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Optimization Design, Modeling and Dynamic Analysis for Composite Wind Turbine Blade

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Abstract

The aerodynamic contour design and performance analysis of wind turbine blades are important parts of the design theory and application of wind turbine. Taking 20KW the horizontal axis wind turbine blade as an example, the program for optimization design of the blade's aerodynamic contour has been solved in this paper using MATLAB tool, based on the design process of Wilson method. According to the space coordinate transformation theory, the space coordinates of the blade elements have been calculated. Aiming at the dynamic performance analysis of composite blade, a modeling method of combining SolidWorks with ANSYS was proposed referred to the actual layer structure. Dynamic analysis was performed for the blade by using the finite element method. This study has been successfully applied to production of 20KW composite wind turbine blades.

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Keywords: composit wind turbine blade; optimization; modeling; finite element analysis

1. Introduction

It is difficult to calculate the axial and circumferential inducible factor of wind turbine blades, which is critical in the aerodynamic contour design. The space shape of the blade is complex; in addition, today's high-performance wind turbine blades are made of glass fiber or carbon fiber composite layer structure, so how to model the blade precisely so as to describe the layer structure becomes a difficult problem, which is also important in mechanical analysis[1]. The Ref. [2] introduced the basic theory of wind turbines. The papers [3, 4] studied design and modeling of the wind turbine blade, using MATLAB to solve three-dimensional coordinates

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of each blade section, then adopted Pro/E to build the solid model. The Ref. [5] used finite element method for static strength analysis of the blade with the shell element discretization over the skin and three-dimensional ‘sandwich’ element to simulate the spar web.

Taking the issues above into consideration, this paper aimed to develop a computer program that would enable optimization calculation of the blade inducible factors and built a blade model to precisely describe the blade’s actual shape and layer structure for dynamic or mechanical properties analysis.

2. Optimization design of aerodynamic contour

Referring to the data of 20KW blade which were provided by a wind turbine company, parameters of the blade were given as follows: rated power $P=20\text{kw}$, design wind speed $V=10\text{m/s}$, rotor diameter $D=10\text{m}$, blade number $B=3$. According to the tip speed ratio range of high-speed wind turbines, $\lambda = 7.5$ was selected. The airfoil was NACA 63415. $\alpha=3^\circ$ was chosen as the optimum angle of attack according to the design data, with the corresponding lift coefficient $C_l=0.72$, drag coefficient $C_d=0.006$.

2.1. Optimization calculation for blade element chord length C and twist angle θ

Optimization design for span-wise shape of wind turbine blade is to obtain the maximum wind energy utilization coefficient using some calculation methods. An advanced method-Wilson method was adopted in this paper, which is based on Blade Element - Momentum Theory. The blade is divided into a number of blade elements along the span. Chord length and twist angle of each blade element should be calculated so as to make the wind energy utilization factor of each blade element $dC_p/d\lambda$ maximum. The optimization model [6] is given as follows:

$$\min \quad -\frac{dC_p}{d\lambda} = \frac{8}{\lambda^2} b(a-1)F\lambda^3 \quad (1)$$

$$\text{s.t.} \quad a(1-aF) = b(1-a)\lambda^2 \quad (2)$$

$$F = \frac{2}{\pi} \arccos(e^{-f}) \quad (3)$$

$$f = \frac{B}{2} \frac{R-r}{R \sin \varphi} \quad (4)$$

$$\tan \varphi = \frac{1-a}{1+b} \frac{1}{\lambda} \quad (5)$$

The twist angle of each blade element can be determined as:

$$\theta = \varphi - \alpha \quad (6)$$

The chord length of each blade element is calculated as:

$$\frac{BCC_l}{r} = \frac{8\pi b F \cos \varphi}{1+b} \quad (7)$$

Where,

C_p is wind energy utilization coefficient; λ is the blade element tip speed ratio; a is axial inducible factor; b is circumferential inducible factor; F is tip loss coefficient; f is an intermediate variable; R is radius of rotor; r is distance between blade element cross-section to the rotor center; φ is oncoming flow angle; C_l is blade airfoil lift coefficient; C is blade element chord length; θ is blade element twist angle;

The 20KW blade was divided into twenty blade elements along the span from 0.15R to R. Each blade element tip speed ratio is calculated as $\lambda_i = \lambda_0 r_i / R$. The non-linear constrained optimization function ‘fmincon’ in MATLAB was applied on the blade element chord length and twist angle optimization iterative calculation [7]. Three M files were created in the programming, one of which was the main file named ‘main.m’, the other two files were the constraint file named ‘confun.m’ and the target file named ‘object.m’. The main file calls the other two files. Figure 1 shows the calculation process:

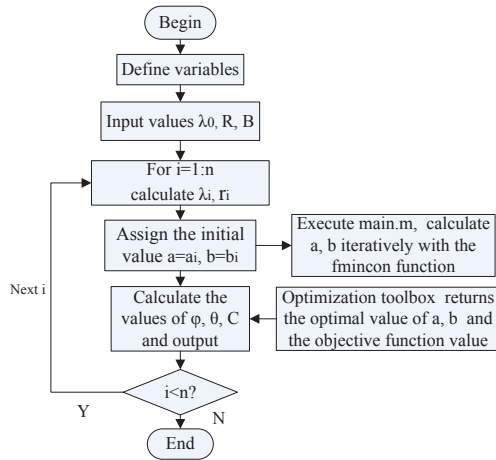


Fig. 1. MATLAB optimization calculation flow chart

2.2. Chord length and twist angle revision

The calculated values of chord length and twist angle at the blade root are often too large. It is necessary to modify them aiming at easy modeling and saving materials for manufacturing. The data of the blade elements from $R=1.5m$ to $R=4.91m$ were selected to be fitted along the span using quartic polynomial with the curve fitting function `polfit(r, C, 4)` under MATLAB. The revised values of chord length and twist angle were obtained by substituting the radius of the blade root with the function ‘polyval’. Figure 2 shows the distribution of chord length and twist angle along the whole blade span.

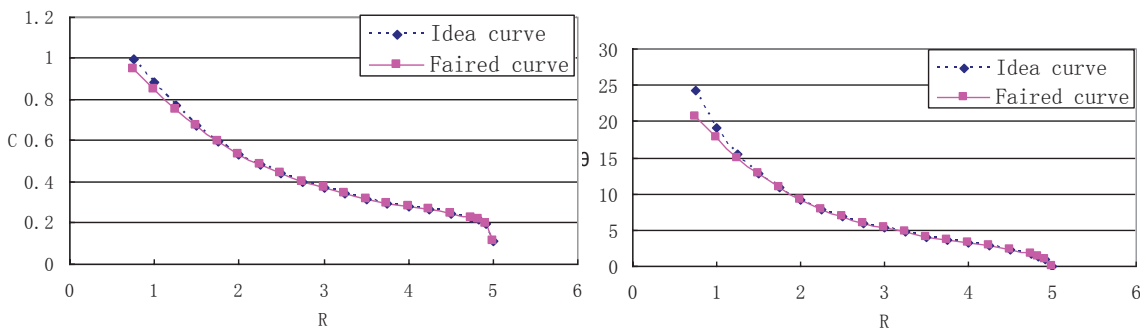


Fig. 2. (a) Distribution of chord length along the blade span-wise; (b) Distribution of twist angle along the blade span-wise

3. Calculation of space coordinates for each blade element

The coordinates of discrete points on each blade cross-section were calculated by coordinate transformation based on the two-dimensional coordinates of the original airfoil points (X_0, Y_0) , which could be obtained from Profili or naca software directly. The 2-D coordinate system takes the trailing edge as the origin, the blade chord direction as x-axis, while the space coordinate system takes the $r=0$ blade element plane as the XOY plane and the aerodynamic center as the origin. Z-axis forward is along span-wise of the blade. Suppose the reference chord length as C_0 (which is 100 units in this paper). Distance from the aerodynamic center to the trailing edge of the airfoil is considered as $C_0 / 3$. Process of the coordinate transformation [7] is as follows:

Two-dimensional coordinate translation:

$$\begin{cases} X_1 = X_0 - \frac{1}{3} C_0 \\ Y_1 = Y_0 \end{cases} \tag{8}$$

Three-dimensional coordinate transformation:

When $X < 0$,

$$\begin{cases} X = -\frac{C}{100} \times \sqrt{X_1^2 + Y_1^2} \times \cos(\arctan \frac{Y_1}{X_1} + \theta) \\ Y = -\frac{C}{100} \times \sqrt{X_1^2 + Y_1^2} \times \sin(\arctan \frac{Y_1}{X_1} + \theta) \\ Z = r \end{cases} \tag{9}$$

When $X > 0$,

$$\begin{cases} X = \frac{C}{100} \times \sqrt{X_1^2 + Y_1^2} \times \cos(\arctan \frac{Y_1}{X_1} + \theta) \\ Y = \frac{C}{100} \times \sqrt{X_1^2 + Y_1^2} \times \sin(\arctan \frac{Y_1}{X_1} + \theta) \\ Z = r \end{cases} \tag{10}$$

The process above can be calculated with EXCEL or MATLAB. The root of blade was simplified to a cylinder according to the actual installation, so this section of blade elements should be simplified to a number of circles, the radius of which were determined in accordance with size of the wheel. The calculated coordinate data of all points should be saved in txt format. Figure 3 shows the cross-section charts of some two blade elements after coordinate transformation.

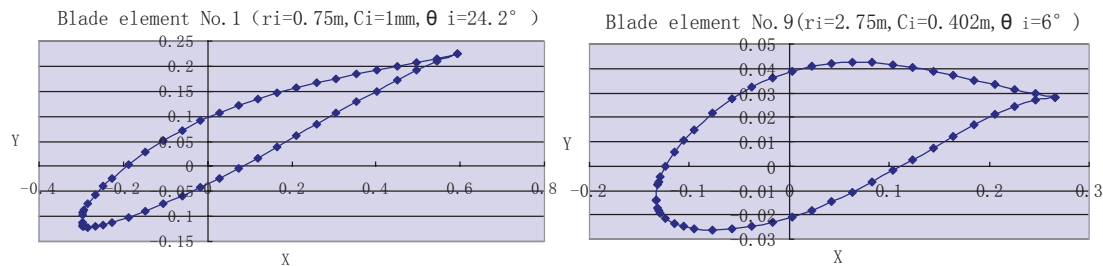


Fig. 3. Cross-section charts of blade elements

4. Three-dimensional surface modeling of the blade

The SolidWorks software was used to carry out the 3-D surface modeling of the blade. The curve of each blade element was created by the calculated coordinate data of discrete points above; subsequently, entire surface of the blade was produced through lofting.

Each blade element curve can be automatically generated by selecting the txt file of the coordinate data through steps of ‘insert’-‘curves’-‘curve through XYZ points’. The blade was divided into several parts according to different way of layering. These segmental swept skin surfaces of the blade were created by selecting the cusp of the curve sequentially, using the order ‘lofting surface’. Finally made the blade spliced into a whole. Combined with the data of circles at the root, an entire three-dimensional surface model of the blade was created successfully (e.g. Fig. 4 (a)). The model was saved as x_t form, so as to exchange data with the ANSYS software easily.

5. Dynamic finite element analysis of the blade

Dynamic finite element analysis of the blade mainly refers to the vibration modal analysis using the finite element theory. Modal analysis is used to identify natural frequencies, especially low-order frequencies and vibration modes of wind turbine blades. From the modal we can learn in which frequency range the blade will be more sensitive to vibrate. Blades should be designed to avoid the resonance region with the tower and other components in order to prevent some destruction of related components. In this paper, the finite model of the blade has been established in ANSYS by importing the blade surface model created previously combined with the actual layer structure of the existing 20KW blades. Modal analysis was carried out to check whether the mechanical properties of the blade meet certain safety requirements.

5.1. Finite element modeling

The contour and cross-sections of the blade are very complex, if the precise model is established in SolidWorks, the model information is prone to missing in ANSYS when importing the intermediate format. To solve this problem, the method of combining the two kind of software to establish the blade model was proposed in this paper. The modeling of spar web structure was added taking advantage of the ANSYS modeling way of bottom-top.

The x_t file was imported into ANSYS. The accuracy of the model should be ensured. The blade was divided into six segments after importing so the web was also made up of six planes for convenience of modeling. Key points of each web plane surfaces were first created. After that, the edge curves were generated by connecting these points using the order ‘Overlaid on Area’. Then the plane surfaces of the web were formed by connecting the corresponding curves. Finally the whole geometric model of the blade was established by the order of ‘Glue’ to make all the surfaces stick together (e.g. Fig. 4 (b)).

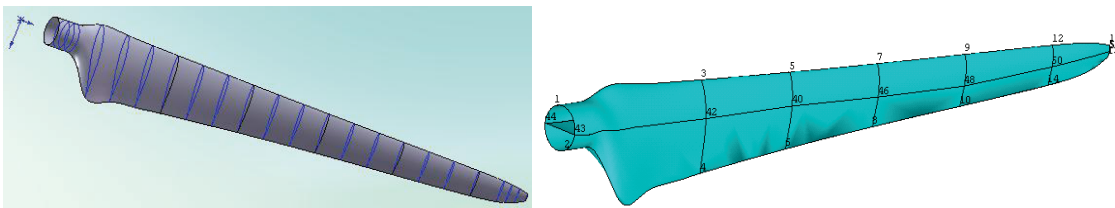


Fig. 4. (a) The blade 3-D surface model created in SolidWorks; (b) The model of blade with web structure established in ANSYS

The shell unit shell 99 was chosen to simulate the composite layer structure of the blade surface. Ten real constants were created to define the materials, angle and thickness of the blade skin and spar web layers. The

material properties were approximately defined as orthotropic, as the blade was made of glass fiber composite materials. The material number and properties were defined by the Material Models menu. The corresponding real constants were distributed to every part of the blade and appropriate grid size was set. All the areas were meshed by MASHTOOL in the way of Free Mesh. The created FEM model of the blade consisted of 1634 elements, 3715 nodes (Fig.5 (a)). Fig.5 (b) shows the lamination attribute of one selected element.

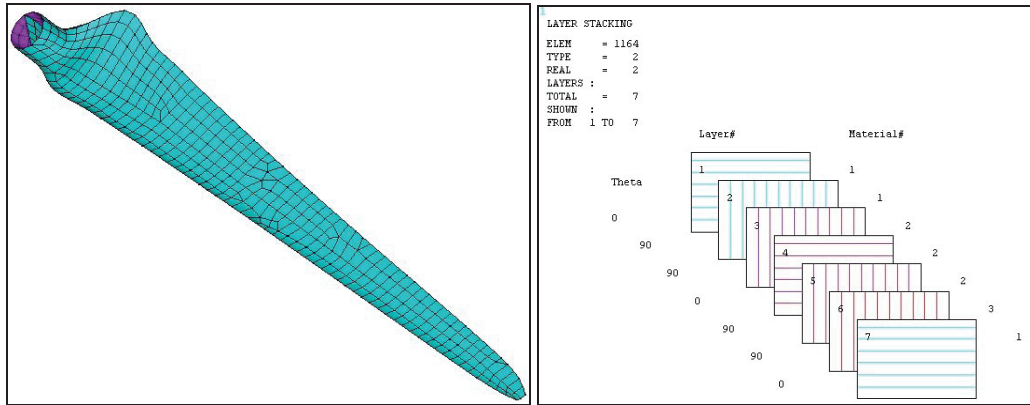


Fig. 5. (a) FEM blade model; (b) lamination attribute of one element

5.2. Modal analysis of the blade

There are many ways for ANSYS modal analysis, of which the Block Lanczos method is most widely used because of its powerful features. Moreover, it is frequently applied with model of solid units or shell units [8], that is why this paper chose Block Lanczos to perform the modal analysis. The vibration modes of the first six orders were extracted with the frequency range of 0~9999Hz. The connections of blades and hub could be regarded as fixed, so it is only need to restrict all DOFs of the root, for modal analysis does not require applying loads. At last, after solving with the solver, the vibration modes of all the orders (Fig. 6) and the result of frequencies (Table 1) could be observed in the post-processor.

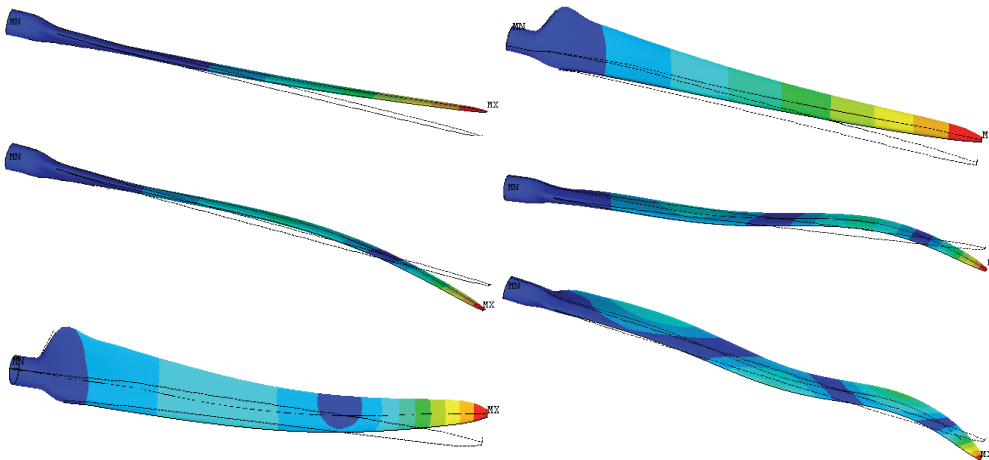


Fig. 6. The first six vibration modes of the blade

Table 1. Frequencies of the first six orders

Mode orders	1	2	3	4	5	6
Frequencies	5.6309	13.696	19.417	41.257	58.805	68.704

In the designed condition with the wind speed $V=10\text{m/s}$, the blade tip speed $V_{tip} = \lambda_0 \bullet V = 7.5 \times 10 = 75\text{m/s}$. The excited frequency of the rotating rotor with three blades shall be calculated as:

$$f = \frac{3\omega}{2\pi} = \frac{3 \times \frac{75}{5}}{2\pi} = 7.16\text{Hz}$$

Compared with table 1, it is clearly to see that the first natural frequency is far away from exterior excited frequency. Therefore, no resonance will happen when blades run at rated wind speed.

6. Conclusion

This paper applied MATLAB programming to realize the aerodynamic contour optimization design of wind turbine blade. The way of combining SolidWorks and ANSYS was adopted to establish the blade model so as to describe actual shape and layer structure of the composite blade precisely. The dynamic performance of the blade was checked by modal analysis, providing a reference for structure design and other analyses.

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