Lift and Drag Coefficient Map of NACA4415 Airfoil

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Abstract—The NACA4415 airfoil was numerically simulated with the help of the Fluent software to analyze its aerodynamic characteristics. Results are acquired as follows: The calculation accuracy of Fluent software is much higher than that of XFOIL software; the calculation result of SST $k$-$\omega$ (sstkw) turbulence model is closest to the experimental value; within a certain range, the larger the Reynolds number is, the larger the lift coefficient and lift-to-drag ratio of the airfoil will be, and the smaller the drag coefficient will be; when the angle of attack is less than the optimal angle of attack, the Reynolds number has less influence on the lift-to-drag coefficient and the lift-to-drag ratio; as the Reynolds number increases, the optimal angle of attack increases slightly, and the applicable angle of attack range for high lift-to-drag ratios becomes smaller.

1. Introduction

Airfoil is the key to the design of airfoil, wind turbine blades, and ocean current turbine blades\textsuperscript{[1-4]}, which play a pivotal role in the study of its dynamic characteristics.

There are many studies on the dynamic characteristics of airfoils. Wang Wei et al.\textsuperscript{[5]} analyzed the aerodynamic characteristics and vortex shedding modes of the airfoil under low Reynolds number; Kushiro et al.\textsuperscript{[6]} used the lattice Boltzmann method to numerically simulate the flow characteristics of an airfoil under low Reynolds number; Zhao Hui\textsuperscript{[7]} discussed the influence of turbulence model coefficient uncertainty on the simulation of airfoil flow; Qin Hao\textsuperscript{[8]} studied the flow mechanism around asymmetric airfoil. In general, some of the above studies focused stall mechanism, and some paid attention on the calculation methods or models. However, the dynamic characteristics and flow field characteristics of airfoils under different Reynolds numbers are rarely studied. For example, when designing wind turbine blades, the lift coefficient and drag coefficients of the airfoil under the specified Reynolds number will be required. Nowadays, airfoil aerodynamic calculation software such as XFOIL software is widely used, but the accuracy of the calculation results still needs to be confirmed. Therefore, in this paper, the Fluent software is applied to verify the accuracy of the XFOIL software, then the dynamic characteristics of the NACA4415 airfoil under different Reynolds numbers are analyzed to form a set of lift and drag coefficient maps, which provides reference for wind turbine blades design.

2. Calculation Method

2.1. Governing equations

The fluid medium is incompressible and viscous air, and the governing equations are the continuity equation and the N-S equation\textsuperscript{[9]}.
\[
\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \quad (1)
\]
\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)
\]
\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (3)
\]

Three different turbulence models, namely S-A, realizable k-\(\varepsilon\) (rke) and SST k-\(\omega\) (sstkw) are selected to couple pressure-velocity with the help of the COUPLED algorithm.

2.2. Computational domain and meshing

The calculation domain of the airfoil is circular, and the center of the circle is the trailing edge point of the airfoil. Besides, the radius is about 20 times the airfoil chord length, and a quadrilateral structured grid is adopted. The boundary condition of the outer boundary in the calculation domain is the velocity inlet, and the boundary condition of the airfoil surface is the wall surface. To make the calculation results more accurate, the mesh around the airfoil is encrypted, as shown in Fig. 1.

![Computational domain grid and grid around the airfoil](image)

(a) Computational domain grid  (b) Grid around the airfoil

Fig. 1 Computational Domain and Mesh Division

2.3. Grid independence verification

According to the requirements of the turbulence model, when the Reynolds number is \(6.5 \times 10^5\) and the airfoil chord length is 1m, the grid height of the first layer is \(3.51 \times 10^{-5}\)m and \(y^+\) is basically less than 1. Therefore, to verify that the number of grids will not affect the calculation results, three different numbers of grids are now adopted in this paper. In addition, based on the k-\(\omega\) SST turbulence model, the Fluent software is used to compare the lift and drag coefficients \(C_l\) and \(C_d\) at the angle of attack \(\alpha = 4^\circ\), as shown in Table 1. It can be seen from Table 1 that the calculation results of Grid 2 and Grid 3 are very close, while the calculation results of Grid 1 are quite different from that of Grid 2 and Grid 3. Considering calculation cost, grid 2 is finally selected for calculation.

| Item   | Cells | Lift coefficient \(C_l\) | Drag coefficient \(C_d\) |
|--------|-------|----------------------|----------------------|
| Grid 1 | 11368 | 0.78134              | 0.01635              |
| Grid 2 | 27608 | 0.7726               | 0.01565              |
| Grid 3 | 41528 | 0.77129              | 0.01555              |

3. Airfoil Numerical Simulation

3.1. Verification of calculation results accuracy

To verify whether the lift and drag coefficients calculated by different calculation software and different turbulence models are accurate, the calculation results are now compared with the experimental values \([10]\), as shown in Fig. 2.
It can be seen from Fig. 2 that the results calculated by the XFOIL software deviate from the experimental values. The lift coefficient is too large, the drag coefficient is too small, and the lift-to-drag ratio is seriously deviated from the experimental value, indicating that the calculation results of the XFOIL software are not accurate enough. The calculation results of Fluent software are closer to the experimental value, which shows that the calculation results of Fluent software are relatively reliable. Moreover, for the lift coefficient, the calculation results of the realizable k-ω(rke) turbulence model are the closest to the experimental value, while for the drag coefficient and the lift-to-drag ratio, the calculation results of the SST k-ω(sstkw) turbulence model are the closest to the experimental value. Therefore, the SST k-ω(sstkw) turbulence model is adopted in this paper.

### 3.2. Lift and drag coefficient map

Fig. 3 shows the lift coefficient, drag coefficient and lift-to-drag ratio of NACA4415 airfoil under low Reynolds number.

It can be seen from Fig. 3 that when the Reynolds number has changed from 270,000 to 340,000, the lift coefficient, drag coefficient and lift-to-drag ratio have obvious changes, and their differences corresponding to different Reynolds numbers are quite obvious.

It can be seen from Fig. 3(a) that when the angle of attack is less than 7°, the Reynolds number has a smaller effect on the lift coefficient, while when the angle of attack is greater than 7°, the greater the Reynolds number is, the greater the lift coefficient will be.

It can be seen from Fig. 3(b) that when the angle of attack is less than 7°, the Reynolds number has a smaller effect on the drag coefficient, while when the angle of attack is greater than 7°, the larger the Reynolds number is, the smaller the drag coefficient will be.

It can be seen from Fig. 3(c) that the optimal angle of attack is about 7°, and the greater the Reynolds number is, the greater the lift-to-drag ratio will be. Moreover, under low Reynolds number, the lift-to-drag ratio curve is more “squat”, and the applicable angle of attack range for high lift-to-drag ratio is larger.

Fig. 4 shows the lift coefficient, drag coefficient and lift-to-drag ratio of NACA4415 airfoil under medium Reynolds number.
It can be seen from Fig.4 that the lift coefficient and lift-to-drag ratio under the middle Reynolds number are larger than that under the lower Reynolds number, and the drag coefficient under the middle Reynolds number is smaller than that under the lower Reynolds number. The differences in lift coefficient, drag coefficients and lift-to-drag ratios corresponding to different Reynolds numbers are quite obvious.

It can be seen from Fig.4(a) that when the angle of attack is less than 7°, the Reynolds number has little effect on the lift coefficient, while when the angle of attack is greater than 7°, the greater the Reynolds number is, the greater the lift coefficient will be.

It can be seen from Fig.4(b) that when the angle of attack is less than 7°, the Reynolds number has little effect on the drag coefficient, while when the angle of attack is greater than 7°, the larger the Reynolds number is, the smaller the drag coefficient will be.

It can be seen from Fig.4(c) that the optimal angle of attack is about 7°, and the greater the Reynolds number is, the greater the lift-to-drag ratio will be. Moreover, under the middle Reynolds number, the lift-to-drag ratio curve is “taller and thinner”, and the applicable angle of attack range for high lift-to-drag ratio is smaller.

Fig.5 shows the lift coefficient, drag coefficient and lift-to-drag ratio of NACA4415 airfoil under higher Reynolds number.

It can be seen from Fig.5 that the lift coefficient and the lift-to-drag ratio under the higher Reynolds number are larger than that under the middle Reynolds number, and the drag coefficient under the higher Reynolds number is smaller than that under the middle Reynolds number. The differences in lift coefficient and lift-to-drag ratio corresponding to different Reynolds numbers are obvious, but the differences in drag coefficient are not.

It can be seen from Fig.5(a) that when the angle of attack is less than 7.5°, the Reynolds number has a minimal effect on the lift coefficient, while when the angle of attack is greater than 7.5°, the greater the Reynolds number is, the greater the lift coefficient will be.
It can be seen from Fig. 5(b) that when the angle of attack is less than 7.5°, the Reynolds number has a minimal effect on the drag coefficient, while when the angle of attack is greater than 7.5°, the larger the Reynolds number is, the smaller the drag coefficient will be.

It can be seen from Fig. 5(c) that the optimal angle of attack is about 7.5°, and the larger the Reynolds number is, the larger the lift-to-drag ratio will be. In addition, under a higher Reynolds number, the lift-to-drag ratio curve is “taller and thinner”, and the applicable angle of attack range for a high lift-to-drag ratio is smaller.

The lift coefficient, drag coefficient and lift-to-drag ratio of NACA4415 airfoil under high Reynolds number are shown in Fig. 6.

![Fig. 6. Lift Coefficient, Drag Coefficient and Lift-to-drag Ratio under High Reynolds Number](image_url)

4. Conclusion

Through the numerical calculation of the NACA4415 airfoil and the lift-drag coefficient map, conclusions can be drawn as follows.

1. The calculation accuracy of Fluent software is much higher than that of XFOIL software;
2. The calculation results of SST k-ω(sstkw) turbulence model are the closest to the experimental value;
3. Within a certain range, the larger the Reynolds number is, the larger the lift coefficient and lift-to-drag ratio of the airfoil will be, and the smaller the drag coefficient will be;
4. When the angle of attack is less than the optimal angle of attack, the Reynolds number has less influence on the lift-drag coefficient and lift-drag ratio;
5. As the Reynolds number increases, the optimal angle of attack increases slightly, and the applicable angle of attack range for high lift-to-drag ratios becomes smaller.
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