Load and Deformation Characteristics of Flexible Inflatable Wing Films Considering the Deformation Compensation

Longbin Liu[1,a], Yuan Wei[1, b], Hao Wang[1, c], Yicong Jia[1, d], Weihua Zhang[1,e,*]

[1] College of Aerospace Science and Engineering, National University of Defense Technology, Deya Road, Changsha, China

[a]email: longbuaa@163.com, [b]email: wei-0330@163.com, [c]email: 312883488@qq.com, [d]email: jyc13@outlook.com, [e]email:zwh_kjs@163.com

*corresponding author

Keywords: inflatable wing, flexible structure, deformation compensation, initial form

Abstract. The flexible inflatable wings has become a hotspot with its unique advantages such as the lightweight, portability, small folding volume, fast response, low cost and so on. But because the significant geometric deformation of the flexible film appears under the inflatable pressure, which seriously affects the wing load and deformation characteristics. In this paper, considering the obvious geometrical deformation compensation influence, the pressure load, the envelope stress-strain and deformation law are studied for the flexible inflatable wing. And with the example of element of flexible wing film, the characteristics of the initial shape design and film load analysis are researched, and a analysis method of flexible deformation wing is introduced based on the deformation compensation. And the design of the flexible film load considering the deformation compensation could improve the precision of the flexible wing structure after inflating and the surface accuracy of the large deformation surface, meanwhile, the theoretical analysis method is provided for the initial design and processing of the flexible inflatable wing.

1. Introduction

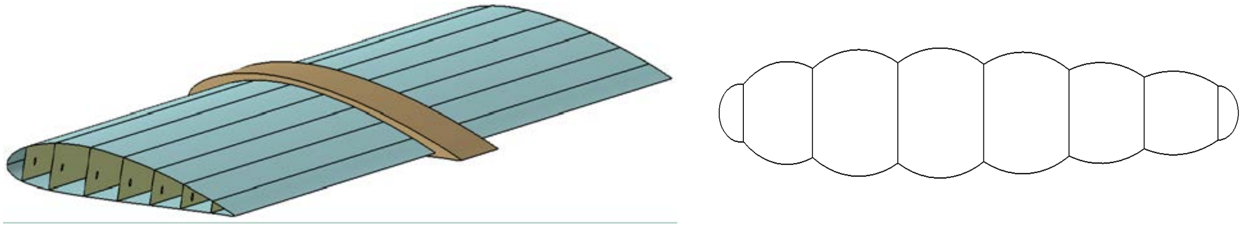
With the progress of materials science and processing technology, folding inflatable structure has become a new type of technology for the structural load and weight loss, with the same structural strength, the structural weight loss of inflatable structure is close to 30%, which is applied more and more widely and involved in many areas [1]. And the structural modal characteristics of the inflatable wing are studied by means of structural design and mechanical with the analysis of conventional wing and flight test. ILC Dover and Kentucky University [2,3] carried out an in-depth study of the inflatable variant aircraft and successfully tested the BIG BLUE inflatable wing. US NASA [4] studied a folding wing expansion technology, and applied that into the inflatable folding wing UAV DrydenI2000, and among the flight test the inflatable wing was expanded with only 0.33 seconds. Harris and Witmer [5,6] changed the airfoil geometry of the inflating surface to improve the aerodynamic characteristics of the high angle of attack for the taking off and landing.

In fact, the flexible wing has obvious elastic deformation under the action of inflatable forming and changing pressure, and the deformation affects the terminal shape of the flexible wing [7], which finally made great influence on the overall bearing stiffness of the flexible wing. Cheng Wujun et al [8] considered the film strain deformation compensation factor for large-scale airship to design the membrane material cutting, which improved the flexibility of film cutting and boom forming accuracy. Based on the principle of strain compensation [9], according to the method of charge pressure, tension level and membrane elastic deformation modulus compensation method, the airship was studied under the basic pressure difference to maintain the expected shape and stiffness. Under the same inflatable situation, with the pressure difference between the inside and outside, flexible thin film deformation compensation range are significantly different.

In this paper, the flexible wing thin film element is taken as the object of study. Considering the influence of the elastic deformation of the film on the load and stress of the flexible wing, and the stress - strain structure of the flexible wing are studied, which could improve the precision of the flexible wing structure after inflating and the surface accuracy of the large deformation surface.

2. Element model of flexible inflatable wing

The flexible inflatable wing is generally a multi-pneumatic or multi-balloon-type configuration of the inflatable drum, which is formed by the internal and external pressure differential to develop the integral stiffness of the flexible envelope to maintain the initial design shape, and the initial shape and the developed inflatable shape are shown in Figure 1.



(a) Initial shape of flexible inflatable wing (b) Inflatable shape of flexible wing

Figure 1 The initial and inflatable shape of the flexible wing.

In fact, the inflated wing grows with the increasing air pressure, and the internal and external pressure increases as well, and the flexible wing envelope has a significant elastic deformation, the result is that the biaxial tensile elongation of the wing envelope occurs, as shown in Figure 2 , *x*, *y* denote the show and chord direction of the flexible wing.

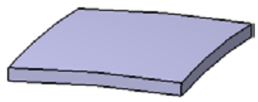


Figure 2 Elastic biaxial deformation of flexible wing envelope films.

According to the quasi-static equilibrium principle of the bearing aerated film [10], the biaxial deformation equation of the thin envelope unit can be constructed, which reflects the physical relationship between the normal deformation and the tensile load and the inflated air pressure of the biaxial elongation film:

$$T_x \frac{\partial_z^2}{\partial x^2} + T_y \frac{\partial_z^2}{\partial y^2} + P_Z - G = 0 \tag{1}$$

Here, T_x, T_y represent the biaxial tension force, x, y represent the geometry of the biaxial element, P_Z is the inflation gas pressure, and G is the face gravity of the flexible film itself. And only considering the gas pressure and its own weight of the flexible wing envelope, the corresponding envelope film biaxial tension (stress) can be further expressed as [11]:

$$\frac{\sigma_x}{R_x} + \frac{\sigma_y}{R_y} = P_Z - G \tag{2}$$

In this equation, R_x and R_y denote the biaxial curvature radius of the thin film unit, σ_x, σ_y represent the envelope stress at the both directions respectively. In the process of the film inflating, with the increasing of the pressure of the inflated gas, the wing film will produce more and more obvious elastic deformation. And the film inflated deformation will lead to change the inflated shape of the formed wing and the volume at the same time, thus internal and external pressure difference will change in the sealer wing chamber, which further causes the changing of internal stress load and deformation significantly of the flexible wing envelope. Therefore, the initial shape design of the flexible wing envelope should consider the deformation compensation.

Considering the strain deformation caused by the biaxial tension of the flexible envelope, it can be obtained by the relationship between the biaxial tension and the strain:

$$\varepsilon_x = \frac{\sigma_x}{E_x} - \mu\frac{\sigma_y}{E_y}; \quad \varepsilon_y = \frac{\sigma_y}{E_y} - \mu\frac{\sigma_x}{E_x} \tag{3}$$

In the equation, E_x and E_y are the biaxial elastic modulus of the flexible film respectively, ε_x, ε_y respectively represent the film biaxial strain, and symbol μ is the Poisson ratio. Equation (3) is transformed into the biaxial tension load shown in Figure 2, and the deformation compensation relation associated with the inflation pressure can be obtained:

$$\varepsilon_x^k = \frac{T_x}{tdyE_x} - \mu\frac{T_y}{tdxE_y}; \quad \varepsilon_y^k = \frac{T_y}{tdxE_y} - \mu\frac{T_x}{tdyE_x} \tag{4}$$

The symbol t is the thickness of the wing film, and the elastic wing film is elastically deformed due to the biaxial tension. Therefore, the biaxial initial length dx and dy of the flexible wing film need to be compensated for deformation compensation before the flexible wing is approached to the standard design range. The biaxial deformation dimensions with the modified deformation compensation can be expressed as:

$$\varepsilon_x^0 = dx(1-\varepsilon_x); \quad \varepsilon_y^0 = dy(1-\varepsilon_y) \tag{5}$$

By bringing the above equation into the physical relations (1) - (3), the physical relationship can be established between the flexible envelope stress and the inflation pressure load without considering the elastic deformation and considering the deformation compensation caused by the elastic deformation. In order to simplify the calculation, it is assumed that the biaxial radius of curvature does not change with the inflated deformation, and only a single typical air chamber of flexible inflatable wing is used as an example to study the effects of isotropic flexible film TPU envelope and Vectran fiber reinforced anisotropic envelope film, and the physical parameters of each material are listed in Table 1.

Table 1 the related parameters of flexible wing envelope material.

Material type	Elastic modulus of x direction	Elastic modulus of y direction	Poisson ratio	Thickness	Face density
TPU envelope	0.85GPa	0.85GPa	0.3	0.12mm	114 g/m2
Fibre reinforced envelope	2GPa	5GPa	0.3	0.16mm	135g/m2

According to the ideal gas state equation, considering the deformation compensation under the condition of different inflatable gas pressure, the influence of the stress and strain inside the flexible wing envelope is considered, and the influence of the gas temperature changing on the internal gas pressure under the inflation condition is not taken into account. According to the biaxial constitutive equation of the flexible wing film, the changing relationship of the biaxial internal stress of the flexible wing under the different pressure of 25kpa, 45 kpa and 75 kpa are calculated by the numerical calculation. And the stress calculated results are shown in Table 2 , The corresponding strain changing values are shown in Table 3.

Table 2 Comparison of stress calculation considering deformation compensation.

Material type	Press-ure /kPa	Stress of x direction /Pa	Stress of y direction /Pa	Compensation stress of x direction /Pa	Compensation stress of y direction /Pa	Deviation of x direction	Deviation of y direction
TPU envelope	25	3432.55	8620.30	3394.54	8525.26	1.11%	1.10%
TPU envelope	45	6191.17	15516.86	6068.90	15211.18	1.97%	1.97%
TPU envelope	75	10329.10	25861.68	9993.38	25022.38	3.25%	3.25%
Fibre reinforced envelope	25	3429.66	8620.23	3419.60	8595.10	0.29%	0.29%
Fibre reinforced envelope	45	6188.28	15516.79	6155.72	15435.39	0.53%	0.52%
Fibre reinforced envelope	75	10326.21	25861.61	10235.94	25635.95	0.87%	0.87%

Table 3 Comparison of strain calculation considering deformation compensation.

Material type	Press-ure /kPa	Stress of *x* direction /Pa	Stress of *y* direction /Pa	Compensation strain of *x* direction /Pa	Compensation strain of *y* direction /Pa	Deviation of *x* direction	Deviation of *y* direction
TPU envelope	25	9.958E-04	1.014E-02	9.847E-04	1.003E-02	1.12%	1.10%
TPU envelope	45	1.807E-03	1.826E-02	1.771E-03	1.790E-02	1.99%	1.97%
TPU envelope	75	3.024E-03	3.043E-02	2.925E-03	2.944E-02	3.27%	3.25%
Fibre reinforced envelope	25	1.198E-03	1.724E-03	1.194E-03	1.719E-03	0.29%	0.29%
Fibre reinforced envelope	45	2.163E-03	3.103E-03	2.152E-03	3.087E-03	0.53%	0.52%
Fibre reinforced envelope	75	3.611E-03	5.172E-03	3.580E-03	5.127E-03	0.87%	0.87%

3. Deformation compensation calculation analysis results

3.1 Stress - strain analysis under the condition of inflation pressure

According to the stress-strain data of the TPU flexible film and the anisotropic vectran fiber-reinforced flexible envelope calculated in Tables 2 and 3, it can be shown that under the same inflated gas pressure condition, the biaxial (*x*, y direction) stress changes and the strain error changes of the isotropic material film are closer.

The stress calculation error of the TPU flexible film of isotropic material under the inflated gas pressure of 25kpa is (1.11% in the x direction and 1.10% in the y direction), which is significantly higher than that of the anisotropic vectran fiber reinforced biaxial to the calculation error (x direction 0.29%, y direction 0.29%).

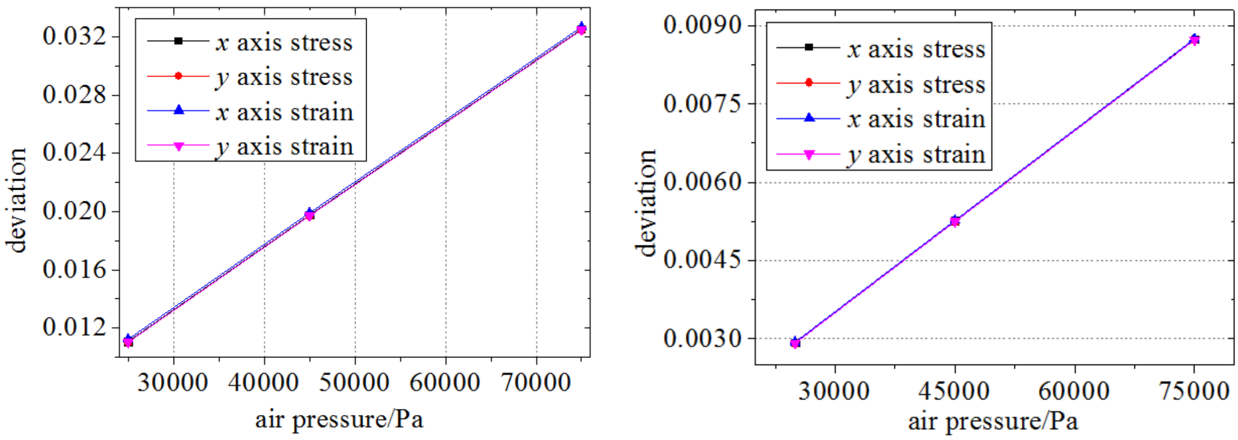
With the increase of the inflation pressure, the stress calculation error of the TPU flexible film of the isotropic material increases gradually. When the inflation pressure increases from 25kpa to 75kpa, the compensation error of the stress deformation in the biaxial x and y directions increases to 3.25%. While the anisotropic material also showed the same trend, but the change was significantly smaller. For the strain calculation error, the same error trend is obtained with the stress calculation error, but the strain calculation error value is slightly higher than the stress calculation error.

It can be seen that under the same inflated pressure condition, the data error obtained by considering the deformation compensation calculation is in the smaller range (<5%), and the biaxial stress calculation error and the strain calculation error are close, indicating that in the process of inflating the flexible wing, it is necessary to consider the biaxial stress-strain deformation compensation error of both latitude and longitude.

3.2 Deformation errors analysis of isotropic materials under different inflation pressure conditions

In the case of different inflated pressure, 25kpa, 45kpa and 75kpa are used as examples to study the calculation deviations of stress-strain deformation of isotropic TPU film (shown in Fig.3(a)).

It can be seen from the curve in the figure that when the pressure of the inflated gas increases from 25kpa to 75kpa, the error in the x direction increases from 1.11% to 3.25%, the stress error in the y direction increases from 1.10% to 3.25%, the error in the x direction increases from 1.12% to 3.27%, the stress error in y direction increased from 1.10% to 3.25%. It is shown that the calculation errors of the biaxial stress and strain of the isotropic materials increase with the increase of the inflated gas pressure, and the calculation error of strain changes synchronously with the stress calculation error considering the inflation deformation compensation. Therefore, for the flexible inflatable wing, the effect of deformation compensation on the initial deformation of the flexible wing needs to be taken into account, and the influence of the deformation of the flexible envelope film caused by the change of the internal pressure of the flexible wing during the flight.



(a) Isotropic TPU film (b) Anisotropic fiber reinforced film

Figure 3 Biaxial stress-strain deformation compensation errors under different inflation pressure.

3.3 Errors analysis of anisotropic material deformation compensation under different inflation pressure

For the anisotropic materials in the case of different inflation pressures, we also use 25kpa, 45kpa and 75kpa to the calculation and analysis. The deformation of the anisotropic material vectran fiber reinforced flexible film compensation of the calculation error of stress-strain is shown in Fig.3(b) above.

It can be seen from the curve that when the pressure of the inflated gas increases from 25kpa to 75kpa, the stress error in the *x* and *y* biaxial directions increases from 0.29% to 0.87%, and the strain error also increases from 0.29% to 0.87%. This shows that for the anisotropic material, the deformation compensation error is much smaller than the isotropic material under the same inflatable pressure conditions because the biaxial elastic modulus is relatively large. However, the deformation compensation error has the same trend, that is, the calculation error of the biaxial stress and strain increase with the inflation pressure, and the calculation error of the strain changes with the calculation error of the stress. Therefore, it can be deduced that when the inflation pressure is larger, it is necessary to consider the influence of the deformation compensation error of the flexible film on the initial deformation of the flexible wing, and consider the flexible envelope film caused by the change of the internal pressure of the flexible wing during the flight Deformation effect.

4. Conclusion

1) Under the same inflated pressure condition, the data error obtained by the deformation compensation calculation is in the small range (<5%), and the calculation errors of biaxial stress and strain are close.

2) For the flexible wing films with the isotropic materials, the calculation errors of stress – strain caused by the deformation compensation are large, and the calculation errors of biaxial stress and strain increase with the increase of the inflation pressure, and the calculation error of strain synchronization changes with calculation error of stress.

3) For anisotropic materials, the variation of the calculation error is consistent with that of the isotropic material, but under the same inflation pressure, the deformation compensation error is much smaller than that of the isotropic material. When the inflation pressure is larger, it is necessary to consider the influence of the deformation compensation error of the flexible film on the initial deformation of the flexible wing.

Acknowledgement

In this paper, the research was sponsored by the Research project of National University of Defense Technology (Project No. ZK16-03-33).

References

[1] Yao Taotao, Zhang Yuzhu. Experiment Analysis of Inflatable System of Expandable Spacecraft [J]. International Space, 2008,01: 32-35 (in chinese).

[2] Lafayette H S．Computational investigation of flow over in floatable airfoils at maniple Reynolds numbers[R]． AIAA-2011-377, 2011．

[3] Hauser T，Johansen T A，LeBeau Jr R P．computational optimization of a low Reynolds number inflatable airfoil[R]． AIAA-2011-3534, 2011． .

[4] James E Murray，Joseph W Pahle，Stephen V Thornton。et a1．Ground and flight evaluation of a small scale inflatable winged aircraft[R]． AIAA-2002-0820, 2002.

[5] Wang J.J., Li Y.C. and Choi K.S. Gurney flap –lift enhancement, mechanisms and applications [J]. Progress in Aerospace Sciences, 2008, 44:22-47.

[6] Zhang Qing, Ye Zhengyin. Novel Method Based on Inflatable Bump for Vertical Tail Buffeting Suppression[J]. Journal of aircraft, 2015, 52(1):367-371 (in chinese).

[7] Cui Yujia.Three-dimensional initial morphological analysis of inflatable wing [D]. Harbin Institute of Technology, 2012 (in chinese).

[8] Chen Wunjun, Xiao Weiwei, Ren Xiaoqiang et al. Cutting design procedure for large non-rigid airship envelope[C]. Beijing: 2007 Float Conference, 2007, 369-373 (in chinese).

[9] Xiao Weiwei, Chen Qinjun, Fu Gongyi. Design and analysis method for cutting and patterning of the envelope fabric of double axis ellipsoid form airship [J]. Spatial structure, 2008,13(4): 55-57 (in chinese).

[10] Xie Changchuan, Wang Weijian, Yang Chao. Analysis of flutter characteristics of inflatable wing [J] .Journal of Beijing University of Aeronautics and Astronautics, 2011,37 (7): 833-838.

[11] Wang Wenjun, Li Yong, Yao Wei, et al. Estimation of the Relationship between the Pressure in Airship Ballonet and the Tension [J]. Journal of Astronautics, 2007, 28 (5): 1109-1112 (in chinese).