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STRUCTURAL DESIGN AND FLUTTER ANALYSIS OF SWEPT BAFFLED INFLATABLE WING

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Abstract

Inflatable wing is an inflatable membrane structure applied to the aerodynamic surface of aircraft which has unique advantages. It is a special structure with promising benefits for application of small aircraft platforms with limited volume because of the characteristics like light weight, small storage volume and rapid deployment. However, the rippled surface and stereotyped structural configuration limit the performance of traditional baffled inflatable wings. Based on the combination of traditional structure and aeroelastic tailoring design, a design method of a new inflatable wing with swept arranged inflatable beams named swept baffled inflatable wing is proposed to realize the purposeful design on shape and stiffness distribution for improving the aerodynamic and aeroelastic performance. Geometric design method of swept baffled inflatable wing is discussed. On this basis, the aerodynamic characteristics are compared and analyzed by computational fluid dynamics method, the wet mode is analyzed with considering the influence of air and the flutter characteristics are analyzed and compared by frequency domain method. The results show that the swept baffled structure can improve the lift drag ratio and delay the classical flutter, so as significantly improve the aerodynamic and aeroelastic performance of the inflatable wing. Works in this paper are of positive significance for the design and application of inflatable winged aircraft.

Keywords: Inflatable wing, Structural design, Aerodynamic characteristics, Flutter analysis

1. Introduction

Inflatable wing has the advantages of light weight, portability and low cost. It is widely used in loitering munition and unmanned aerial vehicle (UAV) [1-7]. The chordwise rippled surface of the traditional baffled inflatable wing leads to a high drag [8-10], and the high flexibility of the membrane structure leads to serious aeroelastic effect [11-17], which limits the application of inflatable wing. Due to the unique mechanical behavior and structural configuration of inflatable membrane structure, the aeroelastic design method for traditional rigid wing is difficult to apply to inflatable wing. Therefore, it is of positive significance to develop an aeroelastic design method for inflatable wing.

Focusing on the shortcomings of the traditional configuration, a new swept baffled inflatable wing with swept arranged inflatable beams is proposed based on the principle of aeroelastic tailoring. The aerodynamic characteristics, structural dynamic characteristics and flutter characteristics of the swept baffled inflatable wing are analyzed and compared with the traditional baffled inflatable wing. The results show that compared with the traditional configuration, the swept baffled inflatable wing has significant advantages in performance.

2. Structural design

According to the structural configuration, the inflatable wing is mainly divided into two types: multi tube type and baffled type [18]. Due to the better bearing capacity, the baffled inflatable wing is more widely applied [15]. However, due to the rippled shape and the high flexibility of membrane structure, the aerodynamic and aeroelastic characteristics of the baffled inflatable wing are mediocre, which limits the airworthiness of inflatable wing aircraft to a certain extent. Because the aerodynamic shape is directly affected by the structure, the structural configuration and design method of inflatable wing need to be further developed.

Some scholars [18-20] have proposed the design method of baffle inflatable wing based on the bubble principle, and achieved ideal results. On this basis, focusing on the shortcomings of the traditional baffled inflatable wing in aerodynamic and flutter performance, and according to the aeroelastic tailoring principle, the swept baffled inflatable wing is proposed in this paper. The design method is as follows:

Taking the rectangular wing with symmetrical airfoil as an example, for the wing with determined geometric parameters and airfoil, the main design parameters are spacing x and swept angle θ of inflatable beam. The total length l of a single air beam can be expressed as:

$$l = \frac{b_r}{\cos\theta} \tag{1}$$

Where b_r is the chord length of the original airfoil after rounding the trailing edge. A designed swept baffled inflatable wing as shown in Figure 1 can be obtained by the following steps: (a) Arraying inflatable beams according to x. (b) Cutting off the array according to the target geometry after trimming. (c) Filling the baffles and tip.

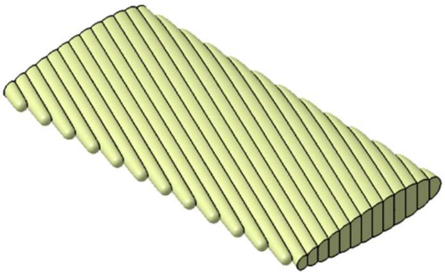


Figure 1 – Geometric model of swept baffled inflatable wing.

3. Aerodynamic characteristic analysis

Different from the airfoil of traditional baffled inflatable wing formed by inscribed circle, the airfoil of the swept baffled type is formed by inscribed elliptical. Under the same number of inflatable beams at section, the ripple of the swept baffled type is shallow, so the approximation effect to original airfoil is ideal, as shown in Figure 2. In order to verify the aerodynamic performance of the proposed configuration, the lift drag characteristics at different angles of attack are analyzed by computational fluid dynamics (CFD).

The parameters of the designed inflatable wing are shown in Table 1. In order to improve the analysis efficiency, the spalart allmaras (S-A) single equation turbulence model is selected, which with a high solution efficiency for macro flow. The boundary condition is set as the pressure far-field, the airspeed is set as Ma 0.2, the angle of attack (AOA) is set as 0 ° and 5 ° respectively, and the pressure, density, momentum and vorticity viscosity are set as the second-order upwind format.

The results are shown in Table 2 and Table 3. When the number of cross-section air beams is the same, the swept baffled type has more ideal lift drag characteristic. There are some performance differences between the forward and backward swept schemes. It is considered that the incoming flow is guided by the ripples between the air beams, forming spanwise flow and changing the distribution of wing tip vortices, thus affecting the induced drag, as shown in Figure 3.

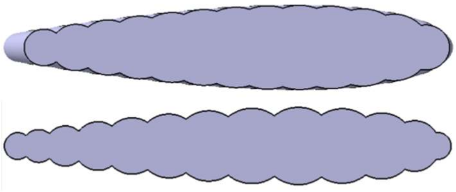
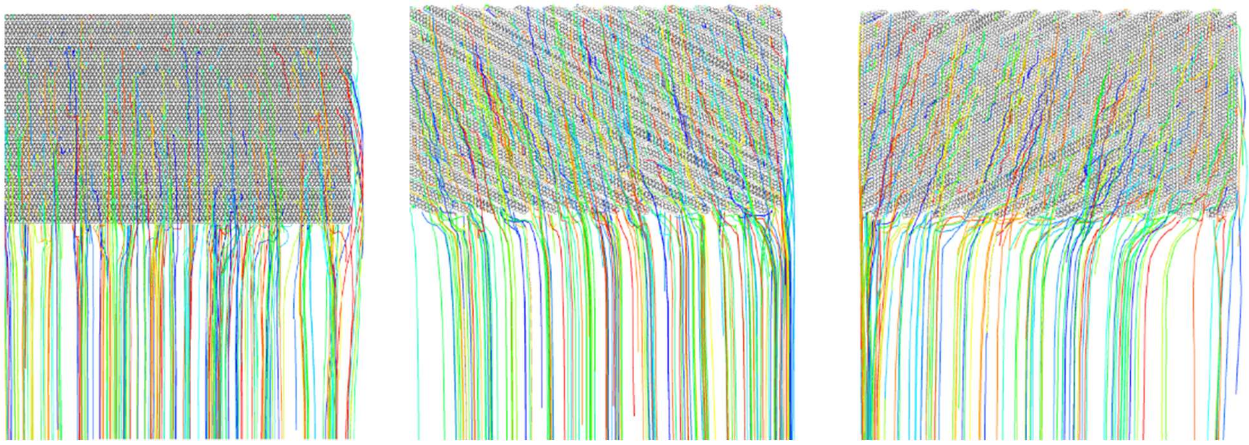


Figure 2 – Airfoil comparison of swept baffled and baffled inflatable wings.



(a) Path lines of integral inflatable wing at 5° AOA (b) Path lines of forward-swept beam inflatable wing at 5° AOA (c) Path lines of swept beam inflatable wing at 5°AOA

Figure 3 – Comparison of path lines of inflatable wings at 5° AOA.

Table 1 – Geometric parameters of inflatable wing

θ°	number of inflatable beams at section	Chord length /mm	Aspect ratio	Airfoil
0	13	433.6	1.85	NACA0016
66		405.5	1.98	
-66				

Table 2 – Comparison of aerodynamic performance of inflatable wing at 0°AOA

θ /°	0	66	-66
Lift /N	0	0	0
Drag /N	51.00	36.21	39.54
Drag reduction ratio	-	29.00%	22.47%

Table 3 – Comparison of aerodynamic performance of inflatable wing at 0° AOA

θ/°	0	66	-66
Lift /N	277.59	258.60	258.93
Drag /N	61.98	45.09	49.11
Lift drag ratio	4.480	5.735	5.272
Proportion of lift drag ratio increased	-	28.01%	17.68%

4. Analysis of structural dynamic characteristics

4.1 Dynamic modeling of inflatable membrane structure

4.1.1 Dynamic modeling of prestressed membrane structure

The membrane balances the load outside the plane by forming the tension. For the inflatable membrane structure, the tension is mainly caused by the inflatable internal pressure. Assuming that the membrane material is isotropic, the equilibrium equation of prestressed membrane of micro element is as follows:

$$T_x \frac{\partial^2 z}{\partial x^2} + T_y \frac{\partial^2 z}{\partial y^2} + p = 0 \tag{2}$$

$$T_x = \frac{1}{2} Eh \left(\frac{\partial z}{\partial x} \right)^2 \tag{3}$$

$$T_y = \frac{1}{2} Eh \left(\frac{\partial z}{\partial y} \right)^2 \tag{4}$$

Where h is the film thickness, E is the young's modulus of the film material and p is the load on element. Substituting equations (3) and (4) into equation (2), the static equilibrium equation of prestressed membrane structure is obtained:

$$\frac{Eh}{2} \left[\left(\frac{\partial z}{\partial x} \right)^2 \left(\frac{\partial^2 z}{\partial x^2} \right) + \left(\frac{\partial z}{\partial y} \right)^2 \left(\frac{\partial^2 z}{\partial y^2} \right) \right] + p = 0 \tag{5}$$

For the vibrating prestressed membrane, the shape of the membrane after compression deformation can be taken as the reference configuration. The set *xoy* plane is consistent with the plane after static deformation of the membrane. It is assumed that the vibration displacement w in the Z direction perpendicular to the *xoy* plane is small, and the tension change caused by vibration can be ignored. Then the differential equation of motion of the free vibration of the membrane is [15]:

$$\rho \frac{\partial^2 w}{\partial t^2} = T_x \frac{\partial^2 z}{\partial x^2} + T_y \frac{\partial^2 z}{\partial y^2} \tag{6}$$

4.1.2 Wet mode modeling

When the structure vibrates in the fluid, it will be affected by the added mass of the fluid attached to the surface of the structure and the viscous blocking effect. The dynamic characteristic of the structure is wet mode. It is different from the dry mode without considering the fluid [21]. Previous studies have shown that the influence of air needs to be fully considered in the analysis of dynamic characteristics of inflatable membrane structure [22-25]. Therefore, this paper will analyze the wet mode of inflatable wing to lay the foundation for subsequent work.

The analysis methods of wet modal can be mainly divided into added mass method and fluid structure interaction (FSI) method. The added mass method regards the influence of air on the structure as the additional mass attached to the structure at the material interface, and the FSI method regards air as the potential fluid and couples the flow field with the structure through the boundary coordination conditions of the interface. In order to accurately reflect the effect of flow field on the structure, the fluid structure coupling method is used to analyse the wet mode of inflatable wing [23]. For ideal incompressible fluid, the basic equation under small disturbance is:

$$\nabla^2 P = 0 \tag{7}$$

Where P is the hydrodynamic pressure. The boundary conditions are:

$$\left. \begin{aligned} &\frac{\partial P_1}{\partial n} = -\rho \ddot{u}_n \\ &\frac{\partial P_2}{\partial n} = 0 \\ &P_3 = 0 \\ &\frac{\partial P_4}{\partial m} = 0 \end{aligned} \right\} \tag{8}$$

Where P_1 to P_4 are the dynamic pressure at the fluid solid interface, fixed interface, free surface and infinite boundary respectively, n and m is the normal direction of the interface, $\ddot{u}_n$ is the normal acceleration and ρ is the density of fluid. The finite element equation is established by Galerkin method:

$$\left. \begin{aligned} &HP + \rho B \ddot{r} = 0 \\ &H = \iiint_{\Omega} \nabla N \nabla N^T d\Omega \\ &B = \left(\iint_{S1} N N_S^T dS_1 \right) \Lambda \end{aligned} \right\} \tag{9}$$

Where N is shape function of fluid element, Ω is fluid element, N_S is shape function of interface, S_1 is area of interface, Λ is coordinate transformation matrix and r is displacement vector. The motion equation of structure can be expressed as:

$$M_S\ddot{r} + C_S\dot{r} + K_S r = F_e + F_e^{P} \tag{10}$$

Where M_s is mass matrix of structure, C_s is damping matrix of structure, K_s is stiffness matrix, F_e^P is dynamic force at interface and F_e is external excitation vector. According to the principle of virtual work:

$$B^T P = F_e^{P} \tag{11}$$

It can be obtained by simultaneous equations (8) - (11):

$$\left.\begin{aligned} &(M_S + M_A)\ddot{r} + C_S\ddot{r} + K_S r = F_e \\ &M_A = \rho B^T H^{-1} B \end{aligned}\right\} \tag{12}$$

Where M_A is added mass matrix of fluid, which represents the influence of flow field on structure [25].

4.2 Wet modal analysis of inflatable wing

In order to verify the accuracy of the established model, the inflatable beam is selected as an example to be verified. The geometric, material parameters and boundary conditions are consistent with previous studies. Inflation internal pressure is 1 kPa [25] and the Lanczos method is adapted to analyze modal parameters. Average error of the results is 6.35%, and the modal shapes appear in pairs, which is consistent with the previous research, as shown in Figure 4 and Table 4. Therefore, it is considered that the accuracy of the constructed model is desirable.

On the basis of the verified method, the wet modal analysis of the inflatable wing with different θ is conducted. Referring to the previous research, the same membrane material as the inflatable beam is selected. The wing root is fixed and the internal pressure is 5 kPa. The results show that the swept angle has an obvious effect on the vibration mode of the swept baffled inflatable wing. The natural frequency of bending mode increases slightly, while the natural frequency of torsional mode decreases, as shown in Figure 5 to 6 and Table 5.

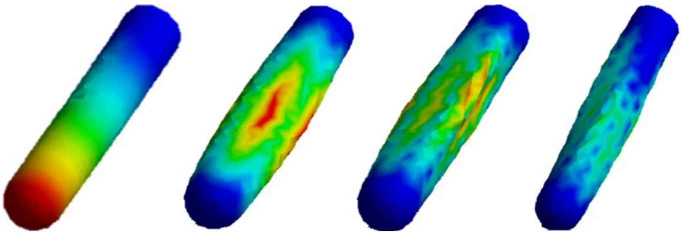


Figure 4 – Wet modal shape of inflatable beam

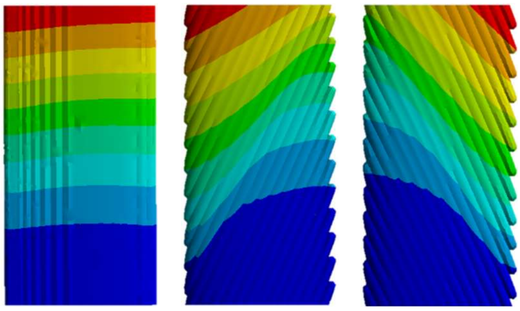


Figure 5 – 1st wet modal shape comparison of inflatable wings

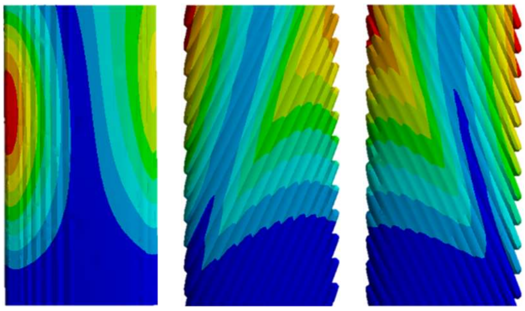


Figure 6 – 2nd wet modal shape comparison of inflatable wings

Table 4 – Natural frequencies comparison of inflatable beam in wet mode

Natural frequency order	1	3	5	7
Simulation result /Hz	16.605	32.159	40.129	62.239
Result in [26]/Hz	17.091	35.591	44.332	60.771
Average error	6.35%			

Table 5 – Natural frequencies comparison of inflatable beam in wet mode

θ/°	0	66	-66
Frequencies of 1st wet mode /Hz	14.377	14.656	15.542
Frequencies of 2nd wet mode /Hz	45.516	40.783	40.697

5. Flutter analysis

5.1 Mechanical modeling of flutter

For the two degree of freedom wing shown in Figure 7, the motion equation can be expressed as:

$$\left.\begin{aligned} m\ddot{h} + S_\alpha \ddot{\alpha} + K_h h &= L \\ S_\alpha \ddot{h} + I_\alpha \ddot{\alpha} + K_\alpha \alpha &= M_E \end{aligned}\right\} \tag{13}$$

Where m is mass of wing section, h is deflection at elastic axis of wing, S_α is the static moment of the wing section to the elastic axis, K_h and K_α are the bending and torsional stiffness of the wing respectively, L is aerodynamic force, I_α Is the inertia of the wing section to the elastic axis and M_E is the aerodynamic moment. It is assumed that the wing vibrates harmonically during flutter, which can be expressed as:

$$\left.\begin{aligned} h &= h_0 e^{i\omega t} \\ \alpha &= \alpha_0 e^{i\omega t} \end{aligned}\right\} \tag{14}$$

The flutter determinant can be obtained by simultaneous equations (13) and (14):

$$\left|A_F\right| = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \tag{15}$$

$$\left.\begin{aligned} a_{11} &= \frac{m}{\pi\rho b^2}\left[1-\left(\frac{\omega_h}{\omega_\alpha}\cdot\frac{\omega_\alpha}{\omega}\right)^2\right]+L_h \\ a_{12} &= \frac{m}{\pi\rho b^2}x_\alpha + L_\alpha - (\frac{1}{2}+\alpha)L_h \\ a_{21} &= \frac{m}{\pi\rho b^2}x_\alpha + M_h - (\frac{1}{2}+a)L_h \\ a_{22} &= \frac{m}{\pi\rho b^2}r_\alpha^{\,2}\left(1-\frac{\omega_\alpha^{\,2}}{\omega^2}\right)+M_\alpha \\ &\quad -(\frac{1}{2}+a)(L_\alpha+M_h)+\left(\frac{1}{2}+a\right)^2 L_h \end{aligned}\right\} \tag{16}$$

Where ω_α and ω_h is the natural frequencies of pure torsion and bending modes of the wing section respectively, x_α Is the distance from the center of gravity to the elastic axis, r_α is the radius of gyration of the elastic axis, a is the distance from the elastic axis to the half chord length. The leading direction is set to positive direction.

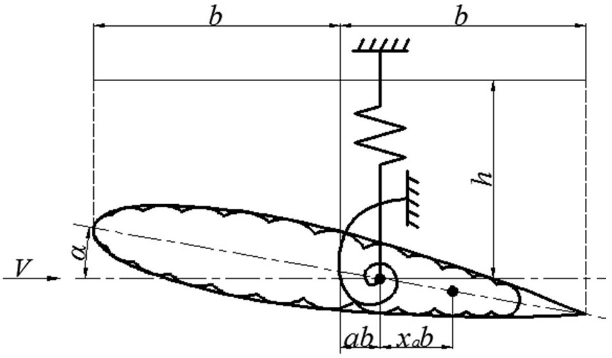


Figure 7 – Motion model of 2-DOF inflatable wing

5.2 *V-g* method

V-g method is a classical frequency domain method in flutter analysis. The principle is to introduce the structural damping coefficient *g* into the motion equation of the wing. The sum of structural damping force and elastic restoring force can be expressed as:

$$\left.\begin{aligned}(1+ig_h)K_h h&=(1+ig_h)m\omega_h^2 h_0 e^{i\omega t}\\(1+ig_\alpha)K_\alpha \alpha&=(1+ig_\alpha)I\alpha\omega_\alpha^2\alpha_0 e^{i\omega t}\end{aligned}\right\}\tag{17}$$

$$\left.\begin{aligned}a_{11}&=\frac{m}{\pi\rho b^2}\left[1-(1+ig)\left(\frac{\omega_h}{\omega_\alpha}\cdot\frac{\omega_\alpha}{\omega}\right)^2\right]+L_h\\a_{12}&=\frac{m}{\pi\rho b^2}x_\alpha+L_\alpha-(\frac{1}{2}+\alpha)L_h\\a_{21}&=\frac{m}{\pi\rho b^2}x_\alpha+M_h-(\frac{1}{2}+a)L_h\\a_{22}&=\frac{m}{\pi\rho b^2}r_\alpha{}^2\left[1-(1+ig)\frac{\omega_\alpha{}^2}{\omega^2}\right]+M_\alpha\\&\quad-(\frac{1}{2}+a)(L_\alpha+M_h)+\left(\frac{1}{2}+a\right)^2 L_h\end{aligned}\right\}\tag{18}$$

Introducing the intermediate variable *Z* as equation (19), and expressing *g* in the form of equation (20). Flutter frequency can be obtained by solving the flutter determinant when $g = 0$ [26].

$$Z=(1+ig)\frac{\omega_\alpha^2}{\omega^2}\tag{19}$$

$$g=\frac{Z_{\mathrm{I}}}{Z_{\mathrm{R}}}\tag{20}$$

Referring to the previous research on the flutter analysis of inflatable wing, the Theodorsen function is used as the aerodynamic input [27], the natural frequency and modal shape of wet mode is used as the structural input, and *g* is taken as 0 for obtaining the conservative value. The flutter characteristics of inflatable wing with different *θ* are analyzed by *V-g* method. The *V-g* diagram is shown in Figure 8. In conclusion, the flutter speed of the baffled inflatable wing analyzed in this paper is about 67.5 km / h. The forward sweeping of the inflatable beam moves the elastic axis of the inflatable wing forward, and the moment of aerodynamic force to the elastic axis is reduced to a negative value, which reacts with the inertia term and then delays the flutter. When the inflatable beams sweep backward, the rigid center will move backward correspondingly. As a large swept angle is adopted in this paper, the rigid center will exceed the center of gravity, and there will be no classical flutter [26].

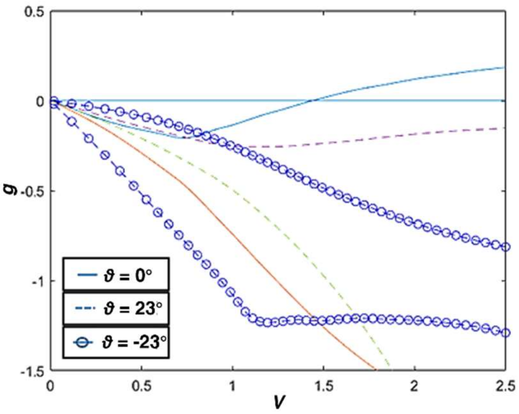


Figure 8 – *V-g* graphs comparison of inflatable wings

6. Summary and discussion

The contents of this paper are summarized and the work is conducted as follows:

(1). Focusing on the unsatisfactory performance of the traditional baffled inflatable wing, this paper proposed the swept baffled inflatable wing, and analyzed the design method.

(2). The CFD method is used to compare the aerodynamic characteristics of inflatable wings with different swept angles of inflatable beams, and the aerodynamic performance advantages of the swept baffled types are analyzed.

(3). The frequency domain flutter analysis method is conducted to compare the flutter characteristics of inflatable wing considering wet mode. The conclusion shows that the swept baffled structure can significantly delay or even eliminate the classical flutter of inflatable wing.

7. Copyright Statement

References

[1] BROWN G, HAGGARD R and NORTON B. Inflatable structures for deployable wings. *16th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar*, Boston, Massachusetts, America, pp 19-26, 2001.

[2] CADOGAN D, GRAHAM W and SMITH T. Inflatable and Rigidizable Wings for Unmanned Aerial Vehicles. *2nd AIAA "Unmanned Unlimited" Conf and Workshop & Exhibit*, San Diego, California, America, pp 1-9, 2003.

[3] CADOGAN D, SMITH T and LEE R, et al. Inflatable and Rigidizable Wing Components for Unmanned Aerial Vehicles. *44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. Norfolk, Virginia, America, pp 1-8, 2003.

[4] PULLIAM W, NORRIS R. Historical Perspective on Inflatable Wing Structures. *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Palm Springs, California, America, pp 1-10, 2009

[5] SIMPSON A, SANTHANAKRISHNAN A and JACOB J, et al. Flying on Air: UAV Flight Testing with Inflatable Wing Technology. *AIAA 3rd "Unmanned Unlimited" Technical Conference, Workshop and Exhibit*, Chicago, Illinois, America, pp 1-14, 2004.

[6] Deng K, An H, Chen W. Study of the Status and Critical Techniques of Flexible Wing Aircraft, *SPACECRAFT RECOVERY & REMOTE SENSING*, Vol. 37, No. 5, pp 19-26, 2016 (in Chinese).

[7] Ye Z, Lu Q, Li D. Research and development of inflatable UAV, *Symposium on aircraft development and aerodynamics of Chinese Academy of Aeronautics*, China, pp 150-160, 2006 (in Chinese).

[8] Feng Z, Li B. Investigation of Aerodynamic Behavior for Bumpy Inflatable Wing, *Advances in*

Aeronautical Science and Engineering, Vol. 5, No. 1, pp 38-45, 2014 (in Chinese).

[9] Wang W, Wang H, Jia Q. Analysis on bearing capacity and aerodynamic performance of an inflatable wing. *Journal of Aerospace Power*, Vol. 25, No. 10, pp 2296-2301, 2010 (in Chinese).

[10]Zhang J, Hou Z, Guo Z. Aerodynamic performance of configurations of two-dimension inflatable wings under high Reynolds number. *Journal of Aerospace Power*, Vol. 32, No. 3, pp 150-158, 2017 (in Chinese).

[11]RENDALL T, CHANG C and MARZOCCA P, et al. Aeroelastic Behavior of a Non-rigidizable Inflatable UAV Wing. *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Newport, Rhode Island, America, pp 1-14, 2006.

[12]SIMPSON A, SMITH S and JACOB J. Aeroelastic Behavior of Inflatable Wings: Wind Tunnel and Flight Testing. *45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, America, pp 1-22, 2007.

[13]SIMPSON A, ROWE J, SMITH S, et al. Aeroelastic Deformation and Buckling of Inflatable Wings under Dynamic Loads. *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, Hawaii, America, pp 1-22, 2007.

[14]BROWN A, JOHNSON E. Modeling and Flight Testing of the Longitudinal Dynamics of an Inflatable Wing UAV. *AIAA Atmospheric Flight Mechanics Conference*. Grapevine, Texas, America, pp 1-21, 2011.

[15]Xie C, Wang W, Yang C. Flutter analysis of inflatable wings, *JOURNAL OF BEIJING UNIVERSITY OF AERONAUTICS AND ASTRONAUTICS*, Vol. 25, No. 10, pp 833-838, 2011 (in Chinese).

[16]Wang W, Xie C, Yang C. Analysis of vibration and flutter characteristics of inflatable airfoil, *Chinese floating empty proceedings of the General Assemble*, China, pp 171-180, 2011 (in Chinese).

[17]Yang Y, Ma Y, Wu Z. Analysis of effect of interior pressure to deformation of inflatable wing with fluid-structure interaction analysis method, *JOURNAL OF BEIJING UNIVERSITY OF AERONAUTICS AND ASTRONAUTICS*, Vol. 40, No. 2, pp 188-192, 2014 (in Chinese).

[18]Lu Q, Ye Z, Li D. Design and Capability Analysis of an Aircraft with Inflatable Wing, *FLIGHT DYNAMICS*, Vol. 25, No. 4, pp 77-80, 85, 2007 (in Chinese).

[19]Chen L, Li, Guo Z, et al. Conformality Design and Aerodynamic Analysis of Inflatable Wing, Advances in Aeronautical Science and Engineering, Vol. 6, No. 1, pp 18-25, 2015 (in Chinese).

[20]Zhu L, Ye Z. Research on a Universal Design Method for Inflatable Wings, *JOURNAL OF AIRFORCE ENGINEERING UNIVERSITY (NATURAL SCIENCE EDITION)*, Vol. 10, No. 5, pp 16-21, 2009 (in Chinese).

[21]Li P, Feng C, Zhang H. Modal Analysis of Carrier Based on Dry and Wet Modal Test, *Journal of Ordnance Equipment Engineering*, Vol. 42, No. 1, pp 219-223, 230, 2021 (in Chinese).

[22]Qiu Z, Cheng W, Zhao B et al. Wet modal analysis and tests for pneumatic empennages, *JOURNAL OF VIBRATION AND SHOCK*, Vol. 35, No. 15, pp 140-148, 2016 (in Chinese).

[23]Qiu Z, Cheng W, Zhao B et al. Wet modal analysis and experiment study on an airship envelop [J]. *JOURNAL OF VIBRATION AND SHOCK*, Vol. 12, No. 36, pp 66-72, 87, 2017 (in Chinese).

[24]Chen Y, Chen W, He Y et al. Wet modal analysis and experiment study on an airship envelop, *JOURNAL OF SHANGHAI JIAOTONG UNIVERSITY*, Vol. 48, No. 2, pp 234-243, 2014(in Chinese).

[25]Gao H, Chen W, Fu G. Modal Analysis Method and Modal Behavior of Prestressed Inflatable Fabric Beam, *Journal of South China University of Technology (Natural Science Edition)*, Vol. 38, No. 7, pp 135-139, 2010(in Chinese).

[26]Chen G, Yang C, Zou C. *Aeroelastic design basis*. 2st edition, Beijing University of Aeronautics and Astronautics Press, China, 2010 (in Chinese).

[27]ZHAO W, DESAI S, MIGLANI J, et al. Structural and Aeroelastic Design, Analysis, and Experiments of Inflatable Airborne Wings, *AIAA Scitech 2021 Forum*, Online, pp 1-39, 2021.