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Study on Inflatable Deployment Characteristics of Flexible Film Wing

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Abstract. The inflation deployment process directly affects the forming and bearing deformation characteristics of the flexible wing. In order to optimize the structural design of the flexible inflatable wing, the inflation deployment process was studied with the finite element simulation calculation for the distribution characteristics of pressure and displacement when the wing is not inflated and after inflation molding. The results show that the inflation process is: for the first stage, when the inflation pressure is lower than the critical forming pressure, due to the effect of gravity, the flexible film wing downward bending, and the skin surface pressure is quite small, while the wing is inflated, the overall deformation and displacement is quite large. for the second stage of inflation molding, the flexible wing has a bearing stiffness, but due to aerodynamic loading upward warping occurred, the pressure of the wing root is large, but the displacement of the wing tip is large, which could provide a valid reference method to study the precision and stability of the flexible wing inflation process.

Introduction

The flexible film inflatable wing has the characteristics of small mass, foldable, small storage space and easy storage, which could be quickly inflated and unfolded and be used for low-altitude and low-speed small unmanned aerial vehicles. Among the working condition, the inflation deployment process is the most critical stage, which will directly affect the stability and reliability of the flight, and even affect the subsequent flight performance of the aircraft including the flight resistance, sometimes even causing the aircraft to stall and unable to continue to fly normally [1-3]. Therefore, the research is very important for the deployment process characteristics of the flexible film wing.

Li Jia et al. [4] based on the application examples of flexible inflatable wing on patrol missiles, and found that parameters such as dynamic pressure, real air velocity, and Mach number could be obtained according to environmental parameters for the design and development of flexible inflatable wings. Peng Lu et al. [5] and others carried out numerical simulation research on the inflation and unfolding process of the slender Z-shaped folding tube, and analyzed the effects of the gravity environment, inflation rate, and restraining force on the damping-controlled inflation unfolding process. scholars [6] also carried out ANSYS modal simulation analysis on flexible film inflatable wings, studied the dynamic characteristics in different states, and found that natural frequency of the structure of the inflatable wing increases with the stiffness. Huo et al. [7] even proposed a deformation scheme of the high-speed inflatable wing, and analyzed the fluid-structure coupling characteristics under typical flight conditions of the high-speed inflatable wing, which showed that the deformation increases with the increase of the internal pressure, and the deformation caused by the aerodynamic load increases significantly with the increase of the flight angle of attack. Mohammad et al. [8, 9] studied the aeroelastic dynamic expansion response of the membrane unit of a flexible membrane paraglider wing，and constructed a cell model of the membrane unit and combined the wind tunnel test to explain the coupling relationship between the flow response around the membrane. Fluent software [10] was used to simulate the aerodynamic performance of the inflatable wing and studied the finite element analysis method to simulate aerodynamic loads. The eigenvector orientation method (EVO) [11] was also used to study the dynamic response prediction rules for rigid wings.

However, few studies have directly analyzed the film loading pressure and deformation simulation of the flexible film wing during the inflation and deployment process, and it can't describe the deformation of the flexible film in an uninflated state.

Based on the existing research results, a typical straight rectangular wing is used as the object, and the finite element analysis method is used to study the effect of aerodynamic pressure on the bearing pressure and deformation of each surface of the flexible film using simulated aerostatic loads.

Flexible Inflatable Wing Modeling

Theoretical Analysis of the Inflation Process

During the inflation process, when the gas is continuously charged, the internal pressure and the volume of the wing will change accordingly. When the flexible wing is not inflated, the flexible wing film only bears its own gravity, and the internal and external pressure difference is quite small:

$$P_{different} \approx 0 \tag{1}$$

Where $p_{different}$ represents the pressure difference between the inside and outside; after inflation molding, because the film has certain load-bearing deformation ability, the volume change is small, at this time the ideal gas state equation is satisfied, and the internal inflation pressure has an approximately linear relationship with the inflation gas mass:

$$P_{different}V_{wing} = (P_{in} - P_{out})V = \frac{m_{gas}}{M} RT_{out}. \tag{2}$$

V represents the forming volume of the inflatable wing; m is the mass of the gas; R is the molar gas constant; T is the ambient temperature. Further, the deformation characteristics can be obtained in conjunction with reference [1]. The finite element method is used for research by establishing a finite element mesh element model; then the force and deformation situation could be obtained.

$$P_{film} / U_{film} = f(P_{in}, P_{out}, V, m_{gas}, T_{out}) \tag{3}$$

p_{flim} and U_{flim} are the bearing pressure and deformation displacement of the flexible film, respectively. The inflatable wing relies on the internal and external pressure difference and internal pull bar to maintain the wing shape and overall bearing stiffness. The inflation process can be divided into two main stages, The first stage is the beginning of filling with gas, the entire structure cannot support the load, the stress in the flexible thin film membrane is nearly zero, and the pressure difference between the inside and outside is almost constant, and the gas undergoes isobaric expansion, the wing undergoes large-scale deformation, and the volume of the wing increases in proportion to the volume of air filled. In the second stage, when the inflation volume is large enough, the structural rigidity increases and could withstand aerodynamic loads, the membrane structure of the wing begins to bear tension, and the internal pressure of the wing is stronger than the environmental pressure to maintain the wing shape with small-scale deformation at the same time.

Finite Element Simulation Model

The inflatable wing is a straight rectangular wing, which is simulated and fixed on one side during the simulation, and the other end is not subject to constraints. The mesh is divided by the finite element software and the structured mesh has the advantages of fast generation speed, good quality, and high calculation accuracy. The aerodynamic simulation load is to analyze the force under the actual working condition and load. The wing root is fixed, and the parameters are set including: the pressure difference is 0.00125 MPa and the aerodynamic load is 0.00016 MPa, considering the weight and aerodynamic load, and the elastic modulus of the flexible film is 1 GPa. The aerodynamic load in the second stage is equivalently loaded on the upper wing surface, and the pressure difference on the upper wing surface is calculated as 0.10254MPa. Then the film characteristic of the first-stage ias shown in Figures 1 and 2 when it is not deployed.

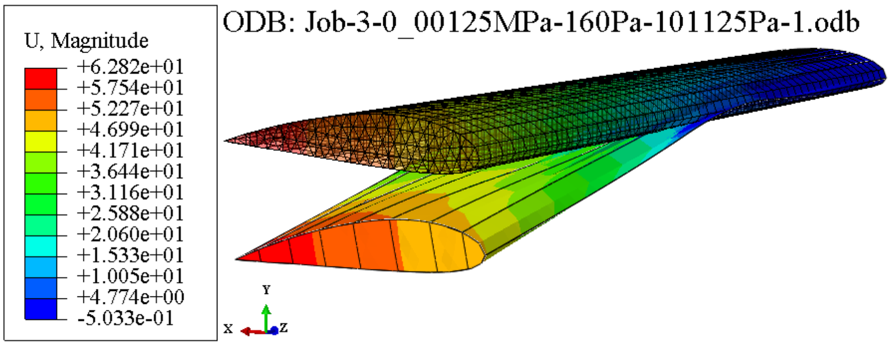

Figure 1. Cloud diagram of the first-stage displacement distribution.

From the Figure 1, the horizontal position is the initial state, and the drooping position is the first state. At the beginning of inflation, the gravity wing sags and bends down. Because the wing root is fixed, When the wing tip sags, it will cause deformation in the central area. The displacement of the wing tip is the largest, reaching 54.4912mm, and the amount of displacement gradually decreases from the wing tip to the wing root. The entire displacement distribution presents a band-like distribution, which is consistent with the pressure distribution of the heavily inflated wing, and it also shows that the flexible film can be folded and compressed for storage when it is not inflated.

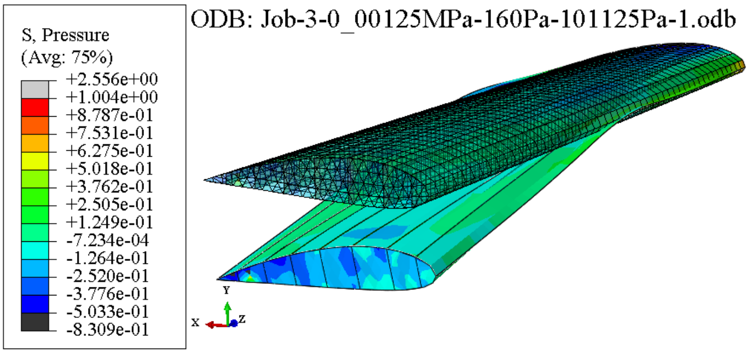

Figure 2. Cloud pressure map of the first stage.

From Figure 2, for the load-bearing and deformation characteristics of the inflatable wing, the pressure of the inflatable wing has a band-like distribution, and the pressure is almost the same at the same distance from the wing root, which is caused by its shape and caused by the structure. The maximum pressure is close to the wing root, with a size of 0.603449MPa, and the minimum pressure is located at the wing tip (0.0344241MPa). In the second stage, considering the weight and aerodynamic load during the inflation flight, the deformation and displacement characteristics and pressure characteristics calculated are shown in Figure 3 and 4, respectively.

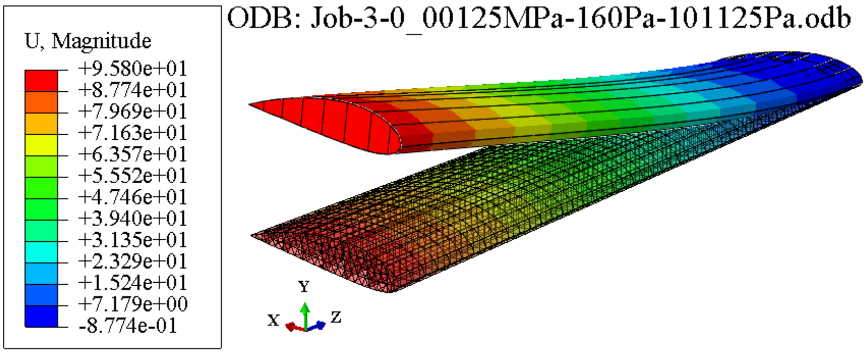

Figure 3. Cloud diagram of the second-stage displacement distribution.

Due to the pressure difference, the inflatable wing warping will occur after inflation with the reinforcement of the ribs. The warping method is that the center of the inflatable wing is depressed downward, because the wing root is fixed, and the wing tip is warped, which will cause the stress distribution to be uneven. The displacement component in the y direction is much larger than the other two directions, almost occupying the size of the total displacement vector. And the rigidity of the flexible film itself in the y direction is much smaller than the stiffness of the other two directions, meanwhile, the aerodynamic simulation load in the upward direction is increased in the second stage, which also causes the wings upward warping is consistent with the actual wing deformation.

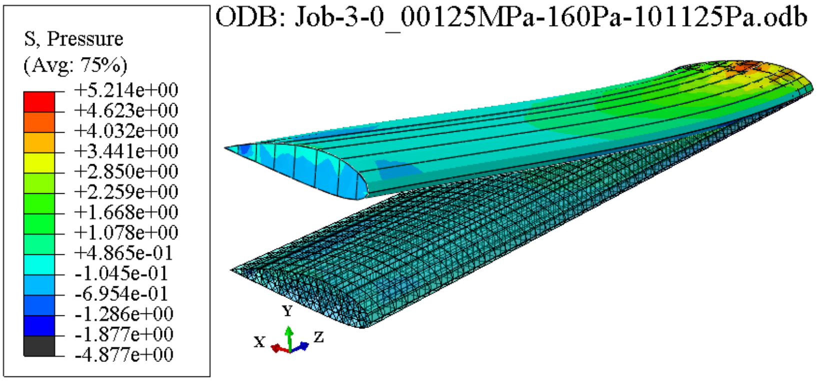

Figure 4. Cloud diagram of the second stage stress distribution.

From Figure 4, the pressure is more evenly distributed on the airfoil surface, which is roughly divided into two sections, and the pressure gradient is large near the wing root. The maximum pressure is close to the wing root (4.47021. MPa), the minimum pressure is located at the tip (0.68189 MPa), and the inflation pressure and displacement data of the middle of the upper airfoil along the flexible film wing span are extracted shown in Table 1. The real model is shown in Figure 5.

Table 1. Deformation and pressure data values in the middle of the upper airfoil.

Node number	unfolded Pressure / MPa	unfolded Deformation/ mm	Pressure during deployment / MPa	Deformation unfolded / mm	Pressure change / MPa	deformation Change / mm
406	-1.375E-01	5.122E+01	5.366E-02	8.898E+01	1.912E-01	3.776E+01
402	-7.992E-02	4.592E+01	-3.434E-02	7.922E+01	4.559E-02	3.330E+01
398	-1.689E-02	4.167E+01	4.165E-02	6.947E+01	5.854E-02	2.780E+01
394	-2.032E-02	3.738E+01	1.642E-01	5.982E+01	1.845E-01	2.244E+01
390	-4.067E-02	3.209E+01	3.427E-01	5.035E+01	3.833E-01	1.826E+01
386	-2.210E-02	2.618E+01	5.775E-01	4.117E+01	5.996E-01	1.499E+01
382	-4.788E-02	2.025E+01	8.631E-01	3.240E+01	9.109E-01	1.215E+01
378	-9.092E-02	1.473E+01	1.212E+00	2.420E+01	1.303E+00	9.474E+00
374	-1.621E-01	1.017E+01	1.625E+00	1.679E+01	1.787E+00	6.619E+00
370	-1.997E-01	6.350E+00	2.080E+00	1.052E+01	2.280E+00	4.170E+00
366	-2.623E-01	2.967E+00	2.504E+00	5.550E+00	2.767E+00	2.583E+00

Figure 5. Physical model of flexible inflatable wing.

From the data in the table 1 and Figure 5, it can be seen that when inflated, the pressure at the wing root is the largest and gradually decreases along the spanwise direction, but the local deformation rate of the wing tip is too large, resulting in a sudden change in local pressure. The tip region has the largest displacement deformation and gradually decreases toward the wing root due to the overall stiffness of the flexible wing, which indicates that the internal pressure of the inflation process has an important effect on the overall film deformation of the flexible film wing. During the design process it is important to consider the changing nature of pressure near the root of the wing.

Summary

When the flexible film wing is not inflated, the pressure of the flexible film is small and it is in a free deformation state, and the flexible wing cannot bear pressure because they have no stiffness. However, due to its own weight, the flexible wing will undergo large free displacement deformation.

When the flexible film wing is inflated, the stress shows a band-like distribution, the maximum stress is near the wing root, and the minimum is at the wing tip, which gradually decreases from the wing root to the wing tip, and its stress distribution is more uniform at the same distance, and the displacement shows a similar change law. The maximum stress is close to the wing tip, the smallest is at the wing root, and it gradually increases along the direction from the wing root to the wing tip, and the stress at the wing root is greater. Under the comprehensive influence of its own weight and aerodynamic load, it is quite necessary to focus on structural optimization design during design.

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