Numerical Study on the Effect of Swept Blade on the Aerodynamic Performance of Wind Turbine at High Tip Speed Ratio

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Abstract. The current situation is that the development of high speed wind energy saturates gradually, therefore, it is highly necessary to develop low speed wind energy. This paper, based on a specific straight blade and by using Isight, a kind of multidiscipline optimization software, which integrates ICEM (Integrated Computer Engineering and Manufacturing) and CFD (Computational Fluid Dynamics) software, optimizes the blade stacking line (the centers of airfoil from blade root to tip) and acquires the optimization swept blade shape. It is found that power coefficient C_p of swept blade is 3.2% higher than that of straight blade at the tip speed ratio of 9.82, that the thrust of swept blade receives is obviously less than that of straight blade. Inflow angle of attack and steam line on the suction of the swept and straight blade are also made a comparison.

1. Introduction

Large-scale use of wind energy is an important measure to address climate change. The current situation is that the development of high wind speed energy saturates gradually, therefore, it is very necessary to develop low wind speed energy in order to better utilize it. However, the popular wind turbine with straight blade designed with existing technology has low power coefficient C_p at high tip speed ratio, that is to say the power coefficient of straight blade is low when it runs low wind speed condition. With millions of years of evolution, birds have swept shape wings, which can freely control its flight direction and speed in the weak winds and have perfect control performance at extremely low speed.

The amount of tip sweep has the largest effect on the energy production and blade loads, the design goal is to increase annual energy production without increasing blade loads [1]. Studies have shown that swept blade can improve the aerodynamic performance of wind turbines at low speed wind condition [2]. Based on bionic principles, this paper presents the investigation on the effect of swept blade on the aerodynamic performance of wind turbine at high tip speed ratio (low wind speed) condition.

The comparison test of the swept-curving blade has been carried on by Ashwill during STAR (Swept-Twist Adaptive Rotor) project. The test results show that the root bending moment of swept-curving blade is similar to the straight blade, while the output power of swept blade is 12% more than that of straight blade [3]. The lift line method with a predetermined wake is used to analyze effect of swept blades on the wind turbine performance by Chattot, and the research shows that the aerodynamic

performance of swept blade has been improved [4]. A backswept blade designed by R S Amano was not only increases the ability to catch the wind at low wind speed, but also delays stall [5] .

2. Optimization method

As shown in Figure 1, a straight blade with LN221 low noise airfoil optimized by Technical University of Denmark. It is a model wind-turbine rotor with the diameter of blade is 1.5m, the detail data can be found in reference [6]. When the centers of airfoils from blade root to tip are connected and the stacking line of blade is formed. As shown in Figure 2, the dash line is stacking line. For straight blade, the stacking line is a straight line, the swept blade is curve line; In order to investigate the effect of stacking line on the aerodynamic performance of swept blade, the straight blade and optimized swept blade have the same distribution of airfoil chord length and local angle variation with radius.
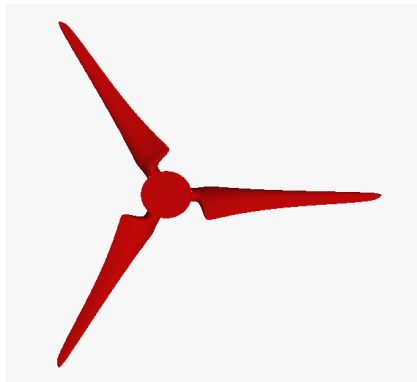

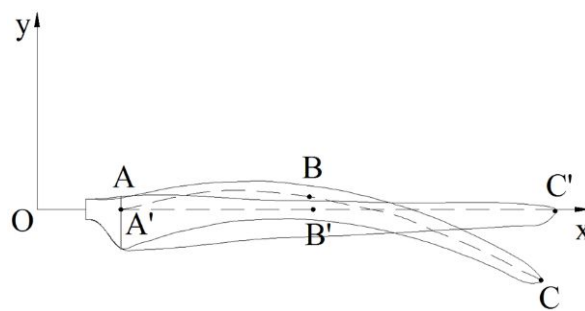**Figure 1.** Original straight blade.   **Figure 2**. Sketch map of swept and straight blade.

In Figure 1, on the stacking line of swept blade, three points from left to right in turn are point A (x_A, y_A), point B (x_B, y_B), point C (x_C, y_C). For the points A, B, C, the equation (1) of stacking line of swept blade can be got by using Lagrange interpolation method.

$$y = \frac{(x - x_C)(x - x_C)}{(x_B - x_A)(x_B - x_C)} \cdot y_B + \frac{(x - x_A)(x - x_B)}{(x_C - x_A)(x_C - x_B)} \cdot y_C \tag{1}$$

In order to ensure the optimized blade has the same swept area with the straight blade, the coordinates of point C should meet $x_C{}^2 + y_C{}^2 = R^2$. Where R is a straight blade radius, and x_C can be expressed by equation $x_c = \sqrt{R^2 - y_c^2}$. Point A (x_A, y_A) are determined by hub radius. The other three parameters x_B, y_B and y_C need to be optimized and then obtain the equation of stack line of swept blade.

According to the aforementioned method of sweep-curving, the optimal model with stacking line of swept blade is established. The specific optimization flow chart is shown in figure 3. At the beginning the parameters x_B, y_B and y_C and wind turbine operation data are initialized. Secondly, the blade geometry and the computational mesh are generated by ICEM (Integrated Computer Engineering and Manufacturing). Thirdly, aerodynamic performance of swept wind turbine is calculated by Fluent, which is a kind of commercial CFD (Computational Fluid Dynamics) software. Fourthly, comparison the current calculated power coefficient C_p with the previous calculation, if it is not maximum one, the parameters x_B, y_B and y_C will be changed and update the blade geometry. The program will not stop until obtain the maximum C_p. A kind of multidiscipline optimization software Isight is used to call different software and run automatically.
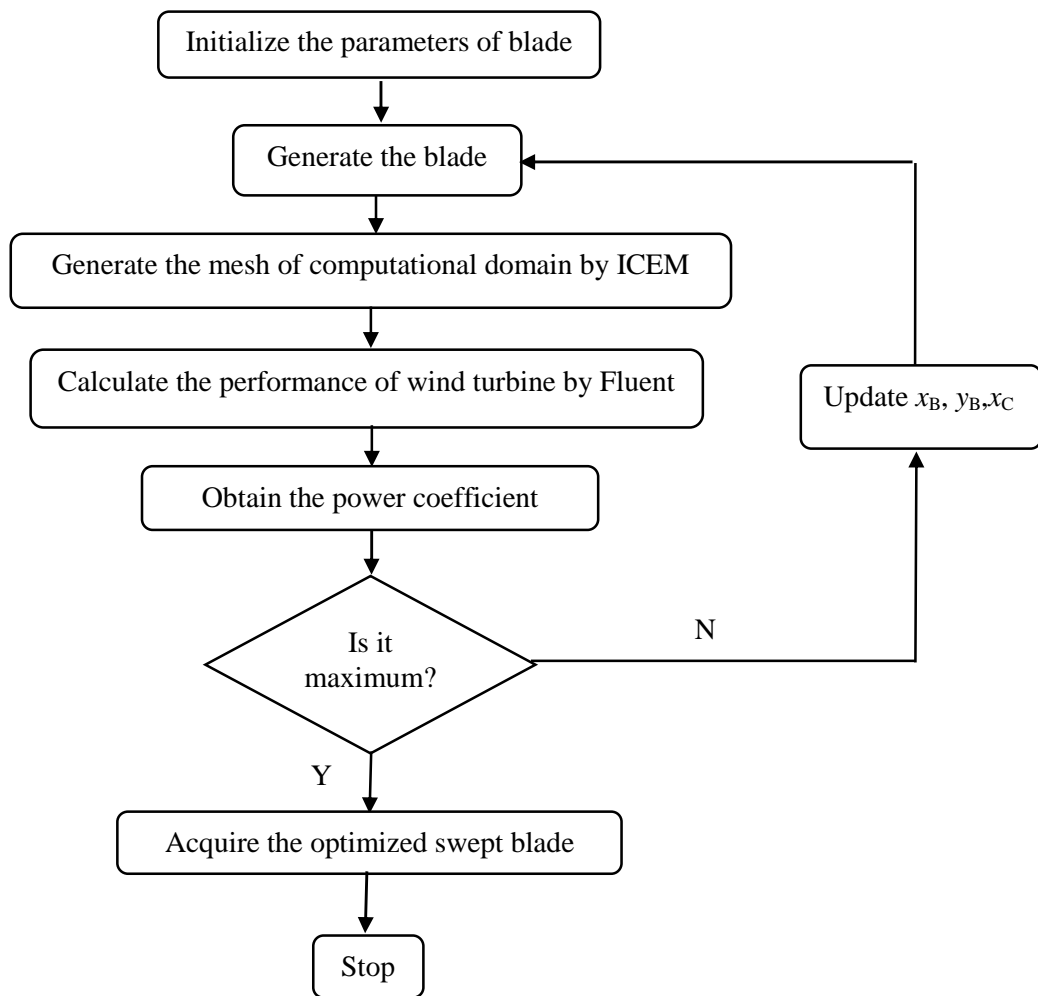
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│   Initialize the parameters of blade   │
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        │  Generate the blade  │                              │
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│ Generate the mesh of computational domain by ICEM │     │
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Figure 3. The flow chart of optimizing the swept blade shape

For the tip speed ratio $\lambda = \omega R / v_0 = 9.06$, where ω is the angular velocity and v_0 is the coming wind speed, the final optimized three coordinate points are A (0.15, 0), point B (0.29305, 0.014743), point C (0.72545, -0.19034). By bringing the coordinate into the above stacking line equation (1), the optimized stack line is obtained as follows. The optimized swept is shown in Figure 4.

$$y = \frac{(x - 0.15)(x - 0.75)}{(0.29305 - 0.15)(0.29305 - 0.75)} \cdot 0.014743 + \frac{(x - 0.15)(x - 0.29305)}{(0.75 - 0.15)(0.75 - 0.29305)} \cdot (-0.19304)$$
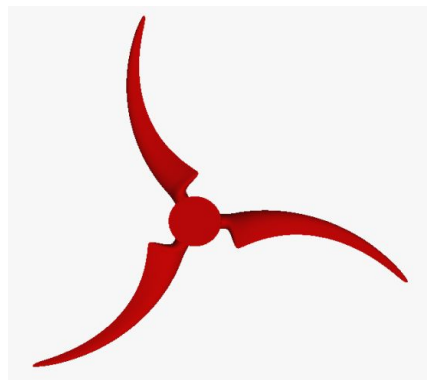
$\hspace{13cm}$ (2)

Figure 4. Optimized swept blade.

3. Numerical simulation method

The computational domain is shown in Figure 5. The diameters of rotating domain and stationary domain are 2 m and 16 m respectively. The distance from the computational domain entrance to the rotating plane of wind turbine is 10 m and the distance from the rotating plane to the computational domain exit is 15m. All the computational domains are meshed by unstructured grid and the grid number of both straight blade and swept blade are equally about 2.81 million after the grid independence check.

Figure 5. Computational domain and mesh.

The *k- SST* turbulence model which based on the velocity pressure correction method is used to solve the steady Reynolds averaged RANS equation [7]. The boundary conditions are set as follows: the computational domain entrance is a flow velocity inlet, the end face of the downstream area of the wind turbine is provided with a static pressure outlet, and the surfaces of the blade and the hub are provided with a non slip solid surfaces. the blade rotation speed is set to $n =1500$ r/min.

Aerodynamic performance of wind turbine is simulated by using Fluent during the optimization at the condition of the tip speed ratio $\lambda = \omega R / v_0 = 9.06$, while the design tip speed ratio of straight blade is 5.71. In order to fully compare the aerodynamic performance of both straight blade and optimized swept blade, flow wind speed from 12 to 20 m/s with the interval of 1m/s is set as entrance condition.

4. Calculation results

4.1. Power coefficient and load

Figure 6 is power coefficient C_p variation with tip speed ratio. As is shown in the figure, when the tip speed ratio is higher than 7, the power coefficient C_p of swept blade is higher than that of straight blade; when the tip speed ratio is 9.82, the power coefficient C_p of straight blade is 10% and that of swept blade is 13.2%; when the tip speed ratio is lower than 7, the power coefficient C_p of swept blade is lower than that of straight blade. Obviously, swept blade has a higher efficiency than straight blade at high tip speed ratio (low wind speed). This shows that swept blade can capture more wind energy at low wind speed.
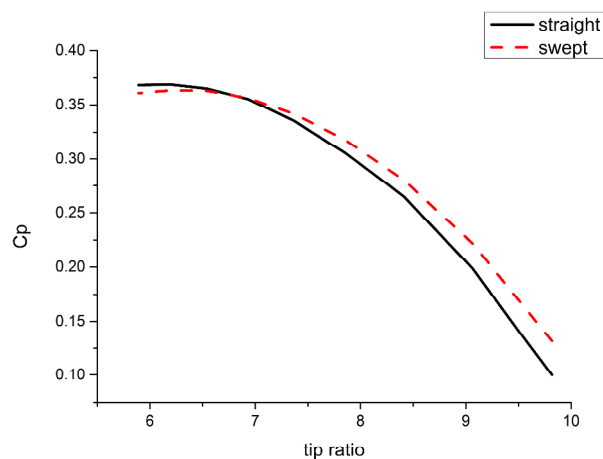
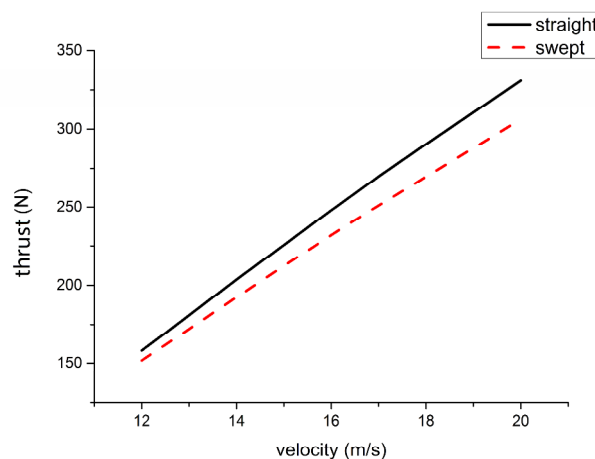**Figure 6.** Comparison of power coefficient with tip speed ratio.

Figure 7. Comparison of thrust force with wind speed.

Figure 7 is the thrust distribution variation with wind speed. As is seen in it, the thrust force of swept blade is significantly smaller than that of straight blade, and the greater wind speed, the more obvious the phenomenon. The peak of the axial force and the structure requirements are obviously reduced, this may lead to reduce the cost of wind turbine.
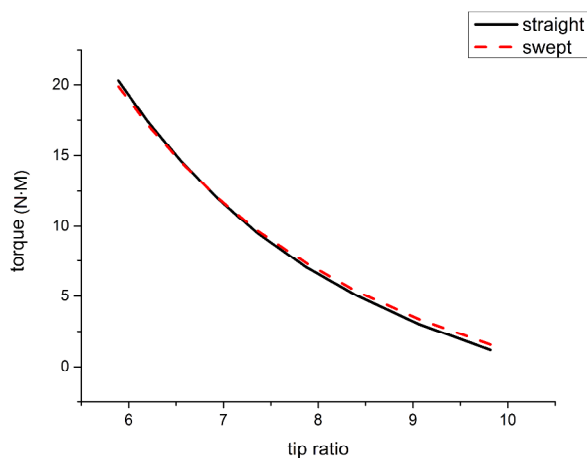

Figure 8. Comparison of torque with tip speed ratio.

Figure 8 is the output torque variation with the tip speed ratio. As is seen from the figure, when the tip speed ratio is greater than 7, the output torque of swept blade is larger than that of straight blade, and the output torque is smaller than that of the straight blade when the tip speed ratio is less than 7.

4.2. Angle of attack

The airfoil angle of attack influences the lift-drag coefficient; as a result, it has effect on the output torque of the wind turbine. The angle of attack at 9 radial cross sections is taken. 9 cross sections are 25%R, 35% R, 45% R, 55% R, 65% R, 75% R, 85% R, 95% R, and 100% R respectively. Two wind speed conditions, 13m/s and 19m/s are provided. The angle of attack is shown in the Figure 9.

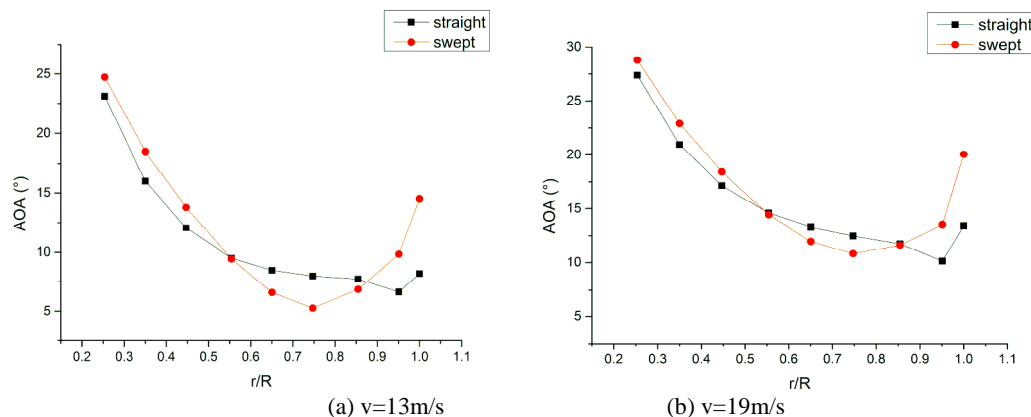(a) v=13m/s   (b) v=19m/s

Figure 9. Angle of attack variation with radius at different wind speed

It can be seen from Figure 9 that the angle of attack of swept blade is larger than that of straight blade when the radius is ≤55%R, and the angle of attack is smaller than that of straight blade when radius is between 55%R and 85%R. When the radius is ≥ 85%R, the angle of attack of swept blade is larger than that of straight. When the wind speed changes from 13m/s to 19m/s, the angle of attack of swept blade and straight blade is gradually increased.

The lift coefficient of LN221 airfoil approaches its maximum of 1.27 at the angle of attack of 11.5 degree. It can be seen from Figure 9 (a) that the angle of attack of the swept blade section throughout most of the span of the blade is larger than that of straight blade section. The angles of attack along most of the span of blade are within 12 degrees, namely, when wind speed is 13 m/s, angle of attack on swept blade section increases so as to improve the lift of the swept blade, as a result, the output torque increases.

It can be seen from Figure 9(b) that when the wind speed is 19m/s, the tip speed ratio is 6.2, the minimum angle of attack of swept blade increases to about 12 degrees, namely, the blade at the wind speed of 19 m/s approaches the stall point of two-dimensional airfoil and the lift coefficient reduces, the output torque of the blade also reduces. This is consistent with Figure 6, when the tip speed ratio is less than 7 the power coefficient C_p of swept blade is lower than that of straight blade slight.

In addition, the angle of attack distribution curve shows that when the radius is between 55% and 85%，the angle of attack of swept blade is smaller than that of straight. This shows that there still has optimization potential by changing the express method of stacking line.

4.3. Stream line on the blade surface

The limit streamline on two blade suction surface at two wind speeds are provided in Figure 10 and Figure 11. There is no separation flow on the two suction surfaces near root blade at 13m/s and 19m/s. It is shown in the figures that the swept shape has almost no effect on the blade root streamline, but near the blade tip, the streamline of swept blade has obvious deviation, and the closer to the tip, the

more obvious the deviation is. The steam line is outward oblique, which may benefit to improve the output torque of swept blade at low wind speed, it is worth studying further.
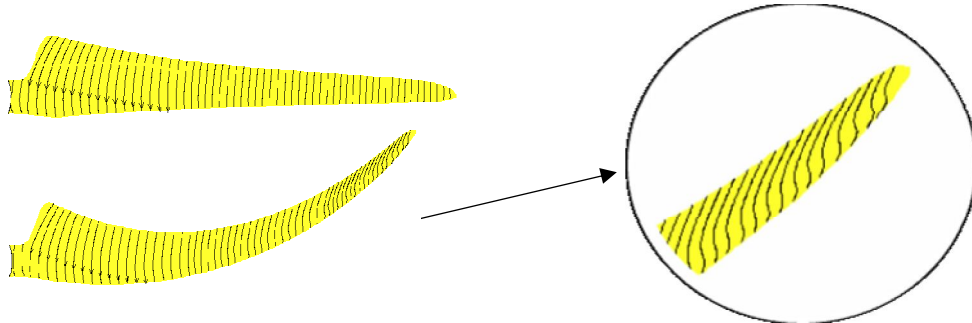

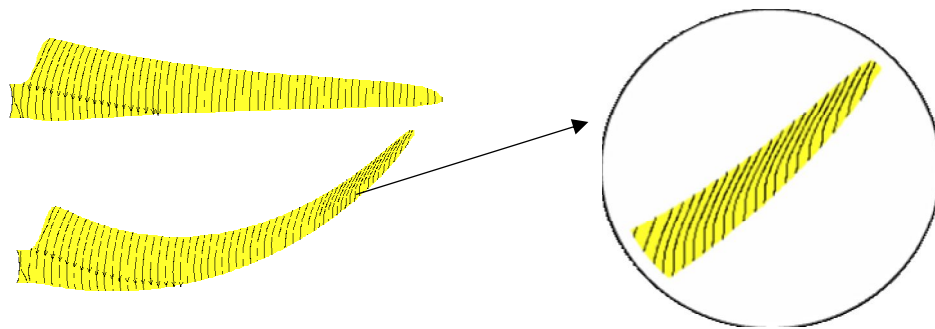**Figure 10.** The limit stream line on the suction surface at the wind speed of 13 m/s

Figure 11. The limit stream line on the suction surface at the wind speed of 19 m/s

5. Conclusions

In this paper, Isight which integrates modeling, meshing and numerical calculation is used to optimize the swept blade shape. After comparing and analyzing the data of the optimized swept blade with straight blade, conclusions may be drawn as follows:

1. It is found that power coefficient C_p of swept blade is 3.2% higher than that of straight blade at the tip speed ratio of 9.82. It shows that the optimized swept wind turbine can capture more wind energy high tip speed ratio.

2. In the calculation of wind speed range, the thrust of swept blade is significantly smaller than that of straight blade; the thrust peak is reduced, and the cost is ruduced also.

3. The steam line on the suction of the swept blade is outward oblique, which may benefit to increase the output torque of swept blade at low wind speed. it is worth studying further.

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