Research on Aerodynamic Characteristics of Forward-swept Wing with Inclined Basic Airfoil

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Abstract. Variable forward-swept wing (VFSW) aircraft is a kind of typical morphing aircraft. With the change of forward-swept angle, the airfoil of Variable forward-swept wing which is based on incoming flow will also be changed, and this change has a very important influence on flight performance. In order to explore this impact, this paper firstly build nine airfoil models under different forward-swept angle, through the calculation by fluent, the impact on airfoil aerodynamic characteristics from angle of attack, mach number and forward-swept angle is analyzed. The results show that, while flying at the sea level in a low angle of attack, the lift coefficient, resistance coefficient and moment coefficient will increase with the rise of forward-swept angle, but while flying in a high angle of attack, these coefficients will decrease with the rise of forward–swept angle. The results also can provide references for further research of aerodynamic configuration of variable forward-swept wing aircraft.

1. Introduction

The variable forward swept wing layout aircraft is a typical variant aircraft. It can change the wing sweep angle according to demand, and change in typical layout states such as straight wing, forward swept wing, and delta wing. The arrangement of the basic airfoil upright does not make the aerodynamic characteristics of the variable-swept-wing aircraft in each configuration state optimal. Therefore, the aerodynamic characteristics of the incoming airfoil with different basic airfoil and the angle between the airfoil roots (basic airfoil oblique) need to be compared to find the best aerodynamic characteristics for each state of the variable forward swept wing. The basic airfoil oblique angle.

In this paper, through numerical simulation calculation, in the process of changing the sweep angle of the variable-sweep aircraft, the analysis of the change law of the cross-section airfoil of the basic airfoil and the root of the airfoil at different angles is aimed at finding a suitable basic airfoil slope. The angle is set so that the variable-sweep wing aircraft has good aerodynamic characteristics in the state of straight wing and forward-swept wing, which provides reference and reference for the design of the optimal wing arrangement of the wing in the later period.

2. Modeling and feature parameter analysis

In order to make the wing of the variable forward swept wing aircraft change smoothly under the states of straight wing, forward swept wing and delta wing, this paper chooses NACA0006 thin symmetrical airfoil as the basic airfoil of the variable forward swept wing aircraft. The basic airfoil of the wing model is at an angle with the wing root. In order to analyze the influence of the basic wing shape and the wing root angle on the aerodynamic characteristics of the wing in the forward-swept state, the basic airfoil and the wing root (or the plane of symmetry of the airframe) are established respectively. Two wing models with an included angle of 20 ° and 40 °.
With the change of the sweep angle, each parameter of the profile airfoil changes to varying degrees. Figure 1 shows the changes in the profile of each group of airfoils at different oblique angles. In the figure, (a) and (b) show the change of the airfoil with the sweep angle when the basic airfoil is inclined at 20° and 40°, respectively.

Figure 1. Schematic diagram of the changes in the airfoil of each group with the sweep angle when the basic airfoil is inclined

| Sweep angle | 0°   | 20°  | 40°  | 60°  |
|-------------|------|------|------|------|
| Basic airfoil inclined at 20° | 7.33% | 6%   | 3.92%| 1.08%|
| Basic airfoil inclined at 40° | 11.50%| 9.57%| 6%  | 1.69%|

It can be seen from the table that no matter how the oblique angle of the basic airfoil changes, the relative thickness of the section airfoil decreases as the sweep angle increases.

3. Aerodynamic characteristics analysis

This section mainly analyzes the change of the aerodynamic characteristics of the forward-swept wing with the forward-sweep angle at different forward-sweep angles when the basic-slave airfoil is inclined. First, after modeling the wing with CATIA, the airfoil was intercepted with the corresponding cross section and imported into ICEM for meshing. The structural grid was used, and the number was about 270,000. When Ma ≤ 0.3, air can be regarded as an incompressible fluid. Therefore, a two-dimensional implicit solver based on pressure is used. When Ma ≥ 0.3, an implicit solver based on density and a transient algorithm are used. Sutherland's law is used to solve the viscous flow model. The boundary conditions are the pressure far-field boundary, T = 288.15K, and Re = 1.1×10^6.

3.1. Aerodynamic characteristics of a section airfoil when the basic airfoil is inclined at 20°

3.1.1. Analysis of lift characteristics

Figure 2 shows the variation law of the lift coefficient of the profile airfoil at different swept angles with the angle of attack and the angle of attack α = 4° when Ma = 0.2.
From the perspective of the curve, as the angle of attack increases, the lift coefficient increases first, and then decreases after reaching the stall angle of attack. When the relative thickness of the section airfoil is large, the lift coefficient of the airfoil decreases as the sweep angle increases. When the relative thickness is small, the lift coefficient of the airfoil increases as the sweep angle increases. Due to their relatively small thicknesses, the $\chi = 40^\circ$ and $\chi = 60^\circ$ airfoils are prone to long bubble separation at the leading edge of the airfoil, so their stall characteristics are moderated. When the forward sweep angle $\chi \leq 20^\circ$, the stall angle of attack, the maximum lift coefficient decreases as the forward sweep angle increases, and when the forward sweep angle $\chi > 20^\circ$, the maximum lift coefficient increases as the forward sweep angle increases.

Under the condition of constant sweep angle, the lift coefficients of the airfoil of each section increase with the increase of Mach number, and the increase rate of the lift coefficient increases with the increase of Mach number; and, under the same Mach number, the airfoil lift coefficient basically increases first and then decreases as the forward sweep angle increases, reaching a maximum when the forward sweep angle $\chi = 20^\circ$.

Therefore, when the basic airfoil is inclined, the random wing sweep angle increases, and its lift characteristics have a significant improvement. In a forward-swept state at $20^\circ$, the wing with a basic airfoil (wing ribs) at an inclined angle of $20^\circ$ increased from 0.83 to 1.08, which increased by about 30%, compared to its forward position. The stall angle of attack has also increased from $8^\circ$ to $10^\circ$.

3.1.2. Analysis of resistance characteristics

Figure 3 shows the change law of the resistance coefficient of the section airfoil at different sweep angles with the angle of attack and the angle of attack $\alpha = 4^\circ$ when $Ma = 0.2$.

![Figure 3. Variation of drag coefficient with angle of attack and Mach number](image)

It can be seen from the figure that under the condition that the forward sweep angle is unchanged, the drag coefficient increases with the increase of the angle of attack, and the slope of the drag coefficient increases with the increase of the angle of attack; at the same angle of attack, the drag coefficient decreases first and then increases as the forward sweep angle increases. When the relative thickness of the airfoil is large, the drag coefficient will decrease as the sweep angle increases. When the relative thickness is small, the drag coefficient will increase as the sweep angle increases. A small airfoil has a smaller stall angle of attack, and its drag coefficient quickly increases to a larger value at a small angle of attack. Generally speaking, the airfoil resistance characteristic of $\chi = 20^\circ$ has the best resistance, not only has a small resistance coefficient, but also has a larger divergence angle of attack compared with other airfoil at the forward sweep angle in the same group. When the basic airfoil is inclined at an angle of $20^\circ$, the resistance coefficient $C_x$ of each section airfoil at an angle of attack of $4^\circ$ is reduced by 11%.

During the process of changing from 0.2 to 0.5, the drag coefficients of airfoils of various cross sections change relatively smoothly. After increasing from 0.5 to 0.7, the drag coefficient increases sharply. This is mainly due to the generation of local shock waves around Mach 0.7, which makes the
drag coefficient of the each wing model increases sharply; the divergent mach number of each airfoil is positively related to its relative thickness, that is, the smaller the relative thickness is, the smaller the divergent mach number is; when the relative thickness is reduced to a certain extent, its resistance coefficient varies with The changes are maintained at a high value, that is, the curve is relatively flat; at the same mach number, the airfoil drag coefficient is the smallest.

3.1.3. Analysis of moment characteristics

Figure 4 shows the variation law of the pitch moment coefficients of the profile airfoils at different sweep angles with the angle of attack and the angle of attack $\alpha = 4^\circ$ with $Ma = 0.2$.

![Figure 4. Variation of the moment coefficient with the angle of attack and Mach number](image)

It can be seen from the figure that under the same forward sweep angle, as the angle of attack increases, the moment coefficient gradually increases. And in the case of a small angle of attack, the torque changes linearly with the angle of attack, and then with the increase of the angle of attack, the torque growth gradually stabilizes. With the angle of attack remaining constant, the moment coefficient of the airfoil of each section increases with the increase of the sweep angle. Comparing the pitching moment coefficients of the basic airfoil at an angle of $20^\circ$ and the cross-section airfoil at an angle of attack of $4^\circ$, the airfoil $C_m$ increased by 1.3 times.

At the same sweep angle, as the Mach number increases, the airfoil's head moment increases, that is, the moment around the airfoil's leading edge point increases. Under the same Mach number, the moment coefficient of the airfoil basically increases with the increase of the sweep angle, but the pitch coefficient of the airfoil is the largest at $\chi = 20^\circ$.

3.2. Aerodynamic characteristics of a section airfoil when the basic airfoil is inclined at $40^\circ$

3.2.1. Analysis of lift characteristics

Figure 5 shows the variation law of the lift coefficient of the profile airfoil at different sweep angles with the angle of attack and the angle of attack $\alpha = 4^\circ$ when $Ma = 0.2$. 
It can be seen from the figure that the wing of the basic airfoil and the root of the wing is 40°, whether in the graph with the angle of attack or the graph with the Mach number, the lift coefficients of each section of the airfoil first increase with the increase of the forward sweep angle and then decrease with the increase of the forward sweep angle, and the maximum value is obtained when χ=40°. Therefore, a wing with a basic airfoil oblique angle of 40° has the best lift characteristics at a forward sweep angle of χ = 40°. The wing with a basic airfoil (rib) at an oblique angle of 40° increased the maximum lift coefficient by 39% compared to when it was upright.

3.2.2. Analysis of resistance characteristics

Figure 6 shows the change law of the resistance coefficient of the section airfoil at different sweep angles with the angle of attack and the angle of attack α = 4° when Ma = 0.2.

It is not difficult to see that, at the forward sweep angle of χ = 40°, the resistance of each group of airfoils is maintained at a small value at a small angle of attack and low mach number. Therefore, a wing with a basic airfoil inclined at 40° at a forward sweep angle of 40° has better resistance characteristics. Comparing the basic airfoil at an oblique angle of 40° and its cross-section airfoil at a 4° angle of attack, the coefficient of resistance $C_x$ was reduced by 9%.

3.2.3. Analysis of moment characteristics

Figure 7 shows the changing law of pitching moment coefficients of various airfoils with Mach number at different sweep angles with different angles of attack and angle of attack $\alpha=4^\circ$ at Ma=0.2.
It can be seen from the figure that a wing with a basic airfoil at an oblique angle of 40° has approximately the same torque characteristics as a wing with a basic airfoil at an oblique angle of 20°, that is, when the relative thickness of the cross-section airfoil caused by the forward sweep of the wing is positively related to the sweep angle of the wing, the torque coefficient increases with the increase of the forward sweep angle. When the relative thickness is small to a certain value, the torque coefficient will show a sharp increase; the subsonic state is that an increase in the Mach number will cause an increase in the torque coefficient, and this effect will become larger when the relative thickness of the airfoil is smaller. Therefore, a wing with a basic airfoil oblique angle of 40° has better torque characteristics when the forward sweep angle is 40°. Comparing the pitch moment coefficients of the basic airfoil at a 40° oblique angle and the cross-section airfoil at an angle of attack of 4°, $C_m$ increased by 0.5 times.

### 3.3. Comparison of aerodynamic characteristics of basic airfoils at 20° and 40°

Table 2 shows the calculated aerodynamic characteristics of the section airfoil when the basic airfoil is inclined at 20° and 40° when the Mach number is 0.2 and the attack angle is 4°.

![Figure 7. Variation of moment coefficient with angle of attack and Mach number](image)

| sweep angle | lift coefficient | resistance coefficients | pitch moment coefficients |
|-------------|-----------------|-------------------------|--------------------------|
|             | incline at 20°  | incline at 40°          | incline at 20°           | incline at 40°          |
| 0°          | 0.436884        | 0.443776                | 0.01176                  | 0.010458                |
| 20°         | 0.446362        | 0.441809                | 0.00868                  | 0.009437                |
| 40°         | 0.442894        | 0.446362                | 0.010926                 | 0.00868                 |
| 60°         | 0.437663        | 0.445358                | 0.028688                 | 0.031779                |

From the above data, it can be seen that the lift coefficient of the cross-section airfoil increases when the basic airfoil is inclined at 40° than when the basic airfoil is inclined at 20° at a sweep angle of 0°, 20°, 40°, and 60°. The resistance coefficients decreased by 11.07%, 20.56%, 8.74%, and 10.78%, respectively; the pitch moment coefficients increased by 39.34%, 214.70%, 47.20%, and 3.60%, respectively. Therefore, the aerodynamic characteristics of a cross-section airfoil when the basic airfoil is inclined at 40° are better than when the basic airfoil is inclined at 20°.

### 4. Conclusion

Through numerical simulations and simulation calculations, the change laws and aerodynamic characteristics of the cross-section airfoil at different angles (different oblique angles) between the basic airfoil and the wing root are analyzed and studied. The following conclusions can be drawn:
(1) There are significant differences in aerodynamic characteristics of the two wings when the basic airfoil is inclined and when it is upright. Under the same conditions, when the basic airfoil is inclined, its lift characteristics, drag characteristics, and pitching moment characteristics are better than the aerodynamic characteristics of the basic wing when the forward sweep angle increases.

(2) When the forward sweep angle of the wing is increased to the same as the oblique angle of the basic airfoil, the relative incoming cross-section airfoil is a standard airfoil at this time. Good aerodynamic performance, that is, it has the best lift, drag and torque characteristics.

(3) Comparing the aerodynamic characteristics of each airfoil when the basic airfoil is inclined at 20° and 40°, in contrast, when the basic airfoil is inclined at 40°, the aerodynamic characteristics of each airfoil are better when the forward sweep angle changes. It can be seen that the aerodynamic characteristics of each airfoil are better when the forward sweep angle changes when the oblique angle of the basic airfoil is larger.

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