Computation of aerodynamic performance for horizontal axis wind turbine considering the rotation effects

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Abstract. The blade element momentum theory is lack of estimating the wind turbine performance changes caused by rotation. The paper analysis the impact of airfoil flow by centrifugal force and the Coriolis force which generated by the rotating blades and defines the airfoil performance at separated changing flow region by numerical simulation. This paper calculates the aerodynamic performance with centrifugal correction model using a commercial wind turbine as an example, The numerical model and results are verified by comparing with the actual measurement. The results show that the correction model considered the rotation effect to estimate the wind turbine power is more accurate and closer to the measured value.

1. Introduction
The aerodynamic design of modern horizontal axis wind turbines is mostly based on the classic leaf element-momentum theory (BEM) or its improved model. The leaf element momentum theory simplifies the wind wheel into mutually independent annular units according to the radius of the wind wheel, and calculates the overall aerodynamic characteristics by calculating the two-dimensional cross-sectional local forces on the independent units. The BEW theory ignores the aerodynamic changes caused by the rotation of the blades and the airflow changes between independent units [1-2]. The disc theory believes that the tangential velocity of the incoming flow through the rotating blades increases from zero to a velocity. The increase of the velocity component means the increase of its own kinetic energy, which will reduce the level of energy absorption. The closer the airflow is to the root due to the squeezing effect of the blade, the greater the tangential velocity of the root will be, and the lower the efficiency of the blade will be [3]. For both theories, it is believed that the rotation of the blade makes the power of the blade lower than the theoretical value.

This paper considers the three-dimensional rotation effect of the blade, and uses a simplified model to analyze the changes in aerodynamic characteristics caused by the separated flow on the blade surface. Based on the centrifugal force correction model, a calculation model was established to calculate the power and aerodynamic characteristics of an actual working blade.

2. Basic equation
For wind turbine blades, the basic assumption is that the flow is incompressible, and the viscous pressure has a linear relationship with the velocity gradient. The basic continuity equation and N-S equation are:

\[
\frac{Dv}{Dt} = F - \frac{\nabla p}{\rho} + \frac{\mu}{\rho} \nabla^2 v
\] (1)
In the formula, \( F \) is the external force per unit length, \( \mu \) is the dynamic viscosity, and \( p \) and \( \rho \) are the pressure and density, respectively. For the three-dimensional rotation of wind turbine blades, write this equation in cylindrical coordinates:

**Continuity equation:**

\[
\frac{\partial v_\theta}{r \partial \theta} + \frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} + \frac{v_z}{r} = 0
\]  

(2)

**Motion equation:**

\[
\frac{\partial v_\theta}{\partial t} + \frac{v_r \partial v_\theta}{\partial r} + \frac{v_\theta \partial v_\theta}{\partial \theta} + \frac{v_z \partial v_\theta}{\partial z} = F_\theta - \frac{\partial p}{\rho r \partial \theta} + \frac{\mu}{\rho} \left( \frac{\partial^2 v_\theta}{\partial r^2} + \frac{\partial^2 v_\theta}{\partial r \partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2} \right)
\]

\[
\frac{\partial v_r}{\partial t} + \frac{v_r \partial v_r}{\partial r} + \frac{v_\theta \partial v_r}{\partial \theta} - \frac{v_z}{r} = F_r - \frac{\partial p}{\rho r \partial \theta} + \frac{\mu}{\rho} \left( \frac{\partial^2 v_r}{\partial r^2} + \frac{\partial^2 v_r}{\partial r \partial \theta} + \frac{\partial^2 v_r}{\partial z^2} \right)
\]

\[
\frac{\partial v_z}{\partial t} + \frac{v_r \partial v_z}{\partial r} + \frac{v_\theta \partial v_z}{\partial \theta} + \frac{v_z}{\partial \theta} = F_z - \frac{\partial p}{\rho \partial z} + \frac{\mu}{\rho} \left( \frac{\partial^2 v_z}{\partial r^2} + \frac{\partial^2 v_z}{\partial r \partial \theta} + \frac{\partial^2 v_z}{\partial \theta^2} \right)
\]

In fact, considering that the installation cone angle \( FZ \) of the actual blade is not zero. However, considering the simplified equation and the small force, \( FZ \) is ignored here.

Figure 1. The blade in the rotating frame of reference

Due to the change of the external force, the flow of the rotating blade is changed compared to the static blade. Corten conducted a detailed analysis of this and simplified the model [4]. The analysis shows that the radial flow \( v_r \) is the dominant velocity in the separation flow, and the separation flow of the rotating blade can ignore the viscosity. The boundary thickness in the separation zone is relatively thick, and the velocity gradient is small so that the effect of viscosity can be ignored. When the flow separates, the chordal velocity and the velocity gradient towards the wall will be small. Therefore, the acceleration and friction in the chord direction can be ignored. In addition, there is a large velocity gradient in a thin layer, and the partial derivative in the \( z \) direction is close to other directions. The formula (3) can be simplified into the following formula:

\[
\frac{\partial v_\theta}{r \partial \theta} + \frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} + \frac{v_z}{r} = 0
\]

\[
\frac{\partial p}{r \partial \theta} = 2\Omega v_r
\]
3. Numerical simulation of separated flow

Aiming at the separation problem of airfoil flow, this paper has carried out numerical simulation on several different separation flows of wind turbine airfoil. The author has expounded the feasibility of the large eddy model for separation flow simulation in the literature [5]. This model is used to investigate several flow conditions and the distribution of velocity and pressure at different angles of attack. Figure 2 shows the velocity distribution of the same airfoil under the same angle of attack and different separation conditions. Figure 3 shows the velocity distribution on the upper surface of the airfoil under these three flow conditions.

From the three flow conditions in Figure 2, it can be seen that at this angle of attack, the flow on the lower surface of the airfoil hardly separates. The above shows that the separation flow has changed with different simulation conditions. Through more numerical results, it is found that at a larger angle of attack, the flow on the lower surface will flow around the wall for a long time without separation. In the calculation, the surface flow conditions under the same Reynolds number with the same angle of attack can be regarded as consistent.

![Figure 2. Velocity contour of three separated flows](image)

From the area indicated by the two arrows in Fig. 3 that the flow separation area gradually expands from 1 to 3. The lift coefficient of flow 1 to 3 is gradually reduced. Therefore, under
the same wind speed and angle of attack, the larger the separation area, the smaller the lift coefficient will be.

Under the action of rotation, the separation flow of the airfoil surface changes. At the separation of the leading edge, the additional force generated by the rotation causes the separation zone to move forward and reduce its range. At the separation of the trailing edge, the separation vortex moves radially to a region with a larger radius. In these two cases, the lift coefficient is improved. For the blade, the closer it is to the root, the more obvious this effect will be. This is because the closer the blade is to the root, the greater the angle of attack. The separation flow around the flow will be more obvious. This paper uses the method of adding radial flow to the surface of the three-dimensional airfoil to simulate the changes in aerodynamic performance caused by the radial flow generated by the rotation of the blade in actual work.

Figure 4. The surface pressure distribution at different radial flow

In order to investigate the pressure distribution, a working plane is established in the middle of the airfoil, that is, the surface perpendicular to the airfoil in the figure, to view the pressure changes. The left picture of Figure 4 shows the pressure distribution without radial flow, and the right picture shows the pressure distribution with radial flow. It can be seen from the left figure that the pressure distribution on the airfoil surface is almost uniform in the radial direction. The center point of the pressure in the right figure develops downstream of the radial flow. The pressure distribution on the airfoil surface is not consistent in the radial direction, but disturbs each other. This disturbance will cause changes in the flow structure and aerodynamic performance.

Figure 5. The contours of velocity at different radial flow

The left and right graphs in Fig. 5 show the changes of velocity cloud graphs with and without radial flow at an angle of attack of 30 degrees. It can be seen from the figure that under the action of radial flow, the separation point is significantly moved forward, the wake area is larger, and the lift change caused by the larger separation flow area is shown in Table 1. This change is compared with the two-dimensional numerical simulation. The results are consistent. But this change will no longer be obvious at higher angles of attack, as shown in Figure 5.
Table 1. Comparison of lift coefficient at different angle of attack.

| Number | Radial flow | Angle (30) | Angle (45) |
|--------|-------------|------------|------------|
| 1      | 0           | 1.26       | 1.15       |
| 2      | 10%         | 1.42       | 1.3        |
| 3      | 20%         | 1.56       | 1.32       |

4. Conclusion
This paper analyzes the flow of the blade under the condition that the additional force is added to the rotation action, and investigates the change of the aerodynamic performance of the airfoil by the separation zone through numerical simulation of the airfoil separation flow. Combining the relationship between the two, using the centrifugal pump correction model to compare with BEM theory and measured data through examples, the results show that:

1. Under the action of rotation, the airfoil surface flow changes. At the separation of the leading edge, the additional force generated by the rotation causes the separation zone to move forward and reduce its range. At the separation of the trailing edge, the separation vortex moves radially to a region with a larger radius.

2. Through numerical simulation, it is found that when the separation flow is obvious, the forward movement of the leading edge separation zone will make the lift coefficient larger. This situation is obviously gradually strengthened with the separation flow.

3. Through the calculation of examples under different wind speeds, it is found that under the action of rotation, the load at the root of the blade changes more obviously. The results of the two models in the middle and rear segments of the blade are almost the same.

4. The correction model of the centrifugal pump takes into account the rotation effect, and the calculation result of the model is closer to the actual blade situation. Through force analysis, it is found that for structural analysis, BEM model calculation is simpler and has certain reliability.

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