Numerical Calculation of Wind Turbine Airfoil Based on COUPLED Algorithm and Validation of Wind Tunnel Test

Quan WANG*, Zheng-Zheng QING*, Xing HONG, Jun WANG

(1.School of Mechanical Engineering, Hubei University of Technology, Wuhan, 430068, China)

Email: quan_wang2003@163.com; 1142767391@qq.com

Keywords: Turbulence model, SIMPLE algorithm, COUPLED algorithm, Wind turbine airfoils, Wind tunnel experiment.

Abstract. When the $\gamma - Re_\theta$ transition model is used to calculate the aerodynamic performance of the wind turbine airfoils, the SIMPLE algorithm is usually applied to solve the equation of speed and pressure for airfoil surface. Consequently the precision of the results by using SIMPLE algorithm is comparatively low. Therefore, For the newly wind turbine airfoil named CQU-DTU-LN118, COUPLED algorithm is selected to solve the equation of speed and pressure for airfoil fluid surface. The results of SIMPLE algorithm, COUPLED algorithm and wind tunnel experiments are studied comparably on the condition of Reynolds number of 2.1×10^6 and the angle of attack from -8° to 15° . Compared with the aerodynamic characteristics (such as pressure distribution, lift coefficients, drag coefficients and among others), it is found that the calculated data for COUPLED algorithm are the same as wind tunnel test. But the results calculated by SIMPLE algorithm are far away from experiment data when the airfoil is in the state of stall. The study validated the accuracy and applicability for the COUPLED algorithm used to simulate the wind turbine airfoils.

Introduction

The power of wind turbines is relative with the aerodynamics performance of airfoils. Therefore, it is important to predicate accurately the aerodynamic characteristic for the wind turbine airfoils. With the development of computational fluid dynamics (CFD) method, it is a good way to select this method to calculate the aerodynamic performance for wind turbine airfoils. It can well capture the airfoil surface pressure and velocity distribution characteristics. P.R.Spalart and S.R.Allmaras [1] firstly present a S-A turbulent model to calculate the aerodynamic performance for the RAE 2882 airfoil. F.R.Menter[2] deduced the SST k- ω turbulent model which can be used widely to airfoil CFD numerical calculation. In 2006 year, Langtry and Menter present a method named $\gamma - Re_\theta$ transition model coupled the SST k- ω turbulent model[3].Some studies[4-6] have validated the accuracy of the $\gamma - Re_\theta$ transition model. However, the aerodynamic performance of the airfoils after stall is still not very accuracy, especially for the lift coefficients after stall. In the past, most of the previous studies have chosen the SIMPLE algorithm to calculate the aerodynamic performance for wind turbine airfoils. Few scholars solve the airfoil surface velocity and pressure equation by using the COUPLED algorithm. Therefore, the COUPLED algorithm for the $\gamma - Re_\theta$ transition model is selected to calculate the aerodynamic performance of CQU-DTU-LN118 airfoil. Lastly the applicability and accuracy of this method is verified compared with wind tunnel experiments.

Numerical Calculation Method

RANS and $\gamma - Re_\theta$ Transition Model

The transition SST model is based on the SST k- ω turbulence model considered $\gamma - Re_\theta$ factor. The transition model triggers and controls the transition by solving the function factor γ and jointly modifying the k equations.

(1) γ equations

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = \frac{1}{R_e} \bullet \frac{\partial\gamma}{\partial x_j} \left[\frac{\partial}{\partial x_j} (\mu + \sigma_\gamma \mu_t) \right] + P_\gamma - E_\gamma$$

Where function P_γ and E_γ are:

$$P_\gamma = c_{a_1} F_{length} \rho S (\gamma F_{onset})^{c_a} (1 - c_{e_1} \gamma)$$

$$E_\gamma = -c_{a_2} F_{tub} \rho \omega \gamma (1 - c_{e_2} \gamma)$$

Where function F_{onset} and F_{tub} are:

$$F_{onset} = \max(0, F_{onset2} - F_{onset3})$$

$$F_{tub} = e^{-(R_t/4)^4}, \quad R_t = \frac{\rho k}{\mu \omega}$$

Where function F_{onset1} , F_{onset2} and F_{onset3} are:

$$F_{onset1} = \frac{Re_v}{2.193 Re_{\theta_c}}, \quad Re_v = \frac{Re \rho \gamma^2 S}{\mu}$$

$$F_{onset2} = \min(2, \max(F_{onset1}, F_{onset1}^4))$$

$$F_{onset3} = \max(0, 1 - (\frac{R_t}{2.5})^3)$$

(2) $\tilde{R}_{\theta}$ function equation

$$\frac{\partial(\rho \tilde{Re}_{\theta})}{\partial t} + \frac{\partial(\rho \tilde{Re}_{\theta} u_j)}{\partial x_j} = \frac{\partial\gamma}{Re \partial x_j} \left[\sigma_{\theta} (\mu + \mu_t) \frac{\partial \tilde{Re}_{\theta}}{\partial t} \right] + P_{\theta}$$

Where function P_{θ} are:

$$P_{\theta} = c_{\theta} \rho (Re_{\theta} - \tilde{Re}_{\theta}) (1.0 - F_{\theta}) / t, \quad t = \frac{1}{Re} \bullet \frac{500 \mu}{\rho U^2}$$

Where function F_{θ} , δ , δ_{BL} and θ_{BL} are:

$$F_{\theta} = \min \left\{ 1.0, \max \left[F_{wake} \bullet e^{-(\gamma/\delta)^4}, 1.0 - \left(\frac{\gamma - 1/c_{\theta 2}}{1 - 1/e_{\theta 2}} \right)^2 \right] \right\}$$

$$\delta = \frac{50 \Omega y}{U} \bullet \delta_{BL}, \quad \delta_{BL} = 7.5 \theta_{BL}, \quad \theta_{BL} = \frac{1}{Re} \bullet \frac{\mu \tilde{Re}_{\theta}}{\rho U}$$

Where function F_{wake} is:

$$F_{wake} = \exp \left[- \left(\frac{Re_w}{1.0 \times 10^5} \right)^2 \right], \quad Re_w = Re^2 \frac{\rho \omega y^2}{\mu}$$

CQU-DTU-LN118 Airfoil Fluent Calculated Model

CQU-DTU-LN118 is designed based on functional integral theory[7]. The maximum thickness is 18%. The length of the fluid **calculation** area is 25 times the chord length and the width is 20 times chord length [8]. The two-dimensional quadrilateral structured grid is used to mesh the fluid field. The grid-independent is analyzed, and it is found that the grid number of 15 million could meet the computing requirements. The height of the first layer is 10^{-5} mm. The fluid wall parameter $Y^+ \leq 1$. The pressure outlet and velocity inlet are determined according to boundary conditions. The criteria

wall free slip boundary conditions is selected. Figure 1 shows the O-H grid for CQU-DTU-LN118 new airfoil.

Fig.1 local amplification of CQU-DTU-LN118 airfoil mesh

In order to study the influence of different algorithms used to the airfoil fluid field, the SIMPLE and COUPLED algorithm are used to solve the pressure function of CQU-DTU-LN118 airfoil. The N-S equations are solved by double-precision and the second-order discrete scheme is adopted. The convergence precision is set to 1.0×10^{-6} .

Comparison and Experimental Verification of Calculated Results

The SIMPLE and COUPLED algorithm is used to solve fluid speed and pressure, respectively. The calculated results are compared with wind **tunnel** experiments which has done in the wind tunnel laboratory of Virginia Polytechnic Institute[9]. The angle of attack is from -8° to 13.5° . Reynolds number is 2.1×10^6 .

Compared with wind tunnel test data, the results calculated by SIMPLE algorithm at the angle of attack of 5.7° is agree with the results calculated by COUPLED algorithm as shown in figure 2. The same results as shown in figure 3 at angle of attack of 10.5° . However, when the angle of attack is 13.6° which the airfoil surface fluid is in the state of stall, the pressure distribution calculated by SIMPLE algorithm is closer to wind tunnel data than that of COUPLED algorithm.

Fig. 2 airfoil surface pressure coefficients distribution($\alpha=5.7^\circ$)

Fig. 3 airfoil surface pressure coefficients distribution($\alpha=10.5^\circ$)

Fig. 4 airfoil surface pressure coefficients distribution($\alpha=13.6^\circ$)

Table 1 comparison of the results of two algorithm and the experiment

Angle of attack($^\circ$)	SIMPLE algorithm		COUPLED algorithm		EXPERIMENT	
	C_L	C_D	C_L	C_D	C_L	C_D
5.7	1.28976	0.01018	1.28398	0.01021	1.34905	0.00935
10.5	1.79187	0.01712	1.78605	0.01692	1.77685	0.01748
13.6	2.07820	0.02600	1.76314	0.04737	1.71509	0.06217

Table 1 shows the comparisons between lift coefficient, drag coefficient calculated by the two algorithms and experiment data. The lift coefficients and drag coefficients are agree with the wind tunnel test at the angle of attack of 5.7° and 10.5° . It indicated that the aerodynamic performances are closed to wind tunnel experiments before stall. But when the angle of attack is 13.6° which the airfoil surface fluid is in unsteady state, the predicted results are not the same as wind tunnel experiments used the steady state numerical solution. The lift coefficient and drag coefficient calculated by SIMPLE algorithm are 2.078 and 0.026, respectively. Compared with the experimental results of 1.711 and 0.062, the error is about 21.2% and 58.2%, respectively. Meanwhile, compared with wind tunnel experiments, the aerodynamic performance are 1.763 and 0.047 calculated by COUPLED algorithm which the errors are about 2.8% and 23.8%, respectively. This indicated that the

aerodynamic performances calculated by COUPLED algorithm are more accurate than calculated by SIMPLE algorithm after stall.

Figure 5 and 6 shows the numerical prediction C_L and C_D of the CQU-DTU-LN118 airfoil for smooth flow (free transition) compared with measured aerodynamic performance. As shown in figure 5 and 6, the aerodynamic performance calculated by the two algorithms are agree with experimental data when the angle of attack is less than 10.5° ; however, when the angle of attack is more than 10.5° , the lift and drag coefficients calculated by COUPLED algorithm is closed to wind tunnel test.

Fig.5 lift coefficients of CQU-DTU-LN118 airfoil varied with angle of attack

Fig.6 drag coefficients of CQU-DTU-LN118 airfoil varied with angle of attack

Fig.7 lift to drag of CQU-DTU-LN118 airfoil varied with angle of attack

Figure 7 shows the lift to drag characteristic varied with angle of attack. The lift to drag calculated by the two method is less than wind tunnel experiments. The main reason is that the predicated drag coefficients are more than wind tunnel experiments before stall. Wherever, the lift to drag calculated by COUPLED algorithm is closer to wind tunnel test, compared with the results calculated by SIMPLE algorithm. In a word, compared with the results predicated by SIMPLE algorithm, the aerodynamic performance calculated by COUPLED algorithm is more agree with wind tunnel data, especially after stall.

Conclusion

Using $\gamma - \text{Re}_\theta$ transition turbulence model, the aerodynamic performance for CQU-DTU-LN118 airfoil is predicated by SIMPLE algorithm and COUPLED algorithm. Compared with wind tunnel experiment, the difference between the results predicated by COUPLED algorithm and that by SIMPLE algorithm is small. However, the results calculated by COUPLED algorithm is more agree with wind tunnel test than that by SIMPLE algorithm after stall. It is verified that the COUPLED algorithm can be applied to the aerodynamic numerical calculation for wind **turbine** airfoil. The next step the whole wind turbine blade will be predicated by COUPLED algorithm.

Acknowledgements

This work is supported by National Natural Science Foundation of China (No.51405140).

Reference

1. P.R.Spaltart, S.R.Allmaras. A one-equation turbulence model for aerodynamic flows[C]. 30th Aerospace Science Meeting & Exhibit, Reno, NV, Jan 1992.
2. F.R.Menter. Two-equation eddy-viscosity turbulence models for engineering applications[J]. AIAA Journal, 1994, 32(8):269-289.
3. F.R. Menter, R.B.Langtry, et al. A correlation-based transition model using local variables—part I: model formulation[J]. Journal of turbomachinery, 2006, 128(3):413-422.
4. Ernesto Benini, Rita Ponza. Laminar to turbulent boundary layer transition investigation on a supercritical airfoil using the $\gamma - \theta$ transition[R]. AIAA 2010-4289.
5. Shirzad Hossenverdi, Masoud Boroomand. Prediction of laminar-turbulent transition flow over single and two-element airfoils[R]. AIAA 2010-4290.

6. Knut Nordanger, Runar Holdahl, et al. Implementation and comparison of three isogeometric Navier-Stokes solvers applied to simulation of flow past a fixed 2D NACA0012 airfoil at high Reynolds number[J]. 2015, 284:664-688.
7. Chen Jin, Chen Jiangtao, SHEN Wenzhong. Research on improved design of airfoil profiles based on the continuity of airfoil surface curvature of wind turbines[J]. *Acta Energiae Solaris Sinica*, 2013, 34(1): 547-553.
8. Zhou Dagao, Liu Yangwei, Wen Xiaoqing, Lu Lipeng. Modification of SA model for predicting airfoil flow separation [J]. *Journal of Beijing University of Aeronautics and Astronautics*, 2012, 38(10): 1384-1388.
9. Cheng Jiangtao, Zhu Weijun, et al. Design and validation of the high performance and low noise CQU-DTU-LN1 airfoils[J]. *Wind Energy*, 2014, 17(12): 1817-1833.