlinear buckling analysis. Kepple et al. [20] numerically simulated buckling behaviors of composite cylindrical shells by using improved stochastic method to model imperfections. Orifici and Bisagni [21] estimated imperfection sensitivity of composite cylindrical shells under compression by using single perturbation load analysis (SPLA) approach and they found that SPLA approach gave a suitable design point for all laminates of composite materials. Lots of investigations have also involved only in buckling analysis of composite cylindrical shells, but they hardly concerned on stability analysis of CTLTs in experiments and numerical simulations. Due to the shape particularity and different constraint modes of cross section of CTLTs, the stability characteristics of CTLTs is various. Thus, to obtain more exact outcome in engineering design, experiments and numerical simulation should be conducted to evaluate the process of wrapping and flattening of CTLTs.

In this paper, the deployable composite thin-walled lenticular tubes are analyzed in terms of modal behaviors in free vibration and cantilever vibration, axial compression experiments and numerical simulations of buckling analysis and parametric study of flattening and wrapping process. In Section 2, the experiments and numerical simulations of modal analysis of CTLTs in free vibration and cantilever vibration are compared each other. Then, the buckling responses of CTLT specimens subjected to axial compression can be estimated by experiments and numerical simulation methods as Section 3. The thickness, numbers and angles of ply lay-up are considered as design parameters to study their effect on the buckling behaviors of CTLT specimens under axial compression. Lastly, the mechanical behaviors of CTLTs in the flattening and wrapping process are predicted by using numerical methods and effect of design parameters on the flattening and wrapping process of CTLTs are also conducted.

2. Modal behaviors of CTLTs

2.1. Theoretical analysis

For finite element analysis, according to Hamilton's principle, free vibration equation of composite thin-walled lenticular tubes can be given as follows:

$$M\{\ddot{v}\} + K\{v\} = 0 \tag{1}$$

where $\boldsymbol{M}$ is mass matrix of CTLTs, $\boldsymbol{K}$ is stiffness matrix of CTLTs, $\boldsymbol{v}$ is amplitude vectors of model nodes.

Thus, the generalized eigen-value equations of CTLTs can be transferred into Eq. (2) below:

$$(K - \omega^2 M)\{\Phi\} = 0 \tag{2}$$

where $\boldsymbol{\omega}$ is vibration frequencies of CTLTs, $\{\boldsymbol{\Phi}\}$ is eigenvalue vectors. In this paper, eigen solver of modal analysis is Lanczos method.

For analytical solutions, free vibration analysis of uniform cross-section beam should ignore its shear deformation, rotational inertia and axial force. Thus,

$$EI\frac{\partial^4 v}{\partial x^4} + \bar{m}\frac{\partial^2 v}{\partial t^2} = 0 \tag{3}$$

where $\bar{m}$ is mass of unit length. According to separation variables method, it is assumed as:

$$v(x,t) = \phi(x)Y(t) \tag{4}$$

Thus, Eq. (3) can be solved by using express (4) substituted into Eq. (3) as follows:

$$\phi(x) = A_1 \sin ax + A_2 \cos ax + A_3 \sinh ax + A_4 \cosh ax \tag{5}$$

$$Y(t) = A \sin \omega t + B \cos \omega t \tag{6}$$

where the four constants A_n in Eq. (5) and constants A, B in Eq. (6) can be obtained by boundary condition of uniform cross-section beam related to shapes and amplitudes of beam vibration.