Experimental study on the effect of blade surface roughness on aerodynamic performance

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Abstract. In order to study the effect of surface roughness of wind turbine blade on aerodynamic performance, the three novel roughness models are proposed, and the corresponding simulation model is also established. Simulation analysis and wind tunnel test are carried out respectively, and the results show that they are consistent with each other. The 5mm-spacing double rectangular roughness strips lead to 64.9\% reduction of the maximum lift/drag, the single rectangular roughness strip pasted on 10\% chord-length can reduce the maximum lift/drag by 30.8\%, both two rectangular strip models can cause early stall, while the effect of arc strip is minimal among three roughness models.

1. Introduction

Wind turbines usually operate in a natural environment. Various types of surface roughness often occur after long time operation due to contamination caused by insect, rain, ice and snow, erosion by sand and dirt [1-4], etc. and result in a decrease in efficiency of wind turbine. Many studies have shown that the increase of surface roughness can reduce output of wind turbine by 50\% [5].

Numerical simulations and wind tunnel experiments are effective methods to study the effects of roughness. Rooij studied airfoils of three thicknesses using RFOIL and found that the 10\% chord line on suction surface is a sensitive location for dust accumulation [6-7]. In addition, numerical simulations can provide environment that are difficult to achieve in experiments, such as high Reynolds numbers. Timmer studied the effect of Reynolds numbers on roughness sensitivity, and results show that for uniformly distributed roughness, the increase of Reynolds number would lead to decrease of roughness sensitivity, while under the same Reynolds number, roughness will also lead to lot of energy loss [8].

On the other hand, experiments can provide more convincing results. Soltani compared the traditional roughness model and the contamination distribution model which is established based on the wind field data, wind tunnel experiment results showed the new model is more practical[9]. In the traditional roughness model, the Z-shape emery paper and strips were used [10]. However, these roughness strips were small in height, usually less than 1 mm and the actual surface roughness was generally serious. Mohammed conducted research of wind turbines in the desert area, it was found that dust accumulation tended to concentrated near the stagnation point, where the size of dust particles can reach to 28mm approximately after 3 months of operation [11]. Furthermore, for the working wind turbine blade, it is difficult to simulate the actual surface roughness, because there is barely no data of the distribution of pollutants or erosion [10].

Generally, the location of the contaminants and erosion is concentrated at the leading edge [12], but the size and distribution of these shape are irregular [13-14]. In this paper, some novel roughness
models are designed, different from traditional roughness model, these models have large size and novel shapes, to simulate different kinds of roughness conditions. The simulation and wind tunnel experiment are conducted respectively, and results show good agreement in two methods.

2. Roughness and simulation model

2.1. Roughness model

As shown in Figure 1, the airfoil studied in this paper is NACA 4415, chord length $C$ is 1m.

![Figure 1. NACA4415 airfoil.](image)

Figure 2 shows the type of surface roughness on the airfoil, including rectangular band, double rectangular band, arc-shaped band. Double rectangular band are composed of two rectangular bands, and are divided into three groups according to the spacing, that is spacing of 5mm, 10mm and 15mm, respectively. The band near the leading edge is located at 10% $C$.

![Figure 2. Band types.](image)

The maximum thickness of the arc-shaped band is 3mm, and is divided into three groups according to the location of maximum thickness, respectively, by the front 5mm, middle and by rear 5mm. Table 1 shows the size of bands.

2.2. Simulation model

The SST k-ω turbulence model is selected for the numerical simulation. The calculation error of this model is small, and the calculated result is similar to the experimental data [15].
Table 1. Band size.

| Type             | Width& Height | Location        |
|------------------|---------------|-----------------|
| Rectangular      | 25*2.5        | 10% C, 20% C, 30% C |
| Double rectangular| 25*2.5        | 10% C           |
| Arc-shaped       | 25*3          | 10% C           |

The SST k-ω turbulence model uses the k-ω model near the wall and the k-ε model at the outside of the boundary layer. A modified turbulent viscosity equation is included, which accounts for the effect of turbulent shear stress. The SST model can accurately simulate the size of the separation point and separation zone caused by the backpressure gradient.

As shown in Figure 3, the outside flow field of simulation model is C-type, and the radius of front semi-circle is 20C, the length of rear rectangular ab is 30C.

![Figure 3. CFD domain.](image)

ab, bec and cd are velocity inlet boundaries; ad is pressure outlet boundary, the back pressure is atmospheric pressure. The turbulence intensity is 1% and turbulent viscosity ratio is 5. The SIMPLE algorithm is used to deal with the coupling of velocity and pressure. The variables are discretized by the second-order upwind difference format with the residual redundant at 10^-6 magnitude.

As shown in Figure 4, mesh density is increased near the wall of airfoil. After grid-independent verification, the total number of grids used is about 160,000.

![Figure 4. Simulation model.](image)

The calculated wind speed is 10 m/s and the corresponding Reynolds number is 6.85 × 10^5. The angle of attack for calculation is -6° ~ 13°.
3. Simulation results

Figure 5 shows the convergence history of lift coefficient $C_l$ and drag coefficient $C_d$. The contours of static pressure under different surface roughness is shown in the Figure 6.

As can be seen from Figure 6, when the airfoil is maintained an effective design shape, the pressure of the suction surface of the original airfoil is low, and the transition point is close to the trailing edge, so that better design lift and less resistance can be obtained. After the roughness band is set on the suction surface, the pressure distribution on the suction surface of the airfoil has been affected significantly. There is obvious disturbance near the roughness band, and the smallest pressure also appears on the band. Meanwhile, the overall pressure on the suction surface increases, the transfer point moves forward, the laminar flow area decreases and the resistance increases.

![Cl convergence history](image1)

![Cd convergence history](image2)

**Figure 5.** Convergence history.

3.1. Wind tunnel laboratory

The wind tunnel laboratory is a horizontal direct-flow, single-stage, low-velocity wind tunnel, and the whole body is made of steel. The size of wind tunnel is $21m \times 4.0m \times 3.0m$, and the Maximum wind speed is 30m/s.

![Original airfoil](image3)

![10%e rectangular band](image4)

(a) Original airfoil  
(b) 10%e rectangular band
Figure 6. Contours of static pressure (pa) in Fluent.
3.2. Experiment model

The experiment model is a three-dimensional model of NACA4415 airfoil, chord length is 1m, and height is 1.5m. The model is made of PVC, with internal steel bracket, the support shaft extends the bottom of the model, and connect the base. The pressure tubes are arranged on the middle section of the model, as shown in Figure 7, to measure the pressure on the airfoil surface and the test results will be used to calculate the lift coefficient and drag coefficient of the airfoil.

As shown in Figure 8, the left side is the wind direction. The anemometer, total pressure pipes and static pressure pipe is 4m away from the blade model. Blade model is connected to the support base, which the base is fixed on the wind tunnel turntable. The different angles of attack can be obtained by rotating the turntable to adjust the inflow angle. In order to obtain the experimental results at angles of -6°~13°, considering the deviation of turntable rotation, the actual measurement range is -7°~14°, and the test is finished every 1 degree. Meanwhile, the measurement is achieved per 0.5 degree between -2° and 2°.

![Blade model](image1)
![Model size](image2)
![Tubes arrangement](image3)

**Figure 7.** Blade model and pressure tubes arrangement.

The wake rake concludes 50 pressure tubes and 3 hydrostatic tubes, and mounted 1.3 times the chord length from the model, as shown in Figure 9. The installation height is the same as the centerline of model. The measurement width is 1.5 m and the center line is the model string.

![Installation of experiment equipment](image4)
![Wake rake equipment](image5)

**Figure 8.** Installation of experiment equipment.

**Figure 9.** Wake rake equipment.
3.3. Experiment conditions
The experiment is divided into two kinds: free transition and fixed transition. The free transition is under the situation of original surface, while the fixed transition corresponds to the case where the rough band is pasted on the suction surface of the model. In both cases, the experiment is carried out at a wind speed of 10 m/s.

The experiment uses the same roughness settings of numerical calculation. There are three kinds of roughness band: rectangular, double rectangular, arc, as shown in Table 1.

3.4. Data processing
After the data are collected and recorded, the pressure distribution of the entire surface can be obtained by interpolation with discrete pressure of pressure tubes. The lift coefficient, drag coefficient and lift/drag ratio can be calculated according to the pressure distribution of the blade surface.

The pressure coefficient $C_{pi}$ of each point is defined as following

$$C_{pi} = \frac{P_i - P_{\infty}}{0.5 \rho U^2}$$

where $P_i$ is measured pressure, $P_{\infty}$ is static pressure of the flow, $U$ is wind speed, $\rho$ is air density.

The normal force coefficient $C_y$ and axial force coefficient $C_x$ can be calculated by Eq. (2) and Eq. (3)

$$C_y = \int (C_{pu} \times \cos \theta_u \cdot ds - C_{pu} \times \cos \theta_l \cdot ds) dx$$

$$C_x = \int (C_{pu} \times \sin \theta_u \cdot ds - C_{pu} \times \sin \theta_l \cdot ds) dx$$

where $x, y$ is dimensionless coordinates of the airfoil coordinate relative to the chord length, $x = x/C$, $y = y/C$, $C$ is the chord length, $ds$ is the differential of airfoil surface, $\theta_u, \theta_l$ is angle between $ds$ and $X$ axis, subscript $U, L$ mean supper and lower surface, $C_{piu}, C_{pil}$ is pressure coefficient of each point.

According to the Eq. (4) and (5), the lift coefficient $Cl$ and drag coefficient $Cd$ can be calculated. Here the calculation of drag coefficient only applies to situation after stall.

$$Cl = C_y \times \cos \alpha - C_y \times \sin \alpha$$

$$Cd = C_y \times \cos \alpha + C_y \times \sin \alpha$$

where $\alpha$ is angle of attack.

Before the stall, using surface pressure distribution to calculate drag coefficient will cause some deviation. Therefore, the wake pressure which is measured by the wake rake has to be taken into consideration to calculate drag coefficient. The final experimental drag coefficient is calculated as following

$$C_d = \frac{2}{c} \int \sqrt{C_{pw}} (1 - \sqrt{C_{pw}}) dz$$

where $z$ is wake rake coordinates, $C_{pw}$ is pressure coefficient measured by total pressure tubes with the wake static pressure $P_w$ and hydrostatic pressure $P_{\infty}$ as reference pressure respectively. $w$ is tail integration area.

4. Results and discussion

4.1. Experimental and simulation result of smooth model
Experimental results are compared with data in Profili and Fluent result. Figure 10 shows the difference of lift and drag coefficient are within 10% in most angles. However, the experimental lift is lower than the software and the drag is higher. The reason may be that the wake pressure is not in high precision, furthermore, it is difficult to guarantee a good uniform smoothness of the model surface during the processing, so that the original model actually has a certain degree of roughness.
4.2. Results of rectangular strip model

Figure 11 shows the experimental test results of airfoil with rectangular band, and it is compared with simulation results, where F represents Fluent and E represents experiment.

Figure 11 shows the lift decreases and drag increases obviously after the rectangular strips are pasted on the suction surface. The lift/drag ratio under three conditions is relatively close, while the 10%c strip has the biggest reduction, strips cause an early stall by approximately 2°.

Table 2 shows the effect of rectangular strip on the aerodynamic performance of airfoil.

At about 6° angle of attack, original airfoil achieves the maximum lift/drag ratio, while the fixed transition achieved maximum lift/drag ratio at around 4°. At the same time, it can be seen that the closer the rectangular roughness band is to the front end of suction surface, and the more the lift/drag ratio decreases. The maximum lift coefficient can be reduced 30.97%, the drag coefficient is increased 14.57%, resulting in a drop of lift/drag by 39.74%.
Figure 11. Test results of rectangular strip.

| Type          | Angle | Cl   | Cd   | Cl/Cd  |
|---------------|-------|------|------|--------|
| Original airfoil | 6°    | 1.09 | 0.01 | 99.67  |
| 10%e          |       | 0.7507 | 0.0125 | 60.06  |
| 20%e          | 4°    | 0.7829 | 0.0121 | 64.7   |
| 30%e          |       | 0.7905 | 0.012  | 65.88  |
| Change rate (%) | 10%e  | -30.97 | 14.57 | -39.74 |
|               | 20%e  | -28.00 | 10.90 | -35.09 |
|               | 30%e  | -27.31 | 9.99  | -33.90 |

4.3. Results of double rectangular strip model

It can be seen from Figure 12 that the influence of double rectangular bands on aerodynamic performance is more obvious than one of single rectangular band. Meanwhile, the effect of spacing between rectangular bands cannot be ignored, among which 5mm spacing has the greatest influence, followed by 10mm spacing and finally 15mm.

For double rectangular band, the stall is continue to be ahead of time, and the lift/drag ratio reach the maximum value when the angle of attack is about 3 degree. For the 5mm strip, however, the maximum lift is reduced 31.69%, and the maximum drag increases 65.37%, resulting in a big drop of lift/drag by 58.69%, as shown in Table 3.
Table 3. Effect of double rectangular strip model.

| Type  | Angle | Cl   | Cd   | Cl/Cd |
|-------|-------|------|------|-------|
| 5mm   | 3°    | 0.6197 | 0.0154 | 40.30 |
| 10mm  |       | 0.6639 | 0.0144 | 46.03 |
| 15mm  |       | 0.6922 | 0.0133 | 52.22 |

Change rate (%)

| Type  | Angle | Cl/Cd |
|-------|-------|-------|
| 5mm   |       | -31.69 |
| 10mm  |       | -26.81 |
| 15mm  |       | -23.70 |

Figure 12. Results of double rectangular strip in experiment and software.

4.4. Results of arc strip model

Figure 13 shows that arc strip has slight effect than rectangular strips. Among the three arc strips, the front-thick strip has the biggest effect, then is the rear-thick strip, and the middle-thick strip has the least effect. However, the difference between the three arc strips is small. Besides, arc strip doer not cause an early stall.

Table 4 shows that the effect of arc band on aerodynamic performance. The maximum lift/drag of both free and fixed transition is achieved at about 6° angle of attack. For the front-thick strip model, the maximum lift decreases 7% and the maximum drag increases 29.26%, resulting in a drop of lift/drag of 28.05%.
Figure 13. Results of arc strip in experiment and software.

Table 4. Aerodynamic performance of arc strip model.

| Type          | Angle | Cl     | Cd     | Cl/Cd   |
|---------------|-------|--------|--------|---------|
| Front thick   | 6°    | 1.0113 | 0.0141 | 71.71   |
| Middle thick  | 6°    | 1.0580 | 0.0121 | 87.42   |
| Rear thick    |       | 1.0406 | 0.0126 | 82.27   |
| Front thick   |       | -7.00  | 29.26  | -28.05  |
| Middle thick  |       | -2.71  | 10.93  | -12.29  |
| Rear thick    |       | -4.31  | 15.93  | -17.46  |

5. Conclusions
In the paper, the simulation and experiment of roughness model is conducted. Comparable result shows a good agreement between the two methods.

However, the experiment tends to have lower lift and high drag in most case, especially with higher angle, but the difference is small. The new roughness model gets good feedback. The single rectangular strip pasted on 10% C reduces lift by 30.97% with 14.57% increase of drag, result in the drop of lift/drag ratio by 39.74. Besides, 5m-spacing double rectangular strip reduces lift by 31.69%, but the drag increase by 65.37%, which leads to the drop of lift/drag ratio by 58.69%. However, the arc strip has little effect on the lift coefficient, among which the front thick strip reduces the lift by only 7%, while accompany with 29.26% increase of drag, result in 28.05% drop of lift/drag ratio.

Furthermore, rectangular strip leads to an early stall by approximately 2° in the angle, while the double rectangular strip leads to an early stall by approximately 3°, but the arc strip has little effect on stall.
Results show that these roughness models can provide a new approach to study the blade surface roughness in practical.

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