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# Variable Cross Section Aerofoil Blade Design and Aerodynamic Optimization Analysis of Large Scale Wind Turbines

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**Abstract:** Based on blade element momentum (BEM) theory, the optimum design model of blade is established by taking the maximum wind energy utilizing coefficient as the optimization objective, and the chord length, twist angle and the relative thickness as the optimizing variable. Wilson method is adopted to design optimally and revise the chord length and twist angle of variable cross section aerofoil blades . Matlab calculation method is used to optimization calculation blade aerodynamic performance. Taking 1.5MW wind turbine blade for instance, The aerodynamic performance theory calculation and simulation calculation is compared between the variable cross section and single cross section aerofoil blade. The results show that aerodynamic performance of variable cross section aerofoil blade is better than that of a single aerofoil, and can be used for reference in blade shape design of wind energy systems.

**Keywords:** Wind Turbine; Blade; Variable Cross Section Aerofoil; Aerodynamic Performance

## 1. Introduction

The wind turbine pick up energy depend on wind rotor blades, its blade shape is needed to gain wind power, and its aerofoil affect the blade shape directly. Therefore, the aerofoil is especially important. The single cross section aerofoil is used in wind turbine at present, the blades influenced by some factors such as starting torque , runtime environment and aerodynamic characteristic, cannot run in the best state. The different airfoils are adopted at different cross-section of the variable cross section aerofoil blades, each with varying lift-to-drag ratio and attack angles, and select corresponding attack angle under best lift-to-drag ratio to optimize the design of the whole blade. It shall be ensured that, under rated working conditions, the wind turbine have higher efficiency in wind energy and less drag.

Based on Blade Element Momentum (BEM), Wilson method is adopted [1] to design the aerodynamic shape of variable cross section aerofoil blade by taking the maximum power coefficient as the optimization target. With the optimization toolbox of MATLAB, the optimization calculation of blade aerodynamic performance is accomplished.

## 2. Blade Aerodynamics Model

The BEM theory is generally used to study the aerodynamic loads of wind turbine, it assumes that the airflow between the adjacent ring elements does not have the radial interaction [1]. The influence of blade tip hub loss coefficient was taken into account, the blade optimum aerodynamics model is established.

According to blade element theory, and blade tip loss coefficient consideration on normal force and shearing force, the element torque and thrust at rotor radius r can be calculated as in (1)(2)[1]:

$$dT = \frac{1}{2} N r V^2 (C_L \cos f + C_D \sin f) cdr \tag{1}$$

$$dM = \frac{1}{2} N r V^2 (C_L \sin f - C_D \cos f) cdr \tag{2}$$

Where, $\sin j = v_\infty (1-a)/V$

$\cos f = wr(1+b)/V$;

$f$ -inflow angle(deg); $r$ -air density (kg/m3);V-wind velocity (m/s); CL-lift coefficient, CD -drag coefficient, $dr$ -is the blade radius along wingspan direction, $c$ -element chord length (m).

According to blade momentum theory, and with blade tip loss coefficient of axial and tangential consideration, the element torque and thrust at rotor radius r can be calculated as in (3)(4)[1,2]:

$$dT = 4prV^2(1-aF)aFrdr \tag{3}$$

$$dM = 4prVw(1-aF)bFr^3dr \tag{4}$$

Where , $w$ -rotational speed ( $rad/s$ ); $a$ - axial induction factors; $b$ -tangential induction factors; $F$ -blade tip hub loss revise factors.

Equating Eq.(1) and (3), it follows that

$$\frac{aF}{1-a}=\frac{NcC_x}{8\pi r\sin^2\varphi} \tag{5}$$

Equating Eq.(2) and (4), it follows that

$$\frac{bF}{1+b}=\frac{NcC_y}{8\pi r\cos\varphi} \tag{6}$$

If the aerofoil drag is ignored, from eq. (5) and (6), it can be given as:

$$a(1-aF)=b(1+b)\lambda^2 \tag{7}$$

The power output $dP$ acting on the blade element can be written as:

$$dP=\omega dM=4\pi\rho V_1\omega^2(1-aF)br^3dr \tag{8}$$

According to aerodynamic theory, wind energy utilization coefficient along wingspan
direction can be given as:

$$dC_P=\frac{dP}{\frac{1}{2}\rho\pi R^2V_1^3}=\frac{4\pi\rho V_1\omega^2(1-aF)br^3dr}{\frac{1}{2}\rho\pi R^2V_1^3}=\frac{8}{\lambda_0^2}b(1-a)F\lambda^3d\lambda \tag{9}$$

## 3. Aerodynamic Shape Design of the Variable Cross Section Airfoil Blade

Wind turbine blade shape includes: number of blade N, tip speed ratio $\lambda$ , rotor diameter D, Aerofoil parameters, chord C and torsion angle $\theta$ . Taking 1.5MW wind turbine examples, the paper design aerodynamic shape optimization parameters. Where, inflow wind speed is 11.3m/s,cut-in wind speed is 3m/s, cut-out wind speed is 25m/s, N is 3, rotor diameter is 77m, inflow rotational speed 17.3 rpm [4].

### 3.1 Aerofoil Parameters

The wind power produces mainly at nearby 75% of radial. Aerofoil requested has a higher lift coefficient within a certain attack angle range, corresponding drag coefficient is small. It has the good aerodynamic capacity from root to leaf apex. Aerofoil which has great relative thickness and maximum lift coefficient is generally adopted at the root. Aerofoil has minor relative thickness and maximum lift and minimum drag which is adopted generally at the leaf apex.[3] Where, the hub of a wheel is circular, the root is DU series of aerofoil, the middle is FFA-W3 series of aerofoil, ,the leaf apex is NACA63-2xx series of aerofoil, span direction relative thickness of the revised blade are shown in Fig.1.

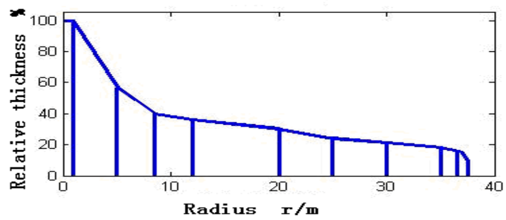


**Figure 1. Relative thickness along wingspan distribution**

### 3.2. Calculation of Blade Chord and Torsion Angle

To make wind energy utilizing coefficient maximum, optimum objective function (9) is obtained under constraint conditions (7), With the optimization tool box of MATLAB, axial induction factor a, tangential induction factor b and blade tip hub loss coefficient F of each aerofoil section are accomplished. Blade chord C and blade torsion angle $\theta$ is given in the expression (10) (11).[4] Wind energy utilizing coefficient CP, span direction chord and distribution of torsion angle of the unrevised blade are shown in Fig.2, Fig.3 and Fig.4.

$$C=\frac{8\pi aF\sin^2\varphi\,(1-aF)}{\cos\varphi\,(1-a)^2}\bullet\frac{NC_L}{r} \tag{10}$$

$$\theta=\varphi-\alpha \tag{11}$$

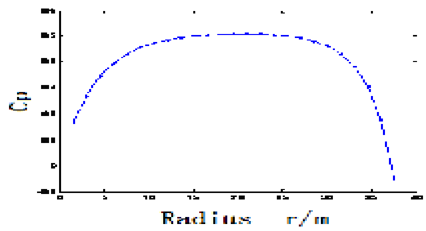


**Figure 2. Wind energy utilizingco efficient distribution curve**

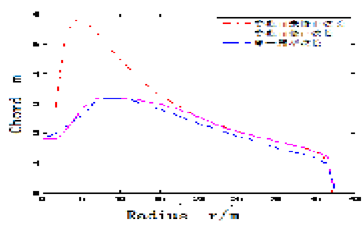


**Figure 3. Blade chord distribution curve**

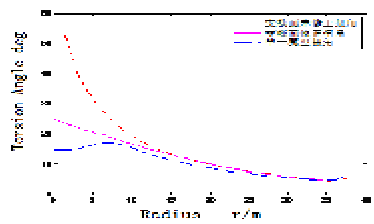


**Figure 4. Blade torsion angle distribution curve**

Fig.2 gives wind energy utilization coefficient CP, since blade tip hub loss and lift-to-drag ratio are taken into account, the CP 0.5 in the radial direction under Betz 0.593. The result shows that CP calculated is great successful. Fig.3 gives the unrevised blade chord, the blade root chord is oversized, it will cause the blade a large of quality, which will influence blade manufacturing and running and so on. Fig.4 gives the unrevised blade torsion angle, which will influence blade structural stability. Therefore, it must be revised in term of blade chord and torsion angle.

### 3.3. Revision of Blade Chord and Torsion Angle

The chord and torsion angle of the revised blade are shown in Fig.3 and Fig.4, The blade root section transits outward to external aerofoil section smoothly, the blade part near seventy-five percent contributes major to the total power output, blade chord should approach original value, the closer the original value, the smaller energy loss by revise. The blade part near the hub contributes quality of blades and a little to the total power output, the blade chord should be appropriately decreased to reduce total weight of blade and control the cost. The wind turbine power output can be increased with the decrease of blade root torsion angle, but axial thrust is raised and utility longevity is shortened.

## 4. Aerodynamic Performance Calculation of Blade

To studying aerodynamic performance of blade aerodynamic shape. The blade performance calculation is to calculate aerodynamic performance of variable cross section aerofoil and single aerofoil and evaluate the overall aerodynamic performance of the designed wind wheel. It mainly involves: power coefficient CP, moment coefficient CM and axial thrust coefficient CT.[5] Their calculation results are shown in Fig.5.

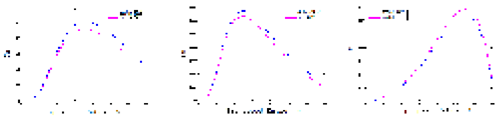


**Figure 5. Relationship between Aerodynamic performance coefficient of blade and tip speed ratio**

The utilization coefficient of wind energy CP is shown in Fig.5 (a),we can see that tip-speed ratio λ increases, CP grows gradually, when λ is about 7, CP reaches maximum, after that, as the tip-speed ratio λ increases further, the CP value will decrease gradually. The variable cross section aerofoil CP is higher than single aerofoil. It shows that variable cross section aerofoil blade improves aerodynamic efficiency.

According to aerodynamic theory, moment is produced caused by aerodynamic lift, axial thrust is caused by aerodynamic drag. Therefore, in designing wind turbine it is necessary to get the great possible moment and increase power output, but equally limit axial thrust and guarantee operational reliability. As shown in Fig. 5(b), there is a unity of moment coefficient CM and utilization coefficient CT of wind energy, when λ is about 5, CM reaches maximum, variable cross section aerofoil CM is higher than single cross section aerofoil. As shown in Fig. 5(c), variable cross section aerofoil CT of is less than single aerofoil. So the aerodynamic performance of variable cross section aerofoil blade is better than single cross section aerofoil.

## 5. Aerodynamic Performance Simulation of Blade

To farther testify the superior of the blade aerodynamic performance, it is simulated using Matlab/Simulink toolbox.Fig.6 shown simulation model of element aerodynamic performance.Fig.7 shown simulation results.

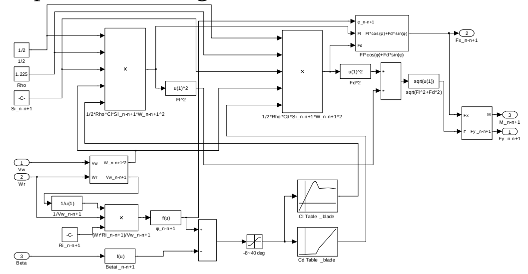

**Figure 6. Simulation Model of Element Aerodynamic Performance**

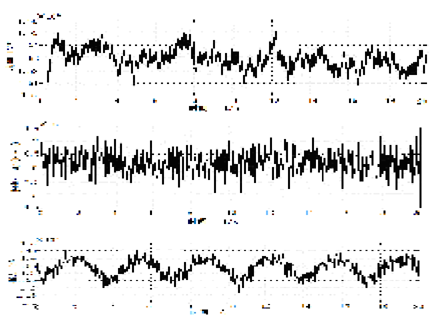

**Figure 7. Simulation Results of Element Aerodynamic Performance**

It can seems from fig.7, when tip-speed ratio is about 7, When the wind speed ranges from 11m/s to 17 m/s, power output achieve 1.53MW, The utilization coefficient of wind energy is high and the fluctuation is small the design conforms to the design power requirements. The Simulation results of aerodynamic performance agree well with the theoretical result from 11m/s to 17m/s. The results show that the optimum design result of variable cross section aerofoil blade is practicable.

## Conclusion

Based on the blade element momentum theory, calculation and revised chord and distortion angle of variable cross section aerofoil blade are carried out by taking the maximum CP, the results show the rationality of optimal design method as Wilson. The power coefficient CP, moment coefficient CM and axial thrust coefficient CT are calculated, compared with aerodynamic performance curve, we draw the conclusion that the aerodynamic performance of variable cross section aerofoil blade is better than single cross section aerofoil. The results show that the optimum design result of variable cross section aerofoil blade is practicable.

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