Effects of Pitching Motion Elements on Aerodynamic Characteristics of Airfoil

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Abstract—The aerodynamic characteristics of NACA4412 airfoil with different pitching motion elements were compared and analyzed based on CFD in this research. The results are acquired as follows: the difference between the lift and drag coefficients of the airfoil during pitch up and pitch down motions becomes larger with the increase of the pitching amplitude or initial angle of attack; as the pitching amplitude increases, the lift coefficient grows slightly greater and the drag coefficient grows much greater; as the initial angle of attack increases, the lift coefficient grows much greater and the drag coefficient grows slightly; the smaller the attenuation frequency is, the larger the lift-to-drag ratio of the airfoil will be.

1. Introduction

Airfoils play an important role in the efficient operation of a wing or wind turbine blade[1]. The study of airfoils is one of the most fundamental tasks. However, most of the airfoils operate under dynamic conditions, and their aerodynamic characteristics differ a lot from those under static conditions[2]. Therefore, it is necessary to study the aerodynamic characteristics of the airfoils under pitching motion.

Many scholars have done researches on the dynamic stall characteristics of airfoils. Xie Kai et al.[3] simulated the dynamic stall of an airfoil under non-constant incoming flow with compound motion. Lu Tianyu et al.[4] analyzed the effect of leading-edge deformation of an airfoil on the dynamic stall effect. Zhang Weigu et al.[5] conducted a numerical study on the dynamic stall and other plasma flow control of wind turbine airfoils. Yang Hesen et al.[6] studied the factors influencing the dynamic stall of an airfoil and flow control. All these researches have greatly promoted the progress of research on the dynamic stall characteristics of airfoils. In general, these researches mainly concentrated on two aspects. One is the prediction and analysis of the dynamic stall characteristics of the airfoils under different working conditions, while the other is the control means of the dynamic stall of the airfoils. However, the influence of different pitching motion elements of the airfoils on their aerodynamic characteristics has been rarely studied. Therefore, this paper adopts the CFD method to compare and analyze the aerodynamic characteristics of NACA4412 airfoil under different pitching motion elements and summarize the influence law brought by each pitching motion element.

2. Numerical Method

2.1. Basic Equations

The numerical simulation targets a two-dimensional airfoil with a Reynolds number (Re) of $6.4 \times 10^5$ and a fluid medium of incompressible and viscous air. The basic control equations are the two-dimensional continuity equation and the two-dimensional Navier–Stokes (N-S) equations[7].

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\begin{align*}
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} &= 0 \\
\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) \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} &= -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)
\end{align*}

Since the aerodynamic characteristics under the pitching motion of the airfoil require high accuracy, the \( k-\omega \) two-equation turbulence model\(^8\) is used in this paper. In addition, the coupled algorithm is used for pressure-velocity coupling, and the computational convergence requirement is below \( 10^{-6} \) for both \( k \) and \( \omega \).

2.2. Grids Division

An O-type fully structured grid is used. The computational domain is circular, with the trailing edge point of the airfoil coinciding with the center of the circle and the radius about 20 times the chord length of the airfoil. The boundary condition of the computational domain is the velocity entrance, and the boundary condition of the airfoil surface is the wall surface. Grids with different number were imported into Fluent software for calculation and comparison, and the final number of grids was determined to be 27370, and the boundary-layer grid near the airfoil surface was denser, as shown in Fig.1. To verify the validity of the grid, the corresponding lift coefficient \( C_l \) and drag coefficient \( C_d \) of each angle of attack \( \alpha \) under the static NACA4412 airfoil obtained from the numerical simulation were compared with the experimental values\(^9\), as shown in Fig.2. As can be seen from Fig.2, the numerical simulation results basically match with the experimental values, indicating that the numerical results are credible. The numerical calculation method mentioned above is also used in the subsequent work of this paper.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Computational Domain and Grid Structure}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig2.png}
\caption{Static Lift and Drag Coefficients of NACA4412 Airfoil}
\end{figure}
3. Airfoil Aerodynamic Characteristics Analysis

The variation law of the angle of attack during the pitching motion of the airfoil is as follows\[^{[10]}\].

\[
\alpha = \alpha_0 + \Delta \alpha \sin(\omega t) \tag{4}
\]

where \(\alpha_0\) is the initial angle of attack, \(\Delta \alpha\) is the pitching amplitude, \(\omega\) is the pitch angular velocity, \(\omega = 2\pi K / c\), \(V\) is the incoming flow velocity, \(K\) is the attenuation frequency, and \(c\) is the airfoil chord length. In this paper, the incoming flow velocity is set to 9.35 m/s, the airfoil chord length is 1 m, and the attenuation frequencies are 0.1 and 0.2. The center of rotation of the airfoil pitching motion is generally at the quarter point of the chord length near the leading edge point\[^{[11]}\], so the aerodynamic characteristics of the airfoil are mainly determined by the initial angle of attack, pitching amplitude, and attenuation frequency. For the time step \(\Delta t\) of numerical calculation, it should not be too large or too small. Taking \(\alpha_0 = 9°\) and \(\Delta \alpha = 3°\) as an example, the calculation results of different time steps were compared, and finally, the results were obtained as follows: \(\Delta t = 0.005s\) and the number of steps is 1008 steps, which contains 3 airfoil pitching motion cycles. The calculation results have been stabilized.

3.1. Effect of Pitching Amplitude

The attenuation frequency was taken as 0.2, the initial angle of attack as 9°, and three sets of pitching amplitudes as 3°, 6°, and 9°, which were numbered as 9-3, 9-6 and 9-9, and then the lift and drag coefficients of the airfoil were calculated respectively.

As can be seen from Fig.3, the common characteristics of the lift and drag coefficients during airfoil pitching are as follows: The lift and drag coefficients of the airfoil under dynamic motion are significantly different from those under static motion; the lift and drag coefficient curves of the airfoil under static motion show a single curve, while those of the airfoil under dynamic motion show a closed curve; the lift and drag coefficient curves move in a clockwise direction as the angle of attack increases and then decreases; for the same angle of attack, the corresponding lift and drag coefficients of the airfoil during pitch up and down motions are not the same, and the corresponding lift and drag coefficients during pitch up motion are larger than those during pitch down motion; the lift coefficient of the airfoil increases or decreases as the angle of attack increases or decreases, respectively; the drag coefficient of the airfoil increases as the angle of attack increases and decreases first and then increases slightly as the angle of attack decreases. Since the attenuation frequency is the same, the rate of curve change with the angle of attack is basically the same.

Due to the same initial angle of attack (9°), i.e., the same center of amplitude of the airfoil, the centers of the three sets of curves were concentrated at the angle of attack(9°).

From Fig.3(a), it can be obtained that the curves become significantly longer laterally and vertically with the increase of pitching amplitude, but the upper edges of the curves almost overlap. It means that the larger the pitching amplitude is, the larger the difference between the lift coefficient of the airfoil will be during pitch up and down motions, and the lift coefficients become slightly larger.
From Fig. 3(b), it can be obtained that the curves become longer laterally and vertically with the increase of pitching amplitude, and the area of the enclosed area surrounded by the curves increases significantly. It means that the larger the pitching amplitude is, the larger the difference between the drag coefficients of the airfoil will be during pitch up and down motions, and the drag coefficients become significantly larger.

During pitch up motion, the lift-to-drag ratios of the three combinations at the angle of attack (9°) were 34.57, 23.88, and 18.12, respectively. It indicated that the pitching amplitude should be reduced as much as possible to maintain a high lift coefficient.

3.2. Effect of Initial Angle of Attack
The attenuation frequency was taken as 0.2, the pitching amplitude as 6°, and three sets of initial angles of attack as 0°, 3°, and 6°, which were numbered as 0-6, 3-6 and 6-6, and then the lift and drag coefficients of the airfoil were calculated respectively.

From Fig.4, it can be seen that the common characteristics of lift and drag coefficients during airfoil pitching obtained in Fig.3 still hold.

Since the pitching amplitude was the same, the transverse spacing of all three sets of curves was 12°.

From Fig. 4(a), it can be obtained that the curves become slightly longer vertically with the increase of the initial angle of attack, and the overall position moves upwards vertically. It means that the larger the initial angle of attack is, the larger the difference between the lift coefficients of the airfoil will be during pitch up and down motions, and the lift coefficients become significantly larger.

From Fig.4(b), it can be obtained that the curves become longer vertically and shift to the right laterally with the increase of the initial angle of attack, and the area of the enclosed area surrounded by the curves increases. It means that the larger the initial angle of attack is, the larger the difference between the drag coefficients of the airfoil will be during pitch up and down motions is, and the drag coefficients become slightly larger.

During pitch up motion, the lift-to-drag ratios of the three combinations at the angle of attack (6°) were 25.46, 21.12, and 25.34, respectively. It indicated that the initial angle of attack should be adjusted and close to the static stall angle of attack as much as possible to maintain a high lift-to-drag ratio.

3.3. Effect of Attenuation Frequency
The attenuation frequency was taken as 0.1, the initial angle of attack as 9°, and the pitching amplitude as 3°, which was numbered as 9-3L, the lift and drag coefficients of the airfoil were calculated respectively.
From Fig.5, it can be seen that the smaller the attenuation frequency is, the smaller the difference between the lift and drag coefficients of the airfoil will be during pitch up and down motions, and the smaller the rate of curve change with the angle of attack.

From Fig.5(a), it can be obtained that the attenuation frequency becomes smaller and the lift coefficient becomes larger in general.

From Fig.5(b), it can be obtained that the attenuation frequency becomes smaller and the drag coefficient becomes smaller in general.

During pitch up motion, the lift-to-drag ratios at the angle of attack(9°) for the two cases are 34.57 and 38.91. It indicates that the attenuation frequency should be reduced as much as possible to maintain a high lift-to-drag ratio.

4. Conclusion

From the numerical simulation analysis of the aerodynamic characteristics of the airfoil during pitching motion, it can be concluded as follows.

(1) For the same airfoil, the rate of change of lift and drag coefficients with the angle of attack is basically the same only when the initial angle of attack or pitching amplitude is different.

(2) As either the pitching amplitude or the initial angle of attack increases, the difference between the lift and drag coefficients of the airfoil during pitch up and down motions becomes larger.

(3) When the initial angle of attack is the same, the centers of the lift and drag curves at different pitching amplitudes are concentrated at the same angle of attack. As the pitching amplitude increases, the lift coefficient becomes slightly larger, and the drag coefficient becomes significantly larger.

(4) When the pitching amplitude is the same, the transverse spacing of the lift and drag curves under different initial angles of attack is twice the pitching amplitude. As the initial angle of attack increases, the lift coefficient becomes significantly larger, and the drag coefficient becomes slightly larger.

(5) The pitching amplitude should be reduced as much as possible to maintain a high lift coefficient, and the initial angle of attack should be adjusted as much as possible and close to the static stall angle of attack. The attenuation frequency should be reduced as much as possible to maintain a high lift-to-drag ratio.

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