Effect of main spar ply Parameters on performance of composite wind turbine blades

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Abstract. The change of layer parameters of composite material will affect the performance of wind turbine blades. In this paper, in order to study the regularity of the variation of the ply parameters of the main spar on the structural performance of the large-scale wind turbine blade, a 5 MW wind turbine blade was taken as the research object. By changing the angle of the main spar ply and the ply ratio at different ply angles, the different wind turbine blades were established which had different ply plans. The numerical simulation was conducted to get the pressure on the blade surface through FLUENT software at rated wind speed. After this, the static analysis and modal analysis were been performed to the blades which applied load. The results show that the maximum stress the blade bears is the smallest when the main spar layup angle of fibre was 0°, illustrating that 0° layup angle could withstand bending load better. So the angle 0° should be the main layup angle of the main spar. And the modal frequency and structural performance of blades is best when the angle 0° accounts for layup angle 49.333%.

1. Introduction

With the increasing of wind turbine power, wind turbine generator system is becoming more and more large-scale, which results in the increase of the weight and size of the blades. Therefore, higher requirements are put forward for the structural design of wind turbine blades [1]. The blade, which is one of the most critical components of the wind turbine, is a source of wind power and mainly carries components. It plays a key role in the safe operation of the entire wind turbine, is usually made of glass fiber reinforced composite materials [2]. The performance of glass fiber composites will vary due to the change of layup parameters. In order to improve the economic benefits of the blades, the influence of composite layup parameters on wind turbine blade performance should be studied with emphasis in the design of blade structures.

Many scholars both at home and abroad have studied the structural optimization of wind turbine blades. Wang Quan et al. [3] proposed a new fluid-solid coupling method for blade structure design and optimization based on the modified momentum leaf theory. Bottasso et al. [4] describes a method for the structural optimization of wind turbine blades for given prescribed aerodynamic shape. This method implements a multilevel optimization process in a computer program and it is demonstrated on the design of a multi-MW wind turbine blade. Zhu et al. [5-6] proposed a program based on MATLAB combined with ANSYS and applied to the optimization of multi-objective aerodynamic and structural horizontal axis wind turbine blades. Kim et al. [7] analyzed the delamination or matrix failure of composite materials and predicted the realistic behavior of the entire blade region. Subsequently, the buckling stability of wind turbine blades was analyzed. Fagan et al. [8] conducted an experimental
texting on 13 meters long glass fiber epoxy composite wind turbine blades. The results of the text were used to calibrate the finite element model, and then genetic algorithm was used to optimize the design. Wang et al. [9] used a genetic algorithm to optimize the quality of the composite blade by using the number of unidirectional plates, hat caps, and shear web thickness as the design variables. After optimizing, it was significantly lower than the initial design value by 17.4%. Park et al. [10] performed a structural design on a 1 kW horizontal axis wind turbine blade using a natural flax fiber composite material. The structural design results of the flax/epoxy composite blade were compared with the design results of the glass/epoxy composite blade.

In this paper, a 5WM wind turbine blade is taken as a model for research. Through real constants, the laying angle of the main spar are set as 0°, 15°, 30°, 45°, 60° and 0° accounted for 40%, 49.333%, 60%, 69.333%, 80% of the main spar laying angle, then establish different finite element models of wind turbine blades. The surface pressure of wind turbine blade at rated wind speed is numerically simulated through FLUENT software, and the load is applied to the blades to perform static strength analysis and modal analysis. The influence of the change of main spar parameters on the performance of the wind turbine blade is studied, and providing the research basis for the design of the lamination of the main spar structure of the blade.

2. Blade modelling and loading

The finite element analysis theory of blade structure is based on the Finite Element Analysis [11], which disperses the blades into a finite number of unit bodies and implements load transmission between the units through nodes. The displacement vector of an arbitrary unit body is:

\[ U = N_u^e \]  (1)

In the formula: \( U \)—displacement vector of arbitrary unit body; \( N - \) shaped function matrix; \( u^e \)—displacement vector of arbitrary unit body node.

According to the geometric equation of continuous elasticity and equation (1) [12], let \( B = LN \), then the strain vector of an arbitrary unit body is:

\[ e = L \dot{U} = L \dot{N}_u^e = B u^e \]  (2)

In the formula: \( e \)—strain vector of arbitrary unit body; \( L \)—differential operator; \( B \)—strain matrix.

According to the physical equation of continuous elasticity and equation (2), the stress vector of any unit body is:

\[ \sigma = D e = D B u^e \]  (3)

In the formula: \( \sigma \)- the stress vector of any unit body; \( D \) - Elastic matrix.

According to the principle of minimum potential energy, in the volume domain \( V \), the total system load vector is:

\[ P = K U = \sum_{i} K^e N_i u^e \]  (4)

In the formula: \( K \)-system stiffness matrix; \( K^e \)-unit stiffness matrix; \( P \)-system load vector.

According to the principle of instantaneous minimum potential energy, the structural differential equation of motion can be derived:

\[ M \ddot{U} + C \dot{U} + K U = P \]  (5)

In the formula: \( M \)-system mass matrix; \( C \)-system damping matrix.

If the system is in free vibration and the external force is zero, Equation (5) can be expressed as:

\[ M \ddot{U} + C \dot{U} + K U = 0 \]  (6)

From equation (6), the natural frequency and formation of the blade can be determined.

3. Blade finite element model

The research object is a 5MW wind turbine blade model published by NREL [13]. The rated speed is 12.1r/min; the length of the blade in the span direction is 61.63m. The APDL parametric design language is used to model in the ANSYS software. According to the airfoil blade shape and
parameters of the 5WM wind turbine, the program for generating the 3D shell structure of the 5MW large wind turbine blade has been written. The model consists of 136 parts, which are made up of the leading edges (A53~A68, A121~A136), the main spar (A87~102, A36~A51), the trailing edge (A70~A85, A104~A119), webs (A1~A34) and roots (A35, A69, A52, A120, A103 and A86). The finite element model of the blade is shown in figure 1.

Figure 1. Blade finite element model.

The main spar of the blade is mainly used to bear the bending load, which is the main bearing part of the blade. In the ANSYS software, the SHELL181 shell element is used to layer the blade model. In order to make the blade ply closer to the actual condition, the ply is decremented along the direction of the blade. The model uses E-Glass Fiber. Table 1 shows the mechanical properties of the laminates used in the 5WM blade [14].

| material               | E1/GPa | E2/GPa | G12/GPa | μ12  |
|------------------------|--------|--------|---------|------|
| Fiberglass Unidirectional Fabric | 37.00  | 9.00   | 4.0     | 0.28 |
| Bidirectional cloth    | 10.30  | 10.30  | 8.0     | 0.30 |
| Gel coat               | 3.44   | 3.44   | 1.3     | 0.30 |
| Surface felt           | 10.30  | 10.30  | 8.0     | 0.30 |

The main spar layer method in this paper is \([α°/β°/γ°] \text{NT}\), where \(α°, β°\) and \(γ°\) indicates the laying angle, N stands for multiple, T stands for continuous layup. To ensure that the laminating of the leading edges, trailing edges, roots and webs of the blades remains unchanged, and alter the laminating parameters of the blade main spar. The placement of different ply angles is shown in table 2. The scheme for different layering ratios is shown in table 3. Figure 2 shows the ply of the main spar at the root of the blade. Only 20 layers are shown in the figure.

Table 2. Different layer angle plan.

| Lamination method | Program | Lamination scheme         |
|-------------------|---------|--------------------------|
| different angle   | 1       | \([0°/90°]_{10T}\)     |
|                   | 2       | \([0°/±15°/90°]_{10T}\) |
|                   | 3       | \([0°/±30°/90°]_{10T}\) |
|                   | 4       | \([0°/±45°/90°]_{10T}\) |
|                   | 5       | \([0°/±60°/90°]_{10T}\) |
Table 3. Different layout ratios.

| Program | The proportion of 0° | The proportion of 90° |
|---------|----------------------|-----------------------|
| 1       | 40                   | 40                    |
| 2       | 49.333               | 40                    |
| 3       | 60                   | 40                    |
| 4       | 69.333               | 21.333                |
| 5       | 80                   | 0                     |

Figure 2. Paving figure of blade unit.

4. Blade load calculation

In the process of designing wind turbine blades, the acquisition of load is also crucial. This paper uses SOLIDWORKS to establish a blade model and conduct numerical simulation through FLUENT16.0 software to calculate the pressure distribution on the blade surface at the rated working conditions. Figure 3 shows the pressure distribution on the leeward side and the windward side of the blade surface at a wind speed of 11.4 m/s. It can be concluded from figure 3 that the leeward side of the blade is under negative pressure and the windward side is under positive pressure. The difference pressure causes the blades of the wind turbine to rotate. The distribution of the blade load in the figure is consistent with the force of the blade, which illustrate that the calculation results are credible.

Figure 3. Pressure distributions on blade surface (MPa).
5. Calculation result and analysis

5.1. Static strength analysis
The calculation of aerodynamic load of traditional blade is based on the classical momentum element theory, which transforms aerodynamic force into concentrated force loading to the center of blade aerodynamic center [15]. However, this method cannot truly reflect the pressure distribution on the surface of blade. In order to accurately transfer the aerodynamic load on the blade surface, firstly, the surface effect unit SURF154 is built on the surface of the blade in the ANSYS of the established model. The mesh is divided, and the effect data of the blade surface is read and written through Archive Model. Then this data is imported into the fluent that has been calculated in the section 4, and export the load from the corresponding surface. Table 4 shows the pressure data of some nodes on the corresponding airfoil section at r/R=0.8. Next, loading the obtained load on the surface of the blade in ANSYS, fixing and constraining the blade root for static analysis. Figure 4 shows the displacement cloud and stress cloud diagram of the blade at rated wind speed when in scenario 2 conditions. It can be obtained that the maximum displacement of the blade appears on the tip of the blade; the maximum displacement is 2.913 m, which is less than the blade pre-bend. It is easy to see the maximum stress of the blade occurs at the main spar of the blade, mainly in 1/3 to 2/3 of the blade; the maximum stress value is 45.3036MPa, and the allowable stress of the static strength of the glass fiber blade is 255MPa. Therefore, the blade strength meets the wind turbine design requirements when operating under rated conditions.

Table 4. Partial node pressure at section r/R=0.8.

| Distribution of part nodes of airfoil at r/R=0.8 | Node | Pressure(Pa) |
|-----------------------------------------------|------|--------------|
| 1                                             | 1    | 735.2403     |
| 2                                             | 2    | 798.7805     |
| 3                                             | 3    | -1913.98     |
| 4                                             | 4    | -3166.22c    |
| 5                                             | 5    | -3647.67     |
| 6                                             | 6    | -3462.79     |
| 7                                             | 7    | -436.188     |
| 8                                             | 8    | 1061.48      |
| 9                                             | 9    | -900.359     |
| 10                                            | 10   | -320.34      |
| 11                                            | 11   | 566.916      |
| 12                                            | 12   | 951.1693     |

5.2. Analysis of different layup angles
According to the vibration theory, the energy of the vibration process is mainly concentrated in the first and second stages, and the larger the frequency of vibration is, the more possible resonance phenomenon can be avoided. Therefore, the first and second modal frequencies, relative displacements and maximum stresses of several schemes are compared. From figure 5, it is clear that changing the angle of the main spar has an influence on the frequency, relative displacement and maximum stress of the wind turbine blade. From figure (a), the first order frequency of scheme 1 reaches the maximum value of 0.45099 Hz; the relative displacement and maximum stress of scheme 2 are the largest, but the frequency of the first order frequency is the smallest; the first order frequency of scheme 3 decreases compared with scheme 1, which shows that relative displacement increase and the maximum stress decreases slightly; the first order frequency, relative displacement and maximum stress of the scheme 4 are slightly reduced compared with the scheme 1; the first order frequency and maximum stress of scheme 5 are slightly reduced compared with scheme 1, the relative displacement slightly increases. From figure (b), it can be seen that the second order frequency of scheme 2
decreases more than that of scheme 1, and the relative displacement and maximum stress increase more; the second order frequencies of Schemes 3, 4 and 5 have little change compared with the scheme 1, the relative displacement slightly increases, and the maximum stress decreases. When a wind turbine is designed, the first order frequency of the blade is required to be as large as possible to avoid resonance, and the relative deformation of the blade is as small as possible that can increase the service life of the blade. By comparing and analyzing figure 5, it can be concluded that the angle of the main spar ply of the wind turbine blade is optimal at 0°. At this moment, the first order modal frequency of the blade is the largest, the relative deformation of the blade is the smallest and the maximum stress value received is smaller. Compared with the other four schemes, the wind turbine blade structure performance under this scheme is the best. The main reason is that the 0° layer can better withstand the bending load, while the main spar's role is mainly anti-rotation, so the effect on the blade performance is more obvious.

Figure 4. Blade displacement cloud chart (m) and stress cloud chart under static action (MPa).
Figure 5. Blade modal frequency, relative deformation and maximum stress in different schemes.

5.3. Analysis of different layer ratios

Figure 6 shows the variation curves of the first order frequency, second order frequency, relative displacement and maximum stress of the blade at five different ply ratio schemes. From the figure (a), we can see that: In the five schemes, the first order frequency of scheme 1 reaches the lowest value of 0.40379 Hz, while the relative displacement reaches a maximum value of 0.693961 m and the maximum stress reaches a maximum value of 45.3036 MPa. Therefore, the performance of wind turbine blades at scheme 1 is the worst. The first order frequency of scheme 2 is the highest of the five schemes at 0.45553 Hz; the first order frequency of scheme 3 is slightly reduced compared to scheme 2, the relative displacement and maximum stress are slightly increased; the first order frequency of the scheme 4 is also slightly reduced compared with the scheme 2, the relative displacement increases and the maximum stress basically does not change; the first order frequency of the scheme 5 decreases compared with the scheme 2, the relative displacement increases and the maximum stress slightly increases. From figure (b), we can see that in the five schemes, the second order frequency of scheme 2 reaches a maximum value of 0.97216 Hz, the relative displacement reaches a minimum value of 0.534695 m, the maximum stress reaches a minimum value of 28.8994 MPa; the second order frequency of scheme 1 is smaller than scheme 2, while the relative displacement and maximum stress are larger than scheme 2; the second order frequency of scheme 3 is reduced compared to scheme 2, the relative displacement and maximum stress are increased; the second order frequencies and maximum pressures of schemes 3 and 4 have not changed much compared with scheme 2, but the relative displacement has slightly increased. In general, the wind turbine blade performance is optimal at scheme 2. Since the blade has the largest frequency at this time, and the relative displacement and maximum stress are minimum. Therefore, when wind turbine blade main spar is laid, the number at 0°
ply fiber layers accounts for about 49.333% of the total number of plies, which is beneficial to improve the life of wind turbine blades.

![Figure 6. Blade modal frequency, relative deformation and maximum stress in different schemes.](image)

### 6. Conclusions

Based on ANSYS finite element software, a 5WM double-web horizontal-axis wind turbine blade model is established, and the performance parameters of the blade (including frequency, relative displacement, and maximum stress) are analyzed for different main spar paving parameters. From the above analyses, the following conclusions can be drawn.

1. The performance of composite wind turbine blades varies due to the change of layup parameters. The variation of the paving parameters of the blade main spar will affect the overall performance of the wind turbine blade. So the frequency, relative displacement and maximum stress value can be influenced by changing the lay angle and lay up ratio of the main spar.

2. When the angle of the main spar layer changes, 0° ply angle can increase the first order frequency and second order frequency of the blade. At the same time, the relative displacement and maximum stress of the blade decrease. Therefore, the main spar ply is dominated to 0°.

3. When the proportion of main spar layup changes, the number of 0° ply fiber layers accounts for about 49.333% of the total number of plies, which can improve the structural performance of the blade.

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