Research and improvement on design method of morphing wing aircraft

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Abstract. Different from traditional aircraft, morphing wing aircraft can change their own wingspan in the process of flying, so as to adapt to different environments and tasks, and reduce the space they occupy in transportation and storage. In this paper, a reasonable analysis of the aerodynamic layout of the aircraft wing is carried out, and a large number of data research is done on the most important aileron. Based on the basic theory, the working mechanism of the aileron is analyzed, and finally the optimal position of the aileron is obtained, i.e. the position of relative span 15.4% - 57.4%, relative span is up to 42%. Finally, the surface streamline of the aircraft in flight is studied by CFD simulation, and the skin scheme is determined based on it. Profili, a professional airfoil analysis software is applied to analyze parameters of airfoil, it finally results that the change of wingspan of rectangular wing has no effect on lift coefficient, drag coefficient and lift drag ratio, but it has obvious effect on lift, it proves that the aerodynamic layout of the wing is reasonable. Through the load test, it shows that the increase of lift is consistent with the theoretical prediction by about 50%. After a series of ground and flight tests, the practicability and safety of the morphing wing aircraft are proved.

1. Introduction

The research on variable span aircraft has a long history. Since 1930s, the United States and the former Soviet Union began to design and manufacture the first variable wingspan aircrafts to meet the needs of the aircraft lift changes after the continuous improvement of its flight speed. In modern times, with the development of research on variable wingspan aircraft, there are advanced designs such as "Z" wing and "sliding skin". It is noticeable that among these designs, the wing, as the most important component of the aircraft, has been the key point of research and improvement. [1]

Based on the design standard of the US Defense Advanced Research Projects Agency, the change of wing area caused by the change of wingspan should be more than 50%. The large wingspan is more conducive to the glide of the aircraft, while the small wingspan is more conducive to the dive of the aircraft. Under the same flight conditions, the aircraft with large wingspan can produce more lift. Similarly, under the same lift, the aircraft with larger wingspan has lower speed, which can reduce fuel consumption and improve endurance. [2]

As the most important part of wing control, aileron, whether its position, area or turning angle, is more worthy of in-depth analysis and research.
Ailerons are usually installed on the trailing edge of the wing to control the roll motion of the aircraft. In general, the larger the area of aileron and the closer it is to the wingtip, the stronger the control force of aileron to the aircraft. In addition, there is another part similar to the aileron and used for the heavy-load civil airliner, i.e. flap, as shown in Figure 1:

As the variable wingspan aircraft realizes the change of wingspan, there must be some deformations on the direction of wingspan, based on a large number of existing variable wingspan designs, this deformation can be summarized into two forms, one is folding deformation in linear range, i.e. "Z-wing" as shown in Figure 2. The other is the regional form of deformation, i.e. "sliding skin aircraft", as shown in in Figure 3 and "telescopic aircraft" in Figure 4. [3-13]

Thus, in this paper, through the design of a single degree of freedom linear variable wingspan aircraft and prototype test on it, two problems that must be solved in wing improvement in the process of designing linear variable wingspan aircraft are analyzed and studied, i.e. skin form and aileron position selection. In this paper, through the analysis of data and principle of aileron, and CFD simulation and simulation of different skin, a better theoretical solution is obtained as well, and finally the practicability is verified by experiments.
2. Aileron problem of variable wingspan aircraft

No matter which form of deformation mentioned above, it will lead to the same result that there is at least one deformation area on the wing. The aileron can not be installed in the usual way because deformation need to be done in this area, so the relative position of aileron and deformation area should be considered as the research point of the first importance. This paper focuses on studying the folding deformation in the linear range, according to the general aircraft design idea, there are three schemes for the relative position of aileron and deformation area:

I. Aileron across deformation area
II. Aileron placed inward relative to the deformation position
III. Aileron placed outward relative to the deformation position

In scheme I, ailerons need to be deformed along with the deformation area, multiple actuators are required, and aileron structure is complex, all these increase total weight and energy consumption, which is not in accordance with the original intention of morphing wing aircraft design, and the feasibility is poor.

In scheme II, the aileron deformation and multiple actuators are avoided, the overall structure tends to be simplified. But the aileron will be placed as close to the outside as possible in order to increase the rolling moment, so the deformation area need to as close to the outside as possible also.

In scheme III, aileron is close to the outside relative to the deformation area, and aileron conforms to the design principle of aircraft. At the same time, the deformation position is determined according to the load capacity of the deformation area with high degree of freedom.

According to the above preliminary analysis, no further in-depth study will be carried out on scheme I. In the following, scheme II and scheme III will be elaborated and analyzed in detail, and a better theoretical scheme will be selected for prototype production and flight test to verify the performance improvement variable wingspan will bring.

3. Wing design of linear variable wingspan aircraft

3.1. External design of aileron

First of all, let’s explain the external design of aileron. As shown in Figure 5, The design features that the aileron is placed on the outer wing, which enhances the control force of the aileron on the whole aircraft. However, in the process of test connection, it is found that high strength of the connection is required in this design, because in the rolling process, all the moments act on the root of the connection and is transmitted to the aircraft body. In addition, when the aileron is externally placed, there is a higher requirement for the skin installation at the connection. If the rigid skin is adopted, it cannot be fixed relative to the inner wing, otherwise the aircraft will lose the aileron in the contraction state, so the skin can only be fixed relative to the outer wing, which can be regarded as the outer shell sliding on the inner wing surface, which is similar to the telescopic wing in theory, so there is a further strength demand for the connection. If a flexible skin is used, the fold needs to be supported by wing ribs, as shown in Figure 6. However, in order to make the flexible skin fully fit the mechanism to maintain the shape of the wing, and fully retract in the folded state, a vacuum machine similar to Z-wing is needed, which inflates when the wing is unfolded and exhausts when it contracts, so as to ensure that the skin is always kept in a tight state.

![Figure 5. Rigid skin for external aileron](image5.png)

![Figure 6. Flexible skin for external aileron](image6.png)
Because foam machines is initially planned to use for flight test, the design of external aileron is difficult to achieve either in terms of load or component strength. On this basis, a new design scheme is proposed, which can not only meet the strength requirements of components, but also improve the effect of aileron, that is, the aileron moves to the inner fixed wing.

3.2. Design of built-in aileron
In this scheme, of the original idea of placing the aileron on the outside is given up, Instead, consider how to reduce the load of the intermediate connection and move the aileron position out as much as possible. Finally, the scheme shown in Figure 7 is obtained. Compared with the external design of aileron, the location and total length of aileron are improved to a certain extent, which improves aileron controlling of the whole body in the air.

Another advantage of the design is that it reduces the area of the wing extending from both ends, which reduces the lift provided by the outer wing in flight and no-load state, and minimizes the possibility of deformation.

4. Design and analysis on aircraft skin
4.1. folding skin
The idea of folding skin comes from the accordion, as the movement of accordion is very similar to that of wing, and it is a kind of single degree of freedom motion, so this folding method is primarily planned to adopt to make folding skin. Once the aircraft is in the sky, it is very difficult to control it and test its parameters. Therefore, this skin adding method is modeled and simulated first, as shown in Figure 8.

The simulation is carried out in the Flow simulation module of SolidWorks, SolidWorks automatic three-level grid precision division is adopted for grid. The scope of calculation field is that, X direction -457 mm—-1553 mm , Y direction -121 mm— -150 mm , z direction -408 mm— -133 mm. Because it is to simulate the flight state in the open air, the open boundary is used without boundary definition. The horizontal flight is simulated with a speed of 20 m/s, so no speed is set in XY direction, 20 m/s is set in Z direction, with the angle of attack 0 °. First of all, the flow path and surface pressure of the
folding skin are simulated according to the above conditions, as shown in Figure 9 and Figure 10 respectively.

![Figure 9. Streamline simulation of folding skin surface](image1)

![Figure 10. Surface pressure simulation of folding skin](image2)

It can be seen from the figure that when the angle of attack of the wing is 0 °, the position of the gauge pressure is maximized at the tip of the upwind, its maximum value is 0.101331mpa, and the maximum points are all on the relatively weak folding line. It can been seen from the simulation of the flow path that the flow line is divided into several different parts because the position is on the folding surface, this kind of flow is easy to cause flight out of control when disturbed by lateral wind. And the volume of the folding skin is related to the material properties, and the cost of new materials with large shrinkage ratio will increase greatly.

4.2. Sliding skin

In view of the shortcomings of the above mentioned folding skin, a skin design scheme inspired by the telescopic wing is proposed, as shown in Figure 11, the skin is hollow and relatively fixed with the outer wing, and it can slide on the inner fixed wing.

![Figure 11. Sliding skin model](image3)

Under the same conditions as the folding skin, the simulation is done to the sliding skin on flow path and surface pressure. As shown in Figure 12 and Figure 13.

![Figure 12. Streamline simulation of sliding skin surface](image4)
Figure 13. Surface pressure simulation of sliding skin

It can be seen from the figure that when the angle of attack of the wing is 0 °, the maximum position of the gauge pressure also appears at the windward tip, with the maximum value of 0.101519Mpa, slightly greater than the maximum gauge pressure of the folding skin. From the analysis diagram of surface pressure, it can be seen that the pressure on the sliding skin surface is distributing evenly, and pressure distribution on the wing is basically continuous.

From the figure, it can be concluded that the flow path of the rigid skin is evenly distributing relative to the folded skin. Only when the skin contacts the wing and form a stepped surface, then the position will affect the continuity of the flow path and surface pressure.

Therefore, based on the above analysis of the two kinds of skin adding methods, it is considered that the second adding method of sliding skin is the most conductive to improve the aerodynamic performance of the aircraft.

4.3. Analysis of aerodynamic performance of wing

When the aileron position and skin adding method are determined, next, the professional wing parameter analysis software profili will be adopted to calculate the aerodynamic parameters of the wing.

To calculate the parameters of a wing, the Reynolds number of the wing must be known first. Profili has its own calculator to calculate the Reynolds number of the aircraft. Then the flight height, the average aerodynamic chord length and the flight speed of the aircraft need to be provided. Suppose the flight altitude is 40 m, because the aircraft uses rectangular wings, the chord length is 230 mm everywhere, so the average aerodynamic chord length is 230 mm, and the flight speed is 20 m/s after referring to the basic parameters. Then we can get the wing Reynolds number by calculation as follows, i.e.

\[
Re = 313925
\]

(1)

Since the design of variable wingspan only changes the wingspan of the aircraft, both the chord length and the airfoil have not changed, so the Reynolds number before and after the change is the same, that is \(Re = 313925\).

The three most important parameters in the flight process are including lift coefficient, drag coefficient and lift drag ratio.

The lift coefficient reflects the lift obtained by the aircraft in flight, and the drag coefficient reflects the drag force. The lift drag ratio is the objective value of the lift to drag ratio. Because these three data are related to the angle of attack of the aircraft, it is necessary to measure the data within a certain angle of attack at a certain speed.

The aircraft with Clark Y airfoil is used for the experiment, the shape parameters of this airfoil have been recorded in profili's database, so there is no need to measure the wing shape.

When the Reynolds number and the airfoil are constant, the lift coefficient, drag coefficient and lift drag ratio of the wing do not change, thus, a set of lift coefficient, drag coefficient and lift drag ratio are calculated by profili software on the basis of this Reynolds number.

Since the coefficients are related to the aircraft flight angle of attack, when the calculation range is at the angle of attack between \(-8^\circ < \alpha < 13^\circ\), and the curves as shown in FIG. 14, 15 and 16 are obtained.
From the data in the figure, it can be seen that the lift coefficient continues to increase with the increase of angle of attack, and the drag coefficient suddenly increases after reducing for a certain distance, which indicates that there is a maximum value of lift drag ratio. From the curve of lift drag ratio, it can be seen that the maximum value is at the position of $4^{\circ}$ angle of attack.

So it comes to conclusion that, this kind of morphing wing aircraft changes the lift by changing the force area of the wing. When the lift coefficient is kept unchanged before and after the change, the lift force increases through increasing the area of the wing. When the speed of the aircraft decreases, due to the reduction of the lift coefficient, the area of the wing is increased to obtain enough lift.

5. Flight experiment

When all the preparatory work including simulation calculation and prototype production, the flight experiment of the prototype is started to verify whether the rigidity, safety of the whole refitting system and the improvement of aircraft performance meet the requirements by the standard.

The starting point of the connecting part of the final prototype is positioned at 60.4% of the relative length from the center of the wing. The range of aileron is 15.4% - 57.4% in the expanded state, and the relative expanded length is 42%. In the expanded state, the area of the wing is increased by 50.2%.

In the flight experiment, the self weight of the aircraft is 1500 g when is is closed, 1500 g when it is expanded, 300 g in the load, and total weight is 1800 g. The flight process is as shown in Figure 17, 18.
In the experiment, the load and lift improving of the aircraft are tested as follows. The original weight of the aircraft is 900 g, and load is not designed. After being replaced with large-size blades and high-speed motors, its load capacity is increased by increasing the thrust. The load is increased to 600 g, with total weight 1500 g. Based on 1500 g, weights are used in the expanded state to test whether the aircraft can achieve safe flight under a series of loads shown in table 1. The results are also given in Table 1.

| Loading | Safe flight or not |
|---------|-------------------|
| 50 g    | yes               |
| 100 g   | yes               |
| 120 g   | yes               |
| 150 g   | yes               |
| 170 g   | yes               |
| 200 g   | yes               |
| 220 g   | yes               |
| 250 g   | yes               |
| 270 g   | yes               |
| 300 g   | no                |

The flight test proves that the aircraft begins to lose control in case of wind when load increases to 300 g, so it can be considered that the load increases by 270 g, the value may fluctuate with the flight altitude and wind direction. When the aircraft flies with load 600 g in the closed state, the wing area increases by 50.2%, and the safe load capacity increases by about 49%. So the test results are considered as intended.

The maximum lift test is also done on the basis of the load test. In the flight test under the closed state, it is found that when the throttle is at 2 / 3 position, the aircraft can basically maintain the horizontal flight state, the lift is considered to be equal to the gravity at this time. On this basis, the throttle variable is kept at 2 / 3 position by control. Such tests are often destructive, so the aircraft applies a single load of 300 g, and propelled at 2 / 3 throttle on the runway, it proves that the aircraft can fulfil the off-ground action when the elevator is raised, but it can only fly a certain distance horizontally at a height of about 2-3 m from the ground. It proves that lift is equal to gravity at this point, thus it can be further proved that lift increase by about 50.3%. In this test is done through controlling the throttle variable, so the data accuracy is high, the result of which is basically considered as intended.

In both testing under the two states separately, the variable wingspan aircraft can take off and land safely in the expanded and closed states respectively, and the required take-off speed in the expanded state is less than that in the closed state, so the purpose of variable wingspan design is achieved, that is, the required speed of the aircraft decreases by increasing the wing area, which reduces the fuel
consumption and improves the endurance of the aircraft, and the stability, safety and load capacity all meet the predicted level.

6. Conclusion
In this paper, the development of linear variable wingspan aircraft and its possible technical routes are analyzed, and different technical routes are also theoretically analyzed. A better scheme in theory, i.e. the combination of rigid skin and aileron built-in design, is applied for prototype trial production and flight test.

Through flight test on load and safety, it can be seen that the design of variable wingspan not only reduces the minimum speed required for the takeoff of the aircraft, but also achieves the purpose of increasing the load of the aircraft. Through the flight test, it is proved that the aircraft can achieve safe takeoff and landing, and on the basis of improving the flight performance, it also ensures the safety of the flight.

The design of variable wingspan proposed in this paper makes the aircraft adapt to the task requirements at different speeds. reducing the takeoff speed can make the aircraft adapt to a shorter runway, and the aircraft can have a higher maximum speed by reducing the lift. However, the following improvements can still be made, that is, (1) there is still room for improvement in self weight of the aircraft to achieve greater load. (2) The wing to fuselage ratio is still out of line. Because the transformation is done to the existing aircraft, with the wingspan growth, the proportion of wingspan to fuselage is too large. (3) The driver with higher precision can be used to improve the processing accuracy of components, so as to improve the control accuracy and response speed.

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