Study on the Influence of Swept Angle on the Aerodynamic Characteristics of the Cross-Section Airfoil of a Variable Swept-Wing Aircraft

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Abstract. The variable forward swept-wing aircraft is a typical variant aircraft. The airfoil is a variable airfoil during the wing swept, and its aerodynamic characteristics have a huge impact on the flight performance of the variable swept-wing aircraft. It is also an aircraft. One of the difficult problems to be solved first in aerodynamic layout design. In order to explore the unsteady aerodynamic characteristics of the variable airfoil, a variable airfoil model with different relative thicknesses is established. Then the S-A turbulence model is used and the CFD simulation is used to calculate the variable airfoil unsteady. The variation of the angle of attack and the Mach number when the aerodynamic parameters change in the forward sweep angle. The results show that the airfoil lift coefficient and moment coefficient are negatively correlated with the relative thickness, while the drag coefficient is positively correlated with the relative thickness. These aerodynamic characteristics can provide a useful reference for the aerodynamic layout design and dynamic analysis of the variant aircraft.

1. Introduction

The variable swept-wing layout aircraft is a typical variant aircraft, which can change the wing grazing angle according to the needs, but the grazing will bring serious changes in aerodynamic characteristics, which have an impact on flight performance and safety. It is necessary for the aircraft to achieve the evolution of the configuration with changes in flight conditions.

In recent years, model design and numerical simulation and experimental verification have been carried out in the field of variant wings at home and abroad. The research focuses on the layout of the forward-forward wing or the aerodynamic characteristics of the whole wing [1-7], and there are few studies on the two-dimensional state.

With the change of the grazing angle of the wing, the relative thickness of the cross-section airfoil will change with the parameters of the airfoil, which will have a great influence on the aerodynamic performance of the overall wing. Therefore, it is necessary to study the variation of the section airfoil and its influence on the aerodynamic characteristics during the process of wing swept.

2. Modeling and feature parameter analysis

In order to make the wing of the variable swept-wing aircraft change smoothly in the state of flat wing, forward swept wing and delta wing, this paper selects NACA0006 thin symmetrical airfoil as the basic
airfoil of the variable forward swept-wing aircraft wing, and makes it perpendicular to the leading edge of the wing.

The wing is composed of an outer wing and an inner wing hidden in the rear of the fuselage in a flat wing state. The geometry and contour of the wing are shown in Figure 1. According to the principle of relative motion, this paper studies the different planes intercepting the wing around the leading edge point and the trailing edge point of the wing, and obtains 12 kinds of airfoil.

In order to fully consider the convenience and representativeness of airfoil interception, the airfoil section of group A represents the rotation of the leading edge of the wing root, and the airfoil section of group B represents the rotation of the trailing edge of the wing root. The relative size is the largest. During the forward-swept deformation of the wing, the process of the profile of each airfoil with the forward sweep angle is shown in Figure 2.

![Figure 1. Geometric dimensions of the wing](image)

![Figure 2. Schematic diagram of the variation of the airfoil of each group with the swept angle](image)

The group A airfoil is obtained by rotating around the leading edge of the wing root and is located in the triangular portion on the left side of the wing, and its chord length and relative thickness are changed. When the current swept angle of the B-set airfoil is large, its relative thickness will decrease sharply. Since the aerodynamic characteristics of the airfoil are greatly affected by the relative thickness, in order to facilitate the analysis, only the influence of the relative thickness variation on the aerodynamic characteristics of the section airfoil is considered. The relative thickness of the airfoil of Group A and Group B as a function of the forward sweep angle is shown in Table 1.

| Forward sweep angle | 0° | 10° | 20° | 30° | 40° | 50° | 60° |
|---------------------|----|-----|-----|-----|-----|-----|-----|
| A                   | 6% | 7.45% | 8.45% | 9.06% | 9.26% | 9.01% | 8.29% |
| B                   | 6% | 5.61% | 4.99% | 4.21% | 3.25% | 2.16% | 0.88% |

It can be seen from Table 1 that the relative thickness of the airfoil of Group A increases first and then decreases, and the thickness of the airfoil of Group B increases while the thickness decreases gradually, so the relative thickness gradually decreases.

3. Pneumatic analysis

In the section, the corresponding airfoil is used to perform structural meshing. The mesh is of the order of 270,000, and different solvers are used to increase the convergence speed by using the Mach
number of 0.3. The S-A turbulence model is used to select the ideal temperature of 288.15K free flow, calculate the variation law of each aerodynamic parameter.

3.1. Influence of angle of attack on lift characteristics when the sweep angle changes

Figure 3 shows the relationship between the lift coefficient of each cross-section airfoil at different forward sweep angles under the conditions of $T = 288.15K$.

From the curve, the following law can be obtained: as the angle of attack increases, the lift coefficient first increases, and then decreases after reaching the stall angle of attack.

For the A-set airfoil, in the state of $\alpha < 8^\circ$, the lift coefficient increases linearly with the angle of attack at the angle of attack, up to the maximum lift coefficient, and the lift coefficient begins to decrease after the stall angle of attack; As the forward sweep angle increases, the maximum lift first increases and then decreases, and the maximum lift is reached in the state of $\chi = 20^\circ$. Moreover, the increase of the forward sweep angle also causes the stall angle to increase first and then decrease, and stall angle of attack is the largest in the state of $\chi = 30^\circ$. The airfoil of the forward sweep angle is used to illustrate the flow mechanism\[8\]. In the state of $\alpha = 4^\circ$, the upper surface of the airfoil maintains an attached flow, and the lift coefficient increases linearly with increasing angle of attack. When the angle of attack is further increased, the negative pressure zone of the leading edge of the airfoil increases, the suction increases, and at this time the airflow separation begins to occur at the trailing edge of the upper surface of the airfoil. In the state of $\alpha = 12^\circ$, the area separating the upper surface of the airfoil further increases, and the separation vortex of the airflow occurs at the trailing edge of the airfoil, the leading edge negative pressure zone decreases, the suction force decreases, the lift coefficient decreases rapidly, and the airfoil stalls.

For the relationship between the lift and the forward sweep angle, it can be seen from the curve in the figure that when the relative thickness of the cross-section airfoil is large, the lift coefficient decreases as the forward sweep angle increases. This is because as the forward sweep angle increases, the leading edge of the airfoil has a negative pressure region with a smaller absolute value, and the area of this negative pressure region also decreases as the forward sweep angle increases. Therefore, its lift coefficient decreases as the forward sweep angle increases.

For the B-set airfoil, in the state of $\chi \leq 20^\circ$, the stall angle of attack and the maximum lift coefficient decrease with the increase of the forward sweep angle, while the maximum lift coefficient increases with the advance sweep angle in the state of $\chi > 20^\circ$. When the thickness of the section airfoil is small, the lift coefficient will increase with the increase of the forward sweep angle. For example, the airfoil thickness of the B group airfoil is less than 6%. It can also be seen from the lift coefficient curve of Figure 3. As the forward sweep angle increases, the airfoil lift coefficient gradually increases.
3.2. Influence of Mach number on lift characteristics when the sweep angle changes
Figure 4 shows the variation of the lift coefficient of each airfoil group with the Mach number under the conditions of $\alpha = 4^\circ$.

![Figure 4](image)

**Figure 4.** The variation of lift coefficient with Mach number for each airfoil group under the conditions of $\alpha = 4^\circ$.

It can be seen from the figure that the lift coefficient of each airfoil group increases with the increase of the Mach number, and the rate of increase of the lift coefficient increases with the increase of the Mach number. At the same Mach number, as the forward sweep angle increases, the lift coefficient gradually decreases.

With the increase of the Mach number, the pressure on the upper surface of the airfoil has a negative pressure region with a larger absolute value, and as the Mach number increases, the negative pressure region also gradually increases, so the lift coefficient of the airfoil increases. When the Mach number is increased to 0.6, the leading edge of the airfoil gradually generates a shock wave. The appearance of the shock wave makes the absolute value of the leading edge pressure of the airfoil larger, and the area of the negative pressure zone is further increased, so the airfoil lift coefficient has increased dramatically.

3.3. Influence of angle of attack on resistance characteristics when the sweep angle changes
Figure 5 shows under the conditions of $Ma = 0.2$, the variation of the airfoil drag coefficient with the angle of attack at different forward sweep angles.

![Figure 5](image)

**Figure 5.** The variation of the drag coefficient of each airfoil group with the angle of attack under the conditions of $Ma = 0.2$.

It can be seen from the figure that the drag coefficient increases with the increase of the angle of attack as the forward sweep angle is constant, 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 as the plunging angle increases, it increases. For group A airfoil, the increase of the forward sweep angle causes the relative thickness of the airfoil to gradually increase, so the drag coefficient gradually decreases. For the group B airfoil, the increase of the forward sweep angle causes the relative thickness of the airfoil to decrease, when the relative thickness is reduced. When reduced to a certain value, its drag coefficient will rise sharply at a small angle of attack, mainly because the thin-wing type stall angle of attack is small, and the airfoil drag coefficient will increase sharply after divergence.

3.4. Influence of Mach number on resistance characteristics when the sweep angle changes
Figure 6 shows the variation of the lift coefficient of each airfoil group with the Mach number under the conditions of \( \alpha = 4^\circ \). It can be seen from the airfoil of Group A that the change of the drag coefficient of each airfoil at each forward sweep angle is relatively gentle during the process from 0.2 to 0.5, and the drag coefficient increases sharply during the process from 0.5 to 0.7. Mainly due to the generation of local shock waves around 0.7 \( Ma \), the drag coefficient of each airfoil increases sharply \cite{9}; from the B-group airfoil, the larger the forward sweep angle, the smaller the Mach number of the resistance divergence, and the Mach number. The effect on the resistance is also more pronounced, mainly because the relative thickness of each airfoil decreases as the forward sweep angle increases.

3.5. Influence of angle of attack on torque characteristics when the sweep angle changes
Figure 7 shows the variation of the pitching moment of each airfoil with the angle of attack at different forward sweep angles under the conditions of \( Ma = 0.2 \).

![Figure 6. The variation of the drag coefficient of each airfoil group with the Mach number under the conditions of \( \alpha = 4^\circ \)](image)

![Figure 7. The variation of the pitching moment coefficient of each airfoil group with the angle of attack under the conditions of \( Ma = 0.2 \)](image)
It can be seen from the figure that the torque coefficient of the leading edge point of the airfoil gradually increases with the increase of the angle of attack at the same forward sweep angle. At the small angle of attack, the moment has a linear relationship with the change of the angle of attack. Then, as the angle of attack increases, the moment changes gradually. When the angle of attack remains unchanged, the airfoil torque coefficient of group A decreases with the increase of the forward sweep angle, while the airfoil torque coefficient of group B increases with the increase of the forward sweep angle. The reason is that the change of the forward sweep angle causes a change in the relative thickness of the section airfoil, and the moment coefficient of the airfoil is negatively correlated with the relative thickness, that is, the larger the relative thickness is, the smaller the moment coefficient is, and the smaller the relative thickness is, the larger the moment coefficient is.

4. Conclusion
For the change of the cross-section airfoil during the swept process, the following conclusions are obtained.
(1) When the grazing angle of the wing changes, the relative thickness of the section airfoil and other parameters will also change, and the aerodynamic characteristics will change accordingly;
(2) When the angle of attack changes, the lift coefficient decreases with the increase of the forward sweep angle for the cross-sectional airfoil with larger relative thickness; the lift coefficient with the forward sweep angle is the relative airfoil with the relative thickness less than 6%. The increase is slightly increased; when the Mach number changes, the lift coefficient of the cross-section airfoil decreases as the forward sweep angle increases.
(3) When the angle of attack changes, the drag coefficient of each airfoil increases with the increase of the forward sweep angle; when the Mach number changes, the drag coefficient of the cross-section airfoil also appears with the increase of the forward sweep angle. Increase the trend.
(4) When the angle of attack changes, the pitching moment coefficient decreases with the increase of the forward sweep angle for the cross-sectional airfoil with larger relative thickness; the pitching moment coefficient with the relative thickness less than 6% of the cross-section airfoil The angle increases and increases.

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