Comparison of the pressure distribution of a wind turbine blade based on field experiment and CFD

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Abstract. Field experiment and numerical simulation are performed on a 33 kW horizontal axis wind turbine. The distribution of pressure is gathered by disposed 191 taped pressure sensors span-ward on seven particular sections of a blade. And the parameters of experimental condition of inflow and operation condition of the wind turbine are obtained at the same time. And then, the three-dimensional Reynolds averaged incompressible Navier-Stokes equations and the RNG $\kappa - \epsilon$ turbulence model are used to study the aerodynamic characteristics of the wind turbine. The numerical method is proved to be more effective by contrasting the numerical results to the field experimental data. For the calculation results of the blade pressure, the closer to the root of the blade the more consistent to the values of the experiment. A greater differential is shown at the leading edge than the trailing edge. The pressure distribution contours of the blade surface are obtained too.

1. Introduction
Reasonable numerical results have been obtained using N-S equations and $\kappa - \epsilon$ turbulence model[1,2]. Some CFD problems are mainly related to the effects of grid sensitivity and transition model at the tip section of the blade[3-5]. Numerous studies have been performed in wind tunnels in order to reveal the development of wake. These studies are carried out using sonic anemometers or hot wire anemometry[6-8]. PIV technique has been used in wind tunnel to study the evolution of wind turbine wake[9]. For the complexity and variability of the actual inflow, wind tunnel experiment and numerical method can not obtain precise results in actual windfarm. So a great deal of field experiments are necessary for wind turbine aerodynamic study.

Field experiments are performed to study the 3-D effect, wake characteristics and so on. R. J. Barthelmie, G. C. Larsen measured the velocity distribution in wake of a wind turbine on the sea by the method of radar[10]. The program of “the DAN-AERO MW experiments” measured pressure distribution, parameter of in-flow, wake characteristics and parameter of aerodynamic acoustics in a systematic way. The 3-D effect, wake characteristics, Dynamic stall characteristics, Performance evaluation of the wind turbine and boundary-layer flow of the blade are studied. But no detailed experimental results issued especially of wake characteristics[11]. Los Alamos National Laboratory of USA performed field experiment on a wind turbine with rotor diameter of 4.5m to measure the velocity of the inflow and the wake by the method of two LF-PIV and eight CSAT3 Sonic Anemometer[12], the boundary layer flow and the three dimensional separation flow to be measured. Pressures of wind turbine blade are measured in windfarm by taped pressure sensors[13].
In this study, field experiments are performed on a 33 kW horizontal axis wind turbine. The curves of pressure distribution are gathered by disposed 191 taped pressure sensors span-ward on seven particular sections of a blade. To keep balance of the rotor, seven similar dummy balancing bands are disposed on corresponding position on the other blade. And then, Three-dimensional Navier-Stokes equations and $\kappa - \epsilon$ turbulence model are used to predict the aerodynamic performance of the wind turbine. The numerical method that adopted in this paper is proven to be more reasonable by comparing the numerical results with the experimental data.

2. Comparison of the blade pressure
The field experiment and numerical simulation are performed on a 33 kW wind turbine, Its main configuration parameters are shown as follows: rotor diameter is 14.8 m, initial setting angle of blade root is 64.574 deg, hub height is 16.11 m, rated power output is 33 kW, rated wind speed is 11.0 m/s, rated speed is 85 rpm, cut-in wind speed is 4.0 m/s, and cut-off wind speed is 23.0 m/s.

2.1. Field experiment
At the three heights (the height of rotor top, rotor center and rotor bottom) on the anemometer tower, three anemometers and a wind direction sensor are installed at the three positions respectively to measure the wind speed and wind direction, including an anti-icing digital ultrasonic wind sensor installing at the height of rotor center to increase the measurement accuracy of wind speed and direction as the main reference value. At the same time, an atmospheric pressure sensor and a temperature and humidity sensor are installed on the anemometer tower to measure the local atmospheric pressure and air temperature and humidity.

Pressures of the blade are measured by 191 taped pressure sensors. Analog signals are converted into digital signals by A/D converter. And then, through the RS485 interface, digital signals are transmitted to signal adapter by the flexible cable sticking on the blade surface. At last, the signals are transmitted to industrial controller through the Ethernet interface by 50 road signal link. When the data acquisition command is received by the principal processor, the pressure signals will be encoded and then transmitted through receiver-transmitter to the industrial controller.

Table 1 shows the geometric characteristics of blade and the position of pressure band. Figure 1 shows the experimental wind turbine. Figure 2 shows the pressure band and signal transfer film.

| Pressure band | Position to the rotor axis (r/R) (%) | Initial setting angle (°) | Chord length (mm) | The maximum thickness (%) |
|---------------|-------------------------------------|--------------------------|-------------------|--------------------------|
| 1 #           | 96.53                               | -54.8397                 | 213.63            | 16.65                    |
| 2 #           | 89.84                               | -55.7908                 | 237.48            | 17                       |
| 3 #           | 79.84                               | -56.9299                 | 283.12            | 18                       |
| 4 #           | 64.84                               | -59.0316                 | 350.16            | 19.82                    |
| 5 #           | 49.77                               | -60.4791                 | 414.36            | 21.46                    |
| 6 #           | 34.23                               | -62.7345                 | 485.63            | 23.88                    |
| 7 #           | 19.84                               | -64.5740                 | 549.24            | 29.56                    |

Figure 1. Wind turbine.  
Figure 2. Pressure band and signal transfer film.
2.2. Numerical simulation
The governing equations are Reynolds averaged Navier-Stokes equations for three dimensional, viscous, incompressible flow and continuous equation. The Ma is less than 0.3, so the incompressible model is suitable. The turbulence model is the RNG k-ε model. The computation fields of the wind turbine are discretized with unstructured mesh. Figure 3 shows the computational domain. The mesh comprises with 28,904,580 cells, and extends 1D upwind and 5D downwind. The MRF (Moving Reference Frame) option was used to incorporate the blade rotation. The code solves the Navier-Stokes equations with the k-ε turbulence model and incorporates standard wall functions to compute the near wall flow. Second order discretization schemes for all the variables and the SIMPLE algorithm are selected to solve the pressure-velocity coupling. The boundary conditions are implemented by selecting a velocity inlet upwind from the blades. At the inlet, turbulence intensity is fixed to 10%. An outflow condition is specified downwind.

The parameters of simulation are consistent with the value in table 2. The density of inflow is calculated by the formula 1.

\[
\rho' = \rho_0 \frac{273}{273 + t} \times \frac{P - 0.0378 \varphi p_b}{0.1013}
\]

where \( P \) is the pressure of moist air (MPa), \( \varphi \) is the air relative humidity (%), \( p_b \) is the temperature saturation pressure of water vapor in the air (MPa), \( t \) is the air temperature (°C), \( \rho_0 \) is the dry air density under the condition of 101.325kPa and 0°C (1.293kg/m³), and \( \rho' \) is the density of moist air.

2.3. Comparison of the pressure
Following, a set of experimental and numerical results of the blade surface pressure is given. Table 2 shows the average value of the parameters of the experiment condition. All the parameters of experimental condition are obtained by the average of ten times samples values in one second,
including wind speed, atmospheric pressure, air temperature, air humidity, rotor speed, yaw angle and pitch angle. Figure 4 to figure 10 show the comparison of the pressure distribution of the wind turbine blade between field experiment and CFD. Figure 11 and figure 12 show pressure contours of the pressure plane and suction plane of the blade.

Figure 4. Pressure distribution on 1# band.

Figure 5. Pressure distribution on 2# band.

Figure 6. Pressure distribution on 3# band.

Figure 7. Pressure distribution on 4# band.

Figure 8. Pressure distribution on 5# band.

Figure 9. Pressure distribution on 6# band.
It is shown from the figures that a greater differential of the pressure distribution on blade surface for the experiment, which is originated mainly from the three-dimensional rotation effect and flow separation on the blade, and the closer to the root of blade the stronger this effect will be. On the other hand, the closer to the root of blade the larger to the angle of attack, and the airfoil stalling is more violent especially at trailing edge. Separation of the vortex at trailing edge has a greater influence on the pressure distribution on the surface of the blade and a violent pressure fluctuation will be induced. So the pressure distribution curve of the 7# band is irregular, especially near the trailing edge. From the figures we can also see the main power generation section of the blade is from 60% diameter to the tip of the blade.

The closer to the root of blade the more consistent to the results of CFD and experiment of the blade pressure. A greater differential is shown at the leading edge than the trailing edge, especially near the tip of the blade. It is shown from the figure 11, the closer to the tip of blade the more violent
to the pressure gradient change. There is a low pressure area at the tip of the blade on the pressure surface of the blade. It is mainly caused by three-dimensional rotation effect at the tip of blade. In this area, part of the air flows from the pressure surface to suction surface through the tip of the blade.

3. Conclusion
A greater differential of the pressure distribution on blade surface for the experiment from the tip of the blade to the root of the blade.

The closer to the root of blade the more consistent to the experimental results of the blade pressure. A greater differential is shown at the leading edge than the trailing edge near the tip of the blade.

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