Study on modal properties of flexible inflatable wing skin film structure

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Abstract. The flexible inflatable wing has become a hot research focus both at home and abroad for its unique advantages such as small folding volume, light weight, portability, easy transportation, rapid deployment, low cost and high reliability. However, because the flexible inflating wing is the skin film structure, the overall modal characteristics of the wing are affected by the coupling effects of the film material properties, structural forms, inflation pressure, and many other factors. The multi-air beam aerated wing is taken to construct the mechanical model and the structural modal analysis model. And the first 10 modal frequencies and shapes were solved by ABAQUS linear perturbation. It was found that with the increasing of the modal order, the natural frequency of the system increased significantly, and the mode shapes also increased as well showing a positive correlation. Moreover, the first six modes are mainly the one-span and one-way changes, but from the seventh mode, the modes mainly develop toward the span. The influence of different elastic moduli on the modal characteristics was also studied, and the results confirmed the correlation between the frequencies and mode values of each order was basically the same, which provides an effective method for the inflation mechanics analysis and design of the flexible inflatable structure.

1. Introduction
With the development of materials science and processing technology, the folding inflatable flexible structure has gradually become a new type of structural bearing and weight reduction technology. Under the same structural strength conditions, the structural weight loss rate could be close to 30% [1-3], which makes the inflatable structure application become more and more extensive. In the aerospace field particularly, the foldable inflatable flexible wing has many advantages of lightweight, portability, small folding volume, increased lift, drag reduction, transportation, rapid deployment, low cost, and high reliability, while the conventional wings do not possess. The unique advantages have more and more important research value and engineering application prospects [4-8].

However, because the flexible inflated wing changes drastically with the pressure difference between the internal and external pressures and the aerodynamic load, so the dynamic response is quite complex. Therefore, the load-bearing and dynamic modal response characteristics of the flexible inflated wing skin film must be further studied. Wang [9, 10] took the flexible inflatable membrane structure as the research object, and the unit model of the inflatable membrane structural is established, which is used to study the prestressed modal analysis and the harmonic response analysis of the membrane after inflation molding, and the inherent importance of the previous order is obtained as well as the corresponding curves of frequency, mode shape, etc., and the effect of key parameters on the natural frequency and mode shape. Tan et al [11, 12] analyzed the low-frequency vibration
characteristics of the flexible film aerating wing under low-velocity wind with ANSYS simulation of the dynamic characteristics of the inflatable wing structure, and the thickness of different film materials, the inflation pressure, and the inflation wing were compared. The United States [13-15] has conducted extensive research on inflator wings with unique advantages such as small size, light weight, collapsible deployment, and the ease of transportation. Moreover, the most typical wing is the NASA-I-2000 flexible inflatable developed by NASA Wing aircraft. Andrew [16] of Oklahoma University studied the aeroelastic characteristics of the inflated wing based on UAV wind tunnels and flight tests. Wang et al [11, 17] analyzed the structural vibration of the inflatable bladed wing under pre-inflated internal pressure and obtained the frequencies and modes of the first 10 modes, which showed that the front 10th-order mode changing was affected little by the pressure of the inside and outside inflation gas. Therefore, this paper does not apply pressure load to the wing upper and lower wing skins when constructing the inflation wing modal simulation model. The study of the structural modal characteristics of the flexible wing is helpful to understand the dynamic response and deformation coordination law of the skin film, which is beneficial to promote the inflation mechanics analysis and design of the flexible inflatable film structure.

2. Principle of modal analysis of flexible inflatable wing

Based on the Dalambert's principle or the Lagrangian method, the dynamic vibration response equation of the inflatable wing skin membrane can be established. When the external excitation is zero, the free vibration equation of the multi-degree-of-freedom system can be obtained:

$$[M]\ddot{u} + [K]u = 0 \quad (1)$$

In the above equation, $M$ is the system mass, and the symbol $K$ is the system stiffness, $u$ is the displacement. In the case of micro-vibration, the solution of the above equation can be set as:

$$\chi = \{\varphi\} \sin (\omega t + \alpha) \quad (2)$$

Here, $\omega$ is the vibration frequency (Hz), $\alpha$ is the phase angle, and $\varphi$ denotes the amplitude, $\chi$ is the real vibration response. At the same time, the natural frequency of the system can generally be obtained by solving the generalized eigenvalue problem of the above matrix, namely:

$$([K] - \omega^2[M])\varphi = 0 \quad (3)$$

$$[K] - \omega^2[M] = 0 \quad (4)$$

For $n$ multi-degree-of-freedom systems, there are $n$ system natural frequencies, and these natural frequencies are generally only related to the physical parameters of the system itself and are also independent of other conditions (such as external loads). Substituting frequency values into the equation (3), it can obtain the eigenvector values corresponding to the $n$ system, which is the main mode shape $\varphi$. And the main mode shape can be obtained with each natural frequency, and the main mode shape of each stage is only related to the parameters of the system, and independent of other conditions, so the main mode is also called the natural frequency or the main mode.

3. Modelling and modal simulation of flexible inflatable wing structure

3.1. Flexible inflatable wing modelling

According to the theory of flexible inflatable film approximation forming, the distribution pattern of inflatable wings using internal air beam bracing is shown in figure 1. A typical reference wing model NACA4418 is used as an example to study. The design of the aerated wing structure is shown in figure 2. As bellow. The inflatable wing has a wingspan of 600mm and a chord length of 151.03mm, which is a wing-to-air-to-wing wing-type straight wing with a low airspeed and a high Reynolds number. Inflatable wing skin material is a kind of VECTRAN fiber-reinforced laminated composite film material, which has good airtightness, low ductility and tensile strength, and its breaking strength per unit cm length reaches 350-450N (The uniaxial tensile fracture limit is $\sigma_{t}=259.26$Mpa-333.33Mpa),
and the elastic modulus is about 6Gpa, which is a lightweight high-strength composite material. The parameters involved in the modeling and simulation process are shown in table 1 below.

**Figure 1.** The internal structure of multi air beam inflatable wing.

**Table 1.** Inflatable wing skin film material simulation parameters.

| Parameters    | Elastic Modulus | Skin Thickness | Area Density  | Body Density | Poisson’s Ratio | Film Damping |
|---------------|-----------------|----------------|--------------|--------------|-----------------|--------------|
| value         | 6GPa            | 0.135mm        | 155g/m²      | 9.62963E-10 t/mm³ | 0.3             | 5            |

Considering that the wing fuselage attachment only has a fixed effect on the inflating wing, when the simulation of the intrinsic mode and deformation of the flexible inflated wing is performed, the influence of the deformation of the wing fuselage attachment is not taken into consideration. The body connection only has a fixed effect on the inflator wing, that is, only the inflator wing needs to be studied separately, and the six-degree-of-freedom completely fixed manner is used for restraint.

3.2. Finite element simulation of flexible inflated wings
Using ABAQUS finite element software for modal simulation calculations, one end of the inflator wing is completely fixed and the other end is completely free to restrain. The flexible wing skin membrane is set as a shell (skin) unit, and a linear perturbation mode is used to solve and calculate the first ten modes of the flexible wing, including frequency and mode shape. In order to improve the accuracy of the modal solution, the division of the inflatable wing mesh units are different from the static solution. All wings meshes adopt S4R four-node point curved shell or thick shell element type, which adopts reduced integration and hourglass control and is set to finite membrane strain. And the number of nodes is 4987, while the total elements of the model is 4146. Via the abaqus standard, the mesh model of inflated wing modal simulation is obtained showing in figure 3.

**Figure 3.** Flexible Inflatable Wing Modal Solution Grid Model.

4. Results and discussion of modal characteristic parameters
Using the finite element software simulation, the modal characteristics data could be obtained, including the frequency and mode shape values. The linear perturbation mode is used to solve the calculations. The results of the first 10 steps of flexible aerated wing are shown in table 2.
Table 2. Flexible Inflated Wing Modal Simulation Parameters.

| Order | Modal Frequency | Modal Shape Value | Order | Modal Frequency | Modal Shape Value |
|-------|-----------------|-------------------|-------|-----------------|-------------------|
| Mode 1 | 31.469          | 39097             | Mode 6 | 306.66          | 3.71E+06          |
| Mode 2 | 138.45          | 7.57E+05          | Mode 7 | 307.59          | 3.74E+06          |
| Mode 3 | 160.35          | 1.02E+06          | Mode 8 | 310.93          | 3.82E+06          |
| Mode 4 | 196.92          | 1.53E+06          | Mode 9 | 315.86          | 3.94E+06          |
| Mode 5 | 289.27          | 3.30E+06          | Mode 10| 321.99          | 4.09E+06          |

The modal vibration modes obtained by the finite element simulation are shown in Figure 4. From the mode shape chart, it can be seen that with the increase of the mode order of the wing inflated, the natural frequency of the system increases significantly, and for the low-order mode, the modal frequencies of the states (the 1-5th modes) increase significantly with the order, and the response frequencies of the higher-order modes (6-10th modes) change slowly. And the mode values also follow the modal orders increasing gradually. This shows that the vibration frequency and vibration mode value of the flexible aerated wing system have a positive correlation with the mode orders.

Figure 4. Each mode’s cloud image of flexible wing skin film with the 6GPa elastic modulus.

It can be found that from the vibration pattern the 1st order vibration mode is relatively simple, mainly due to the warping deformation of the direction of view, and the vibration frequency is relatively small, which is only 31.469 Hz. The 2nd order vibration mode is also relatively simple, mainly the bending deformation of the string direction, and the natural frequency rapidly increases to 138.45 Hz. The 3rd order mode has both the bending deformation in the chord direction and the warpage in the span direction, and the warpage at the trailing edge is serious and the natural frequency increases significantly. The 4th order vibration mode has both the warping of the spanwise direction and the bending deformation of the chord direction, and the trailing edge of the wing is also twisted, and the direction of the swing shows a wave-like curve change. The 5th order modes are mainly small...
bending on the leading edge with large bends on the trailing edge, which has a little change in the wing. The bending deformation of the middle of the 6th order vibration wing has little change in the wing root and wing. The 7th order mode has changed significantly from the previous stages, which no longer has the single-wavenumber bending or warping. Instead, it exhibits a two-wavenumber mode shape with no change in the tip of each wing with a bending deformation in the middle. The 8th order mode is a three-wave mode with no change in the end of each wing and a similar middle bending deformation. The 9th order mode is a four-wave mode with no changes at the end of each wing and bending in the middle. The 10th order mode is a five-wave mode with no changes at the ends of the wings and bending in the middle. From the above rules, it is found that the front lower six modes are mainly the variation in the direction and chord direction of the single-wavenumber of the wing, and from the 7th order mode, the modes of the flexible wing mainly develop to the direction of development and the wave number gradually increases with the modal vibration orders.

Taking into account the space temperature and long-term flight easily leading to aging of the flexible inflatable wing skin film, which directly makes its elastic modulus reduce and affect the overall modal characteristics of the inflatable wing. Taking the different elastic modulus of skin material 6GPa and 5GPa as examples, the influence of the elastic modulus of different skin film materials on the modal characteristics (frequency and mode shape) was studied by the simulation shown in table 3 and figure 5, and the resulting modal vibration cloud diagram is shown in figure 6.

Table 3. Vibration Frequency Parameters (Hz) and Mode Shape Value Parameters.

| Order | $E_1=6$GPa ($E_2=5$GPa) | $E_2$ Increment | $E_1=6$GPa ($E_2=5$GPa) | $E_2$ Increment |
|-------|--------------------------|-----------------|--------------------------|-----------------|
| Mode 1 | 31.469 (34.473) 9.54% | 39097 (46916) 9.54% | 19.999% | 39097 (46916) 9.54% | 19.999% |
| Mode 2 | 138.45 (151.66) 9.41% | 1.02E+06 (1.22E+06) 9.60% | 20.21% | 1.02E+06 (1.22E+06) 9.60% | 20.21% |
| Mode 3 | 196.92 (215.72) 9.54% | 3.30E+06 (3.96E+06) 20.05% | 20.05% | 3.30E+06 (3.96E+06) 20.05% | 20.05% |
| Mode 4 | 289.27 (316.88) 9.54% | 4.09E+06 (4.91E+06) 20.04% | 20.04% | 4.09E+06 (4.91E+06) 20.04% | 20.04% |
| Mode 5 | 306.66 (335.93) 9.54% | 3.71E+06 (4.46E+06) 20.21% | 20.21% | 3.71E+06 (4.46E+06) 20.21% | 20.21% |
| Mode 6 | 307.59 (336.95) 9.54% | 3.74E+06 (4.48E+06) 19.87% | 19.87% | 3.74E+06 (4.48E+06) 19.87% | 19.87% |
| Mode 7 | 310.93 (340.61) 9.54% | 3.82E+06 (4.58E+06) 19.89% | 19.89% | 3.82E+06 (4.58E+06) 19.89% | 19.89% |
| Mode 8 | 315.86 (346) 9.54% | 3.94E+06 (4.73E+06) 20.05% | 20.05% | 3.94E+06 (4.73E+06) 20.05% | 20.05% |
| Mode 9 | 321.99 (352.72) 9.54% | 4.09E+06 (4.91E+06) 20.04% | 20.04% | 4.09E+06 (4.91E+06) 20.04% | 20.04% |

Figure 5. Comparison of Vibration Frequency Parameters and Mode Shape Values.

From the figure 5, figure 6 and table 3, it can be seen that with the increasing of the elastic modulus, the overall shapes of the first 1-10 vibration modes do not change significantly, but the vibration
deformation area widens, which indicates that the decrease of the elastic modulus of the skin membrane material leads to the decreasing in the overall stiffness of the wing, and the interaction between adjacent membranes weakens causes the decreasing of the natural frequency of the system, but the reduction of the frequency of each order is basically the same, and the frequency of the modal vibration increases by approximately 9.541% to 9.547%, which shows that with the aging and the elastic modulus decreasing of the flexible film, the vibration frequencies of all modes of the flexible inflating wing will decrease synchronously, which will easily lead to the critical threshold of the flexible inflating wing approaching resonance failure and bring about that the flexibility. As a result, the inflatable wings will become more dangerous.

![Figure 6](image)

**Figure 6.** Each mode’s cloud image of flexible wing skin film with the 5GPa elastic modulus.

For the mode shape value, with the elastic modulus decreasing, the vibration mode value also increases, which also shows a positive correlation with the change of the elastic modulus. For the front 10 modes, the mode shape and the magnitudes of mode shape reductions of the various modes are basically the same under the same elastic modulus conditions. And the mode shape values increase by approximately 19.608% to 20.261%, indicating that with the aging of the flexible film elastic modulus decreasing, each mode vibration response value of the flexible inflatable wing will increase synchronously. Moreover, the 1st and 2nd orders' vibration modes are simple, and the warp deformation and the chord-wise bending deformation of the span-wise direction are still mainly present, and the vibration frequency is relatively small. The 3rd order mode has both the bending deformation in the chord direction and the warpage in the span direction, and the warpage at the trailing edge is serious and the natural frequency increases significantly. The 4th order vibration mode has both the warping of the span-wise direction and the bending deformation of the chord-wise direction. Meanwhile, the trailing edge of the wing is twisted and the direction of the span shows a wave-like curve change. The 5th order vibration mode is mainly the small curvature of the leading edge and the large bending deformation of the trailing edge. The 6th order wing of the vibration mode is
bent and deformed. The 7th order vibration mode has undergone obvious changes from the previous stages, which exhibits a two-wavenumber vibration mode. The 8th mode is a three-wave mode, and the 9th mode is a 4 wave mode. In the wave number mode, the 10th mode is a five wave mode with no changes at the ends of the wings and bending in the middle. From the above rules, it was found that with the decreasing of the elastic modulus of the skin film, the vibration mode is still mainly manifested by the variation in the direction and chord direction of the single-wave number of the front six modes, and from the 7th mode, the flexible wing mode mainly develops to the direction of development and gradually increases the wave number of the mode shape.

5. Conclusions
(1) With the increasing of modal order, the natural frequency of the system increases significantly as well, and the mode shape value shows a positive correlation change, and the modal frequencies of the low-order modes (the 1st-5th modes) follow the order. The number increases significantly, and the response frequency of the higher-order modes (6th-10th order modes) changes slowly.

(2) The front six modes are mainly manifested with the changing of the orientation and chord direction of the single wing, and from the 7th mode, the mode develops to the direction of the display, gradually increasing the wave number of the mode shape, but the frequency and changing amplitude value of each mode are basically the same.

(3) The overall modal shapes of the 1-10 vibration modes do not change significantly with the decreasing of skin film elastic modulus, but the vibration deformation area widens. When the adjacent thin film vibrates, the interaction decreases, and the corresponding frequency increases. This shows that with the aging of the flexible wing film, it will easily lead to a critical threshold near the resonance failure of the flexible inflated wing, which makes the flexible inflatable wing dynamic loading and deformation would become more dangerous.

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References
[1] Yao T and Zhang Y 2008 International Space I 32-35 (in chinese)
[2] Lafayette H S 2011 AIAA-2011 377
[3] Hauser T, Johansen T A and LeBeau Jr R P 2011 AIAA-2011 3534
[4] Wang J J, Li Y C and Choi K S 2008 Progress in Aerospace Sciences 44 22-47
[5] Zhang Q and Ye Z 2015 Journal of aircraft 52(1) 367-371
[6] Li J, Wang H and Fang Y 2015 Flying missile 08 60-64 (in chinese)
[7] Wang Z, Wang H and Jia Q 2011 Journal of Beihang University 37(4) 405-408
[8] Zhang Q and Ye Z 2013 Journal of Applied Mechanics 4 504-509(in chinese)
[9] Wang C 2012 Harbin Institute of Technology (in chinese)
[10] Wang C, Du X and He X 2008 Journal of mechanics 40(3) 331-338 (in chinese)
[11] Tan H, Cui Y, Wang C and et al 2011 The Symposium on the 100th Anniversary of Qian Xuesen's Birth 428-436 (in chinese)
[12] Wang L, Cao H, Wang J and et al 2015 Electromechanical technology 04 62-64(in chinese)
[13] Simpson A and Smith S W 2007 collection of technical papers AIAA aerospace sciences meeting
[14] Michiko U, Suzanne U, Weaver S and et al 2004 AIAA 2004 1373
[15] David T, Raymond P and Lebau J 2011 AIAA 2011 377
[16] Allred R E, Hoyt A E, Harrah L A and et al 2004 AIAA 2004 1809
[17] Wang Y 2015 North University of China (in chinese)