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Analysis and Flight Test for Small Inflatable Wing Design

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Abstract**—**This article discusses stress analysis and the shape characteristics of the inflatable wing, and then introduces the design method of inflatable wing, in order to accurately approximate a standard airfoil. It specifically analyses the aerodynamic characteristics of the inflatable wing with the method of CFD, along with comparing to standard airfoil, afterwards we carries out the manufacture of inflatable wing and the flight test.

Keywords**—**Inflatable wing, Stress analysis, Aerodynamic characteristics, Flight test

I. INTRODUCTION

THE inflatable wing, which is produced by using lightweight flexible composite materials, is a new modality of structure with using a special design concept. It has the advantages of low cost, small volume, light weight, high reliability etc. Therefore, for variety of types of aircraft, it has wide application and research prospects [1].

Early in the last century 50's, Company Goodyear in the United States of America has developed several aircrafts with inflatable structure. The type GA-468 inflatable structure aircraft was used to execute the mission of reconnaissance, communications and so on.

Over the years, NASA has also developed inflatable UAVs research. NASA tested an UAV named I2000 with an folding inflatable wing , and achieved great success [2].The wing, being used of plastic film material, has advantages of low cost, light weight, convenient manufacturing, folding, convenient carrying, fatigue resistance, simple maintenance etc. Till 2001 June, I2000 UAVs have already completed 3 flight test in order to validate the technology of inflation.

Big Blue, developed by University of Kentucky in the United States, has developed into a series, and already in practical application [3]. In the research process, the load and deformation, characteristics of structural mechanics of the inflatable wing are analyzed by finite element method [4], and then the result compared with experimental results. BIG BLUE project is considered as the most comprehensive work of the inflatable wing research.

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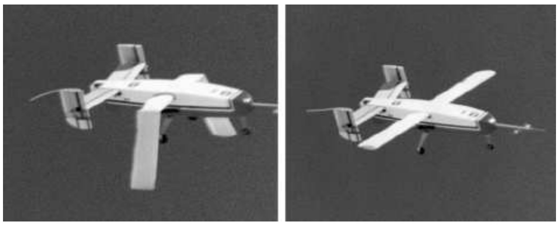


Fig. 1 I2000UAVs

Fig. 2 Big Blue3

This article mainly aims at design, analysis, manufacture and test of the small inflatable wing. Comparing with the previous research of the design method, we do some improvement, and mainly focus on the analysis of the aerodynamic characteristics of the inflatable wing at the same time.

II. DESIGN AND ANALYSIS FOR INFLATABLE WING

A. Design for Inflatable Wing

At present, commonly used design methods for the inflatable wing are: multi-cables structure and multi-pipes structure.

- *Multi-cables structure*

Multi-cables structure inflatable wing is characterized in that the shape of the aerofoil is constrained under the effect of each cable. As each gasbag is communicated with another, the bearing of the whole inflatable wing is uniform. It has a good effect on preventing the wind deformation. At the same time, the performances of bending and torsion of the inflatable wing are similar to the rigid wing. Due to the integral type, the shortcoming is that once damage happens, the whole inflatable wing will not be used again. In addition, the wing skin will meet the problem of losing Stability in some conditions.

- *Multi-pipes structure*

Multi-pipes structure inflatable wing is characterized by the use of different radius of the cylinders. These inflatable cylinders are used as bearing structure; meanwhile, each cylinder is closely arranged to another, keeping tangent with the selected airfoil, in order to maintain the airfoil and the rigidity of the inflatable wing. The skin outside cylinders can maintain the surface shape. This scheme's main advantage lies in the independence of cylinders, so it has a very good anti break capability. However, the performances of bending and torsion are worse than multi-cables structure.

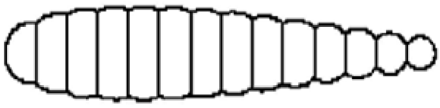


Fig. 3 multi-cables structure

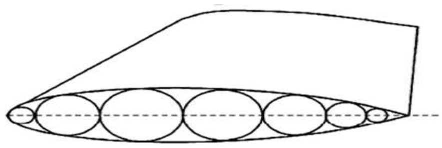


Fig. 4 multi-pipes structure

Comprehensive considering the factors such as design, manufacture and practical application, this article selects the scheme of multi-cables structure.

B. Stress Analysis for Inflatable Wing

In fact, the shape of the Inflatable wing is still different from the standard airfoil. It can only approach the standard airfoil to a certain extent. As for the error, it depends on a variety of factors such as the performance of the inflatable wing's material, manufacture and design method. In this paper, the inflatable wing research method is based on the theoretical analysis, and then identifying the deformation characteristics of the inflatable wing by stress analysis.

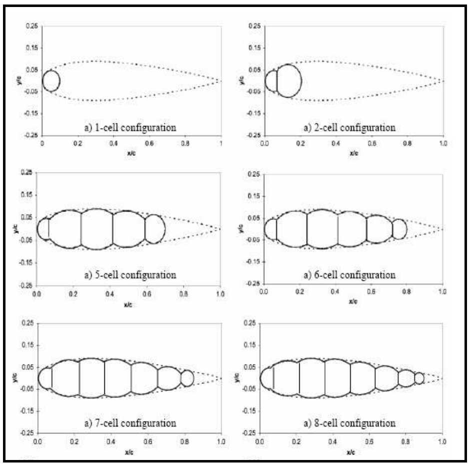


Fig. 5 internally tangential circular arc approach the airfoil

According to the bubble principle, method of using series of internally tangential circular arc to approach the airfoil is now more commonly used to design for inflatable wing [5], as shown in figure 5. While this method is simple, it does not give a specific description of the inflatable wing's shape.

References [6] and [7] also research on the shape of the inflatable wing, but they did not describe the specific shape of the cross-section of inflatable wing. Thus, now we start to do this job.

Without loss of generality, we consider the simple condition that the inflatable wing only contains two cables, as shown in Fig. 6.

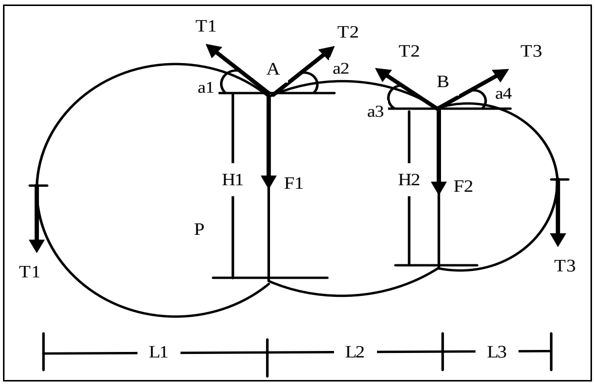


Fig. 6 stress analysis for inflatable wing

Take the upper half to consider, tensions separately generated by three sections of skin are T_1、 T_2、 T_3, at the nodes A and B, the angle between the direction of the force and the horizontal direction are α_1 、 α_2 、 α_3 、 α_4, three skin lengths are L_1、 L_2、 L_3, pressure difference between inside and outside is P, force of two cables are F_1、 F_2, lengths are H_1、 H_2.

For the node A:

In the horizontal direction, according to the force balance:

$$T_1 \cos\alpha_1 = T_2 \cos\alpha_2 \tag{1}$$

In the vertical direction, according to the force balance:

$$F_1 = T_1 \sin\alpha_1 + T_2 \sin\alpha_2 \tag{2}$$

Similarly, the node B:

In the horizontal direction, according to the force balance:

$$T_2 \cos\alpha_3 = T_3 \cos\alpha_4 \tag{3}$$

In the vertical direction, according to the force balance:

$$F_2 = T_2 \sin\alpha_3 + T_3 \sin\alpha_4 \tag{4}$$

For the upper half, the force balance is only in the vertical direction, it is:

$$T_1 + T_3 + F_1 + F_2 = P(L_1 + L_2 + L_3) \tag{5}$$

For the L3 skin segment:

In the vertical direction, according to the force balance:

$$P\frac{H_2}{2} = T_2 \cos\alpha_3 \tag{6}$$

For the L1 skin segment:

In the vertical direction, according to the force balance:

$$P\frac{H_1}{2} = T_2 \cos\alpha_2 \tag{7}$$

In addition, in fact, consider that the stress of the skin is uniform, so:

$$\frac{T_1}{M_1} = \frac{T_2}{M_2} \tag{8}$$

$$\frac{T_3}{M_3} = \frac{T_2}{M_2} \tag{9}$$

M_1、 M_2、 M_3 are lengths of three segments of skin:

$$M_1 = \frac{(90+\alpha_1)\pi}{180} \cdot \frac{L_1}{1+\sin\alpha_1} \tag{10}$$

$$M_2 = \frac{(\alpha_2+\alpha_3)\pi}{180} \cdot \frac{L_2}{\sin\alpha_2 + \sin\alpha_3} \tag{11}$$

$$M_3 = \frac{(90+\alpha_4)\pi}{180} \cdot \frac{L_3}{1+\sin\alpha_4} \tag{12}$$

We first design the length and position of the cables, it means L_1、 L_2、 L_3、 H_1、 H_2、 P are given parameters, according to solved the Eq.(1) ~ Eq.(9) these nine independent equations, we can gain the nine unknowns T_1、 T_2、 T_3、 F_1、 F_2、 α_1、 α_2、 α_3、 α_4.So we can get the value of angle α_1、 α_2、 α_3、 α_4,So far, the skin segments' arc shape of the nodes A and B can be roughly determined.

III. Aerodynamic Characteristics Analysis for Inflatable Wing

A. Model Preprocessing for Inflatable Wing

The choice of standard airfoil is NACA0012.We use the commercial software *Pro.E*, for modeling, as shown in figure 7: outline is standard airfoil, while the inflatable wing is internally tangential to the standard airfoil.

The specific steps are as follows:

- According to the standard airfoil data, design the distribution of the cables, including the cables' number (4 ~ 7 is appropriate), cables' position, cables' length and so on. After that, take leading edge circle's center point of the standard airfoil; take its diameter to length for the first cable.
- Then according to the distribution of the cables, calculate the angle at each node.
- On the upper surface, draw circle arcs with appropriate radius, which the arcs must to meet node angle condition and being internally tangential with the standard airfoil.
- Due to the Symmetry, thus we can get the under surface.
- Until now, we get the model of the inflatable wing.

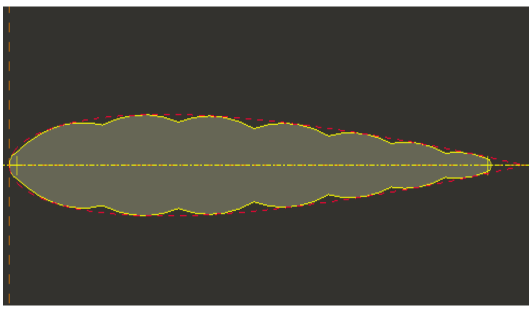


Fig. 7 inflatable wing modeling by Pro.E

Importing the model generated by Pro.E, to the software GAMBIT to carry out the grid pre-processing, we get unstructured triangle meshes about 50000, as shown in fig. 8.

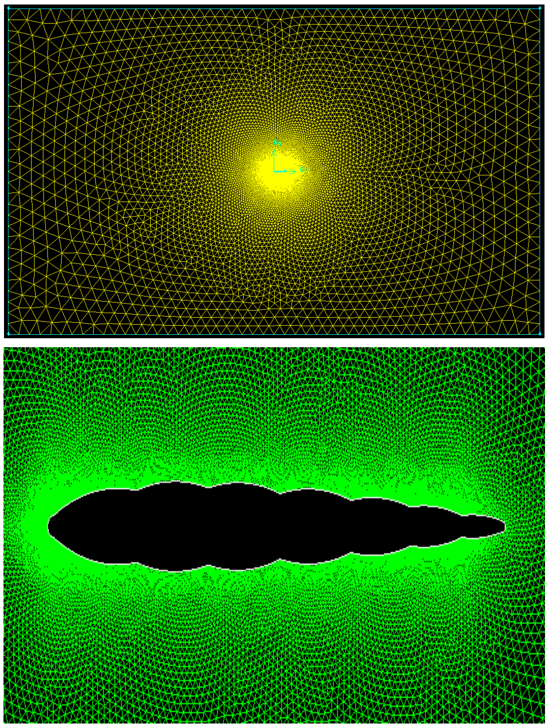


Fig. 8 50000 grids Computational domain

According to the general theory of finite element, we can know that computational domain mesh number and density will directly affect the accuracy of the results.

Therefore, in order to verify whether the results based on the 50000 grids can meet the precision requirement we should do the grid convergence analysis. We respectively generate 200000 encryption grids and 20000 sparse grids, as shown in fig. 9.

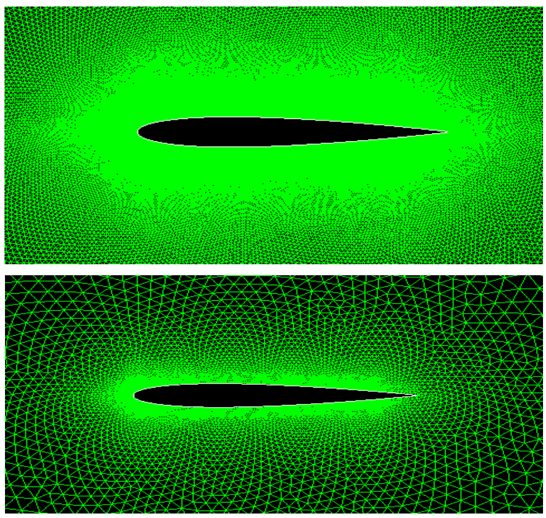


Fig. 9 200000 encryption grids and 20000 sparse grids

Set the work condition:

Reynolds number is 1×10^{6}, attack angle is 3°.

Through iteration, the result is shown in Table I: the results of the differences are relatively small, using 50000 grids to calculate is reliable, and so we can use it to analyze aerodynamic characteristic of the inflatable wing.

TABLE I
LIFT COEFFICIENT UNDER DIFFERENT NUMBER OF GRIDS

condition	number of grids	lift coefficient
Re= 1×10^{6}; attack angle = 3°	200000	0.3391
	20000	0.3247
	50000	0.3328

B. Analysis of the Result

We use commercial software Fluent to calculate the inflatable wing and the standard NACA0012 airfoil in a series of angles of attack getting the lift and drag coefficient. Then we make comparison of the differences between the two.

As shown in figure 10, we can see that the streamline of NACA0012 and the inflatable wing in 3°angle of attack is basic and same, not different too much.

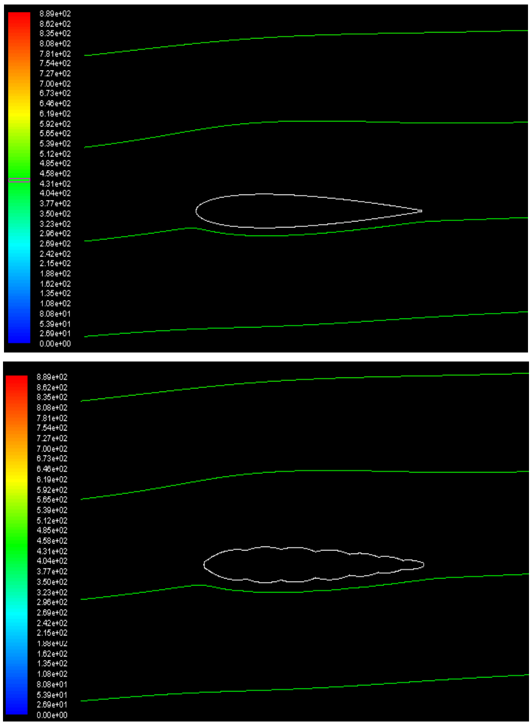


Fig. 10 streamline of NACA0012 and the inflatable wing

Then we get the results of the standard NACA0012 airfoil's (blue line)and the inflatable wing's (red line)lift coefficient, drag coefficient and lift to drag ratio with the variation of angle of attack of the curve, as shown in figure 11 & 12.

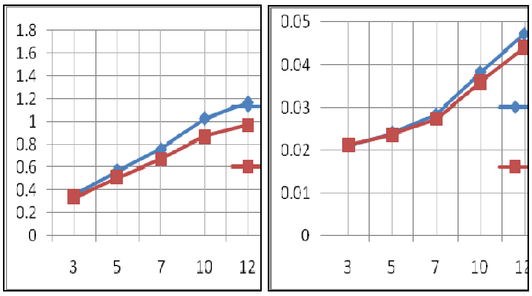


Fig. 11 lift coefficient and drag coefficient curve

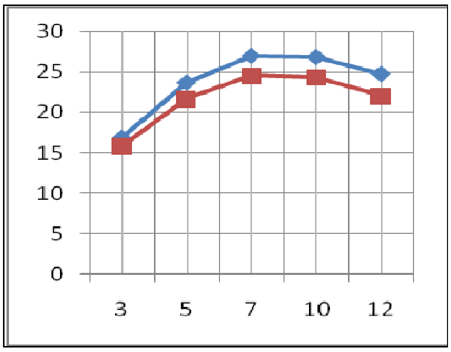


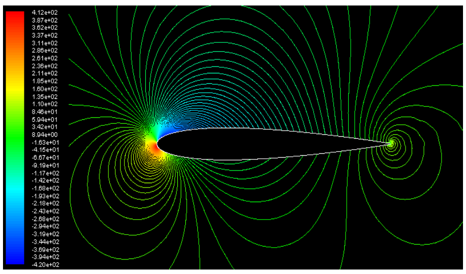
Fig. 12 lift to drag ratio curve

It can be seen from the results that:

- Both the drag coefficient and the lift coefficient of the inflatable wing are less than standard NACA0012 airfoil's, as well as the lift-to-drag ratio, because of the shape deformation of inflatable wing indeed lead to the overall aerodynamic performance decrease somewhat, but not so much.

Analysis of the reasons of reducing resistance:

The static pressure distribution of NACA0012 airfoil and inflatable wing in 3°angle of attack, is shown in figure 13. To the inflatable wing, vortex occurs on its concave and convexity surface to avoid the separation of the laminar flow, therefore the frictional drag is down, while pressure differences drag slightly increasing. However, for us, in this low flow speed and high Reynolds number condition, the frictional drag is more important than total drag is far greater than the pressure difference drag, so the comprehensive effect is that the drag coefficient decreases.



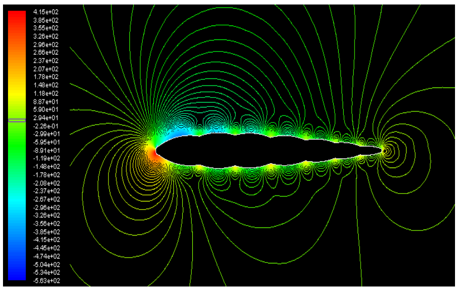


Fig. 13 static pressure distribution of NACA0012 airfoil and inflatable wing

- The results show that, through to the inflatable wing section of the reasonable design, which to some extent approximation standard airfoil, can achieve good effect, and the prior inflatable wing design aspects of the design method is feasible.

IV. Manufacture and Flight Test for Inflatable Wing

A. Manufacture for Inflatable Wing

Manufacture process of the Inflatable wing is mainly about cutting, heat sealing, and finally check the gas tightness.

- *Model tailoring*

Airfoil interception plays an important role to the inflatable wing, so the line length measuring and cutting style and accuracy must be very highly demanded.

In practice, we use Pro.E to do the measuring work. After that the cutting work began. In the cutting process, attention must also be taken to keep a width boundary for heat sealing side, as shown in figure 14:

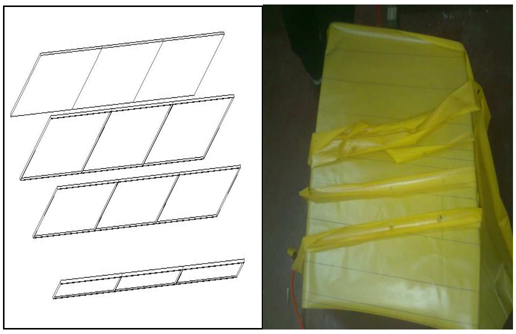


Fig. 14 model cutting

- *Heat sealing*

Because of the limit of heat sealing machine, we should do the job in a proper order, otherwise we are unable to close up the skin. Therefore, in carrying out the heat sealing, we must design the order:

i. Heat seal the gas nozzle, and the nozzle sealing at the wings middle part of the surface, as shown in figure 15.
ii. Heat seal internal cables structure, as shown in figure 16.
iii. Heat seal the skin, finally close up the airfoil trailing edge, as shown in figure 17.
iv. Finally check the gas tightness of the inflatable wing.

Fig. 15 heat sealing of the gas nozzle

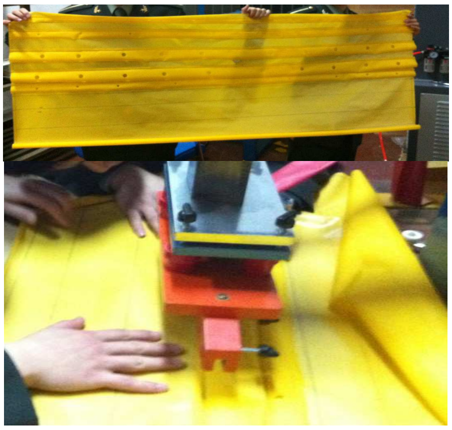


Fig. 16 heat sealing of the internal structrue

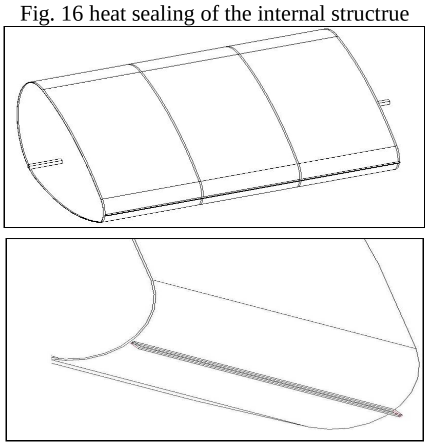


Fig. 17 heat sealing of the tailing edge

By monitoring internal pressure, determine that the gas tightness is good.

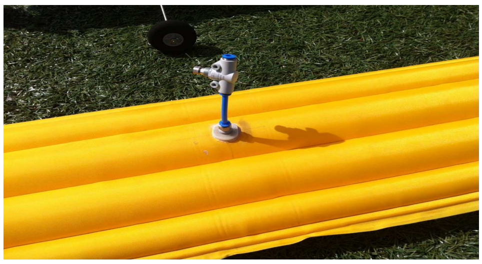


Fig. 18 part of the inflatable wing

B. Flight Test for Inflatable Wing

Firstly, we made a small model UAV (without wings) by ourselves. Then install the inflatable wing, using the rope to fix it. The specific parameters of the small model UAV is that:

Fuselage length is 100 cm;

Span of the wing is 150 cm.

Fig. 19 prepare for the flight test

On March 28 2012, we did the first flight test. Due to the lack of the aileron, aircraft cannot do the rolling control, but because of the inflatable wing has certain flexibility, in the course of the flight, it can also form a dihedral angle, so that it has natural roll stability. Turning control used the rudder and elevator compensating the height. In a word, the flight test is relative successful.

Fig. 20 flight test

V. CONCLUSIONS AND FUTURE WORKS

Through our research, it can be concluded as follows:

- By given the inflatable wing design parameters, with the design method of stress analysis, we can describe inflatable wing shape closely to the standard airfoil in the cross section.
- The successful flight test for the small inflatable wing UAV proves that: using inflatable wing can satisfy some requirements of the common flight.
- Currently, we have not done mechanical performance analysis and testing of the inflatable wing. The next step will focus on this aspect of the work.
- Another future work is carrying small cylinder to control the inflatable wing expand in the air.

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