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Modal behaviors and influencing factors analysis of inflated membrane structures

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ABSTRACT

Accurate modal analysis is the basis to evaluate the dynamic performance of inflated membrane structures, however, it is still a challenge to analyze and testify due to strong nonlinearity of geometry deformation, initial stress and the air-elastic effects. This paper presents modal characteristics of inflated beam and flexible airship envelope. Firstly, an approach to numerically simulate modal behaviors of a plane membrane in the air was validated by testing natural vibration behaviors of plane membranes. This was followed with modal analysis of inflated tube in experimental and numerical methods. The influencing factors for the modal performance of the inflated tube were estimated in terms of boundary condition, internal pressure, elastic modulus and air. Based on this outcome, the verified simulation method was employed to investigate the natural vibration behaviors of flexible airship including dry and wet modal analysis. Thirdly, pressure difference, geometric dimension, welding seam were considered as influencing factors to study their effects on modal characteristics of non-rigid airship hull. Lastly, modal analysis of airship with suspended curtain in self-equilibrium configuration and self-weight and buoyancy was to investigate close practical engineering structural behavior of large airship.

1. Introduction

Stratospheric airship can potentially be used in communication, scientific research and any other civil applications as a particular type of inflatable membrane structures. Airship can fly to station-keeping in the air through a light lifting gas so that it can have long duration, low fuel consumption [1]. Airship structures are developing from rigid airship to semi-rigid airship and flexible airship based on hull configuration with progress of airship technology [2]. Non-rigid airship, which is, flexible airship, has been demonstrated to be the most potential alternative of stratospheric airship. The hull is pneumatically stressed to maintain its stable configuration and enough structural stiffness to take aerodynamic loads, gondola, tail and other concentrated loads, and buoyancy, which could be summarized as dynamic moment, static moment and gradient moment.

Many efforts have been made to support development of the airship technology, Chen et al. [3] evaluated vibration behaviors of a 25 m flexible airship envelope and considered the effect of air on the vibration behaviors of the airship. Li et al. [4] developed three models of structural, thermodynamics and dynamic models of the semi-rigid airship and they studied the thermal performance of airship to guide the structure design of airship. Kang et al. [5] carried out low, room, and high temperatures test for film-fabric laminates made of airship envelope and a close agreement was achieved by comparing experimental results with numerical ones. Chen et al. [6] obtained the key factors affecting tearing strength for the laminated fabrics with central slit as the original manufacturing material of airship by using experimental and analytical models. But aforementioned studies have not carried out a systematic study about modal analysis and modal behaviors of airship structures in vacuum and air based on engineering beam theory.

Due to its lightweight and rather low structural stiffness, airship hull can vibrate easily and experience nonlinear large deformation in the air under the aerodynamic loads, thrust etc. In the meantime, internal and external air can be forced to vibrate together. Thus, effective mass of airship structures should contain mass of internal and external air of flexible airship as added mass. A numerous of researches have investigated nonlinear structural behavior due to large deformation, initial stress and added mass about membrane structures. Xiao et al. [7,8] performed a numerical simulation method to import pre-stress into membrane structures and described wrinkling analysis of membrane structures involving geometric nonlinearity. Apedo et al. [9], Gyuhae et al. [10], Thomas et al. [11] and Nguyen et al. [12] conducted buckling

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analysis of inflated tubes in accordance with engineering beam theory. Wang et al. [13] described the modal analysis and parametric study of wrinkled membrane inflated beams. Tao et al. [14] reported vibration analysis of a novel mesh reinforced membrane beam. Wang et al. [15] compared experimental results of wrinkling analysis and static and modal analysis of a square membrane with nonlinear numerical simulation results, it is found that numerical method can be a good choice to predict the membrane with large deformation. Maheriand Severn [16] compared a number of experimental results about added mass in a flexible structure with classical added mass theory for rigid body vibration. It is found that classical added mass theory is only available to single degree of freedom bodies. Minami [17] proposed the analytical solutions about added mass of a plane membrane vibrating in infinite air and verified his results by comparing with Green's function approach. Yadykin et al. [18] presented a three-dimensional analysis of added mass of a flexible plate oscillating in a fluid. A good agreement with previous test results of a simply vibrating plate. Li et al. [19] assessed a simplified model to estimate the added mass of membrane and verified accuracy and efficiency of the added mass model by an existing membrane structure test. Kukathasan and Pellegrino [20] evaluated effect of air on vibration of pre-stressed membrane structures by using FE simulation, analytical and experimental methods. Veldman et al. [21] induced collapse moment for new model of inflated beam, it was revealed that the new model considering the collapse moment had better correlation than existing model by using experiments. Gosling et al. [22] introduced a very detailed design and analysis of membrane structures by a round robin analysis exercise. Levy et al. [23] reported geometric stiffness matrix of two examples in plane membrane structures using symbolic algebra. Srivastava et al. [24] developed a more realistic model considering fluid-structure interaction between the enclosed fluid and the torus to explore the effect of enclosed fluid on the dynamic response of inflatable structures. Young et al. [25] verified free vibration behaviors of an inflated circular cylindrical Kapton tube and a tensioned rectangular Kapton membrane by experiments comparing with FE models. Ruggiero et al. [26] described vibration of an inflated Kapton torus by using a multiple-input multiple-output (MIMO) modal testing technique. However, most work focused on the analysis and test of simple plane models, the modal analysis and experimental verification in complicated membrane structures are rarely reported yet.

In this paper, a fundamental numerical simulation method to import pre-stress into membrane structures has been introduced and validated, then, the numerical modal analysis method is also verified in Section 2. These methods to analyze influencing factors of inflated tube vibration have been involved in Section 3 due to its similarity with modal behaviors of inflated airship in the air. Based on the verified numerical simulation method to study pre-stressed inflated beam, modal behaviors of pre-stressed flexible airship both in vacuum and air have been numerically conducted in Section 4. Static analyses of airship in two equilibrium systems are also performed. Lastly, the influencing factors such as pressure difference, geometric dimension, welding seams and air added mass and suspended curtain have been reported to assess their effect on vibration behaviors of airship.

2. Methodology and validation

2.1. Modal analysis of plane stressed membrane

2.1.1. Theoretical analysis

For general membrane structures, there are various methods to incorporate the pre-stress into their membrane finite elements. (i) The pre-stress can be defined as a constant stress. Therefore, a form finding analysis has to be done as described in various literature (e.g. force density method [27], dynamic relaxation [28] and updated reference strategy [29]). (ii) The cutting patterns of the membrane structure can be used as the reference configuration in a geometrical nonlinear analysis. Therefore, the pre-stress is the result from the mounting process analysis [30]. However, for fixed shape plane membrane structures, their pre-stress should be generated due to mechanically stressed tension at the proper boundary points or boundary lines. When applying tension to the common tensile membrane structures, the stress of membrane can be created in this step, then the stress of membrane can be automatically carried forward to next step as pre-stress of membrane, and the pre-stressed membrane can be stiffened in the meantime thus, they need not form finding analysis. Whereas for airship structures, its configuration should be designed based on limits of aircraft requirement, aerodynamics and aircraft dynamics. Thus, shape of airship structures should not be decided by means of form finding method of general membrane structures, but should be obtained by identifying proper tension on its curved surfaces to sustain its shape. That is to say, the airship structures can obtain tension geometrical stiffness by being inflated, then stress on the airship surface can be redistributed as load analysis, which is form finding for the curved surfaces of the airships.

Modal characteristics of membrane structures ignoring effect of air or in vacuum circumstance are called as dry modal whereas those considering effect of air or in air are called as wet modal. Membrane structures can generate stable configuration and stiffness after being imported pre-stress into. Thus, for pre-stressed membrane structures, its stiffness can be mainly affected by pre-stress level of membranes. Actually, modal analysis of pre-stressed membrane structures can be regarded as modal behaviors of membrane structures under pre-loads. Thus, for dry modal analysis, equation of modal analysis of membrane structures can be given as [31]:

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

$$\boldsymbol{K} = \sum \boldsymbol{K_e} \tag{2}$$

where $\boldsymbol{M}$ is the mass matrix of membrane structures, $\boldsymbol{K}$ is overall stiffness matrix of membrane structures, $\boldsymbol{r}$ represents displacement vector of membrane structures, $\boldsymbol{K_e}$ is stiffness matrix of elements expressed as follows:

$$\boldsymbol{K_e} = \boldsymbol{K_{el}} + \boldsymbol{K_{nl}} + \boldsymbol{K_{ng}} + \boldsymbol{K_l} \tag{3}$$

where $\boldsymbol{K_{el}}$, $\boldsymbol{K_{nl}}$, $\boldsymbol{K_{ng}}$ and $\boldsymbol{K_l}$ is respectively material elastic stiffness matrix, initial stress stiffness matrix, geometric nonlinearity stiffness matrix and load-dependent stiffness matrix. For the matrix of $\boldsymbol{K_l}$, it can be generated from nonconservative force called as follower force. As modal analysis of membrane structures is perturbation analysis in the equilibrium state and does not involve large deformation and fluid-structure interaction, the $\boldsymbol{K_l}$ is not considered in this paper. According to Eq. (2), the generalized eigen values equation can be obtained as:

$$(\boldsymbol{K} - \omega^2\boldsymbol{M})\phi = 0 \tag{4}$$

where ω is vibration frequencies of membrane structures, Φ is eigen values vectors.

As membrane structures are lightweight and flexible, the effect of air around the membrane structures need be considered when studying the wet modal analysis of membrane structures. According to fluid mechanics [32], the ideal fluid has no shear stresses, viscosity and heat conduction. Its motion equation can be given in the form: