Analysis on Flow Field Characteristics of Airfoil in Pitching Motion

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Abstract—Based on CFD, the flow field characteristics of NACA4412 airfoil are analyzed under pitching motion, and its aerodynamic characteristics are interpreted. The results show that streamline changes on the upper surface of the airfoil play a decisive role in the aerodynamic characteristics. The interaction between the vortex leads to fluctuations in the lift and drag coefficients. Under a big angle of attack, the secondary trailing vortex on the upper surface of the airfoil adheres to the trailing edge of the airfoil, resulting in an increased drag coefficient. Under a small angle of attack, the secondary trailing vortex can break away from the airfoil. The lift coefficient reaches the maximum value of 2.961 before the airfoil is turned upside down, and the drag coefficient reaches the maximum value of 1.515 after the airfoil is turned upside down, but the corresponding angles of attack of the two are equal.

1. Introduction
Airfoil dynamic stall involves a very complicated mechanism, which may greatly impair the performance of airfoil or wind turbine blade\textsuperscript{(1)} , so it is particularly important to study the aerodynamic characteristics of the airfoil in the pitching motion.

There are many studies on the dynamic stall performance of airfoils. Qian Weiqi\textsuperscript{(2)} et al. used different turbulence models to simulate airfoil dynamic stall; Chen Xu\textsuperscript{(3)} et al. analyzed the flow field characteristics of the airfoil dynamic stall; Bai Peng\textsuperscript{(4)} et al. carried out numerical research on upward pitching of airfoil under constant speed. In general, some of the above studies were carried out at a higher Reynolds number or higher Mach number, and some only involved upward motion of airfoil. However, there is little research on the flow field characteristics of airfoil when it pitches at low Reynolds numbers. Therefore, this paper adopts the CFD method to conduct an in-depth analysis of the flow field characteristics of NACA4412 airfoil when it pitches at low Reynolds numbers, thereby revealing the reason for the macroscopic aerodynamic characteristics.

2. Calculation Method

2.1. Governing equation
The fluid medium is air, and the governing equations are as follows with viscosity, not considering compression\textsuperscript{(5)}:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)
\]
\[
\frac{\partial \xi}{\partial t} + \nu \frac{\partial \xi}{\partial x} + \nu \frac{\partial \xi}{\partial y} = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial \eta}{\partial x^2} + \frac{\partial \eta}{\partial y^2}\right) \tag{3}
\]

\(k-\omega\) SST turbulence model\(^2\) is selected and pressure-velocity coupled using the COUPLED algorithm. When \(k\) and \(\omega\) are both lower than \(10^{-6}\), the calculation is deemed as convergent.

2.2. Mesh generation

Take the trailing edge point of the airfoil as the center and draw a circle with a radius of about 20 times that of the airfoil chord length to obtain the calculation area. O-shaped structured grid is used. The circumferential boundary takes the velocity inlet as the boundary condition, and the outer contour of the airfoil takes the wall surface as the boundary condition. The grid density is gradually increased from the perimeter line to the outer contour of the airfoil. The Fluent software was used to calculate and compare grids of different numbers, and the number of grids is determined to be about 27,000, as shown in Fig.1. Now, we take the experimental data\(^6\) when the static NACA4412 airfoil has a Reynolds number of \(6.4 \times 10^5\) as a reference, compare the lift-drag ratio \(C_L / C_d\) obtained by numerical simulation with the experimental value, and observe its change with the angle of attack \(\alpha\), as shown in Fig.2. It can be seen from Fig.2 that the numerical simulation results are basically consistent with the experimental values, indicating that the numerical results have certain reliability.

![Fig.1 Grid structure](image1.png)

![Fig.2 Static lift-drag ratio of NACA4412 airfoil](image2.png)

3. Analysis on aerodynamic characteristics of the airfoil in pitching motion

The changing law of the angle of attack is as follows\(^7\):

\[
\alpha = \alpha_0 + \Delta \alpha \sin(\omega t), \quad \omega = 2\pi f / c \tag{4}
\]

Where, \(\alpha_0\) is the initial angle of attack, taking value 15°. \(\Delta \alpha\) is the pitch amplitude, taking value 15°. \(\omega\) is the pitch angular velocity, \(V\) is the incoming flow velocity, taking value 9.35m/s, \(K\) is the attenuation frequency, taking value 0.2, \(c\) is the airfoil chord length, taking value 1m. The pitching motion center of the airfoil is at quarter-chord length near the leading edge point\(^8\). Through trial calculations of different time steps \(\Delta t\), the final value is 0.005s, and the number of steps is 1008. After 3 pitch cycles, the calculation result tends to be stable.

3.1. Aerodynamic characteristics

The calculated lift and drag coefficients are shown in Fig.3.
Fig. 3 Dynamic lift and drag coefficients of NACA4412 airfoil

The lift coefficient curve in Fig. 3 changes in a clockwise direction, and the drag coefficient curve changes in a counterclockwise direction on the right side of the intersection. The lift and drag coefficient curves display no obvious fluctuations when the airfoil pitches up, but great fluctuation appears when the airfoil pitches down under the big angle of attack. Fluctuations of the lift and drag coefficients show a certain degree of synchronization. As a whole, the lift and drag coefficients increase with the increase of the angle of attack, and decrease with the decrease of the angle of attack. When the angle of attack rises near 29°, a sudden change occurs in the lift and drag coefficients.

It can be seen from Fig.3(a) that the lift coefficient is higher when the airfoil pitches up. On the whole, under the small angle of attack, there is a small difference in the lift coefficients when it pitches up and down, and under the bigger angle of attack, a great difference in the lift coefficients appears when it pitches up and down.

It can be seen from Fig.3(b) that when the angle of attack is smaller than 18°, the drag coefficient is greater when the airfoil pitches up, and there is a small difference between the drag coefficients when it pitches up and down; when the angle of attack is greater than 18°, the drag coefficient is greater when the airfoil pitches down, and great difference in drag coefficient appears when it pitches up and down.

3.2. Pressure

The distribution of pressure $p$ of the airfoil under different angles of attack is shown in Fig. 4. Where, + represents the pitch-up process and - represents the pitch-down process.
It can be seen from Fig.4 that the airfoil surface has a relatively uniform pressure distribution when it pitches up, but fluctuation appears when it pitches down under the big angle of attack. The airfoil surface generally has a greater pressure difference when it pitches up rather than pitching down, and when the angle of attack is small, there is a small difference between pressure difference when it pitches up and down. The pressure difference on the airfoil surface increases as the angle of attack increases, and decreases as the angle of attack decreases. When $\alpha$ transitions from 29$^\circ$ to 30$^\circ$, the pressure difference on the airfoil surface suddenly increases, and when $\alpha$ transitions from 30$^\circ$ to 29$^\circ$, the pressure difference on the airfoil surface suddenly decreases. The above observations are consistent with the conclusion shown in Fig.3.

3.3. Streamline

The streamline distribution of the airfoil under different angles of attack is shown in Fig.5.

![Fig.4 Surface pressure of NACA4412 airfoil](image)

Fig.4 Surface pressure of NACA4412 airfoil

Fig.5 shows the streamline distribution on the airfoil surface at each angle of attack within a pitch cycle. The streamline on the upper surface of the airfoil changes significantly, which plays a decisive role in the aerodynamic characteristics.

When the airfoil pitches up, as the angle of attack increases, the streamlines on the upper surface of the airfoil gradually become denser, indicating that the flow velocity increases and the pressure
intensity decreases, so that the pressure difference on the airfoil surface as well as lift coefficient increases. A vortex is produced at the trailing edge of the airfoil. Referred to as a trailing vortex, it gradually increases and extends to the forward edge. When $\alpha = 29^\circ +$, the trailing vortex almost covers the entire upper surface of the airfoil, and a vortex is generated near the trailing edge point, which is called the secondary trailing vortex. A vortex is generated near the leading edge, which is called a stall vortex. At this time, the stall vortex is unobvious, and the lift coefficient keeps increasing. However, as the stall vortex continues to increase, the lift coefficient changes from increase to decrease. When the angle of attack is about $29.74^\circ +$, the lift coefficient reaches the maximum value of 2.961. When $\alpha = 30^\circ$, the trailing vortex further increases, while the secondary trailing vortex attaches to the trailing edge of the airfoil and gradually increases, resulting in a sudden increase in the drag coefficient so that it reaches 1.374. The stall vortex increases rapidly, and two secondary stall vortices are produced at the leading edge of the airfoil. At this time, the pressure on the upper surface of the airfoil suddenly decreases, resulting in a sudden decrease in the pressure difference and lift coefficient.

When the airfoil pitches down, as the angle of attack decreases, the streamlines on the lower surface of the airfoil gradually become denser, indicating that the flow velocity increases and the pressure decreases, so that the pressure difference on the airfoil surface as well as lift coefficient decreases. When $\alpha = 29^\circ -$ , the secondary trailing vortex is still attached to the trailing edge of the airfoil and further increases, causing the drag coefficient to further increase, reaching 1.392. The stall vortex and the trailing vortex merge into a new trailing vortex that gradually deviates away from the upper surface of the airfoil, so that the drag coefficient changes from increase to decrease. When the angle of attack is about $29.74^\circ -$ , the drag coefficient reaches the maximum value of 1.515. The gradual increase in secondary stall vortex drives the new trailing vortex away from the airfoil, resulting in a rapid decrease in the pressure difference and lift coefficient. When $\alpha = 27^\circ$, the secondary trailing vortex further increases and moves towards the upper surface of the airfoil, resulting in a certain increase in the drag coefficient. The new trailing vortex deviates away from the upper surface of the airfoil, resulting in a decrease in the pressure difference and a slow decrease in the lift coefficient, and a gradual increase is shown in the secondary stall vortex with a tendency to merge. When $\alpha = 20^\circ$, the secondary trailing vortex separates from the trailing edge of the airfoil, resulting in a gradual decrease in the drag coefficient. The new trailing vortex reaches the downstream, and the secondary stall vortex merges into a new secondary stall vortex that gradually decreases, resulting in a decrease in the pressure difference and a slow decrease in the lift coefficient. When $\alpha = 18^\circ$, the new trailing vortex reaches downstream and becomes smaller, the new stall vortex gradually decreases and moves towards the trailing edge of the airfoil, resulting in a decrease in the pressure difference and a slow decrease in the lift coefficient. When $\alpha = 14^\circ$, the new trailing vortex disappears, the new stall vortex reaches the trailing edge of the airfoil, and the streamlines gradually adhere to the upper surface of the airfoil, resulting in a decrease in the pressure difference and a slow decrease in the lift coefficient.

4. Conclusion

Through the numerical simulation analysis of the flow field characteristics of the airfoil in pitching motion, the following conclusions are drawn:

1. The streamline changes on the upper surface of the airfoil play a decisive role in the aerodynamic characteristics;
2. The interaction between the vortex bodies causes fluctuations in the lift and drag coefficients;
3. When the airfoil is pitched up until a large angle of attack is formed, the secondary trailing vortex on the upper surface of the airfoil is attached to the trailing edge of the airfoil, resulting in an increased drag coefficient. When the airfoil is pitched down until a small angle of attack is formed, the secondary trailing vortex can leave the airfoil;
4. The lift coefficient reaches the maximum value of 2.961 before the airfoil is turned upside down, and the drag coefficient reaches the maximum value of 1.515 after the airfoil is turned upside down, but the corresponding angles of attack of the two are basically equal.
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