The stiffness tailoring of megawatt wind turbine

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Abstract. Wind power has developed rapidly in recent years, the wind turbine's blades determine the performance of the device and the power. In this paper, we used integrated tailoring aimed at institutional characteristics of horizontal axis wind turbine with the composite laminated plate theory, then analyzed the composite blades of wind turbine by combining experimental analysis and finite elements method, and finally studied the influences that composite material properties on stiffness tailoring with changes in the number of different layers.

1. Instruction
The choice of materials of blades not only affects the performance of wind power devices, but also determines its cost, so it is essential to choose materials. Composites help to solve this problem, it has so many advantages such as light weight, high specific strength and stiffness, small thermal expansion coefficient, fatigue and corrosion resistance, short manufacturing cycle and convenient maintenance[1]. Studies show that components which made of composites materials can make their weight reduced by about 20% generally based on ensuring the structural design requirements[2]. Stiffness tailoring could control the structural elastic deformation of blades by changing the stiffness direction of the composite materials to complete structural optimization. Composite elastic tailoring design emerged in 1970s, American General Dynamics developed a comprehensive optimizational design process(TSO) on blade aeroelasticity[3]. Appropriate lay-up design can change directions of fibers, and ensure strength and stiffness to meet requirements with varieties of contrivable loading conditions, the finite element method can be used in strength analysis of wind turbine blades composite lay-up structures[4], it provides calculation for designing blades and reliability analysis. Wangyu Liu[5] studied ply angles of the finite element model of blades impacts on its strength reliability by response surface method, the results showed that when the angle is near 45°, APDL can enhance practicality of composite structure optimizational designing.

2. The Analysis Theory of Composite Material

2.1. The Relation of Stress-strain
Calculating the structural parameters of wind turbine blades are based on composite material mechanical theory of stress-strain. Structural characteristic parameters of blades include sectional stiffness, mass density and the position of centroid, which are all indispensable for analyzing on blade modal [6]. Composite materials mechanics bases on classical laminate theory, assuming that meet Kirchhoff proposed about boards and Kirchhoff-Love[7] assumed about shells. Firstly build the coordinate system axis shows in Figure 1:
Coordinate system 1-2. As shown in Figure 1.(a), it is composed of two main directions, 1 is vertical while 2 is horizontal. The coordinate system is also called positive axis coordinate system. With it, the material is orthotropic.

Coordinate system x-y. As shown in Figure 1.(b), directions except positive axial are called off-axis, it usually expresses as x-y. With off-axis, the material is anisotropic.

Orientation angle of laminate. As shown in Figure 1.(b), it’s the angle between axis 1 of the main direction of the material and the x-axis. Specified the angle $\theta$ is positive when it in counterclockwise, otherwise it’s negative. Orientation angle of laminate is the specific structure parameters for composite material.

The conversion formulas for stresses are [8]:

\[
\begin{align*}
\sigma_1 &= (\sigma_x + \sigma_y) / 2 + [(\sigma_x - \sigma_y) / 2] \cos 2\theta + \tau_{xy} \sin 2\theta \\
\sigma_2 &= (\sigma_x + \sigma_y) / 2 + [(\sigma_x - \sigma_y) / 2] \sin 2\theta - \tau_{xy} \sin 2\theta \\
\tau_{12} &= \tau_{xy} \cos 2\theta - [(\sigma_x - \sigma_y) / 2] \sin 2\theta
\end{align*}
\]

(1)

Where, $\sigma_1$, $\sigma_2$ are normal stresses and $\tau_{12}$ is shear stress in positive axis coordinate system; $\sigma_x$, $\sigma_y$, $\tau_{xy}$ are normal stresses and shear stress in off-axis coordinate system.

The relation of stress-strain in coordinate system 1-2 to convert it into coordinate x-y for stress component is:

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} =
\begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & -2\sin \theta \cos \theta \\
\sin^2 \theta & \cos^2 \theta & 2\sin \theta \cos \theta \\
\sin \theta \cos \theta & -\sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_1 \\
\tau_{12}
\end{bmatrix}
\]

(2)

The equation (2) can be written as:

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = T^{-1}
\begin{bmatrix}
\sigma_1 \\
\sigma_1 \\
\tau_{12}
\end{bmatrix}
\]

(3)

Taking stress in coordinate x-y to express it in coordinate 1-2:
{\begin{array}{c} \sigma_1 \\ \sigma_2 \\ \tau_{12} \\ \tau_{xy} \end{array}} = T \begin{bmatrix} \sigma_x \\ \sigma_y \end{bmatrix} \tag{4}

\textbf{T} is the matrix for coordinate conversion. Similarly, the strain equation for shaft conversion is obtained:

\begin{align*}
\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} &= \begin{bmatrix} \cos^2 \theta & \sin^2 \theta & -2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & 2 \sin \theta \cos \theta \\ \sin \theta \cos \theta & -\sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{5}
\end{align*}

The equation (5) can be written as:

\begin{align*}
\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} &= \begin{pmatrix} T^{-1} \end{pmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{6}
\end{align*}

There are:

\begin{align*}
\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} &= T\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{7}
\end{align*}

\begin{align*}
\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} &= T^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = T^{-1} Q \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = T^{-1} Q \begin{pmatrix} T^{-1} \end{pmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{8}
\end{align*}

Taking \(\tilde{Q}\) instead of \(T^{-1} Q \begin{pmatrix} T^{-1} \end{pmatrix}\), then the relation of stress-strain in coordinate can be expressed as:

\begin{align*}
\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} &= \tilde{Q} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \tilde{Q}_{11} & \tilde{Q}_{12} & \tilde{Q}_{16} \\ \tilde{Q}_{21} & \tilde{Q}_{22} & \tilde{Q}_{26} \\ \tilde{Q}_{16} & \tilde{Q}_{26} & \tilde{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{9}
\end{align*}

Where:

\begin{align*}
\tilde{Q}_{11} &= Q_{11} \cos^4 \theta + 2(Q_{12} + Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \sin^4 \theta \\
\tilde{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{12} (\sin^4 \theta + \cos^4 \theta) \\
\tilde{Q}_{22} &= Q_{11} \sin^4 \theta + 2(Q_{12} + 2Q_{66}) \sin \theta \cos \theta + Q_{22} \sin^4 \theta \\
\tilde{Q}_{16} &= (Q_{11} - Q_{12} - 2Q_{66}) \sin \theta \cos \theta + (Q_{12} - Q_{22} + 2Q_{66}) \sin^3 \theta \cos \theta \\
\tilde{Q}_{26} &= (Q_{11} - Q_{12} - 2Q_{66}) \sin \theta \cos \theta + (Q_{12} - Q_{22} + 2Q_{66}) \sin \theta \cos^3 \theta \\
\tilde{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{66} (\sin^4 \theta + \cos^4 \theta) \tag{10}
\end{align*}

Where:

\begin{align*}
Q_{11} &= \frac{S_{22}}{S_{11} S_{22} - S_{12}^2}; Q_{22} = \frac{S_{11}}{S_{11} S_{22} - S_{12}^2}; Q_{12} = \frac{-S_{12}}{S_{11} S_{22} - S_{12}^2}; Q_{66} = \frac{1}{S_{66}}; S_{11} = \frac{1}{E_1}; S_{22} = \frac{1}{E_2}; \end{align*}
\[
S_{66} = \frac{1}{G_{12}}, \quad S_{12} = -\frac{v_{21}}{E_1} = -\frac{v_{12}}{E_2}.
\]

3. The impact of composite properties on stiffness tailoring

3.1. Finite Element Modeling

The three-dimensional model in ANSYS can be obtained by bidirectional CAD interface between Pro/E and ANSYS. Solid elements in finite analysis can improve the accuracy, but much time will be spent. So shell element is used in thin-walled hollow structure analysis in actual finite element, because it’s easy to set up and modify ply[9].

Selecting SHELL 181 and ply-up angles are ±45° to reduce interlayer shear stress between ±45° layer and 0° layer, the finite element model of the blade is shown in Figure 2, the number of elements is 69594, the number of nodes is 69598 by automatic meshing method.

![Finite element model of the blade](image_url)

Figure 2. The whole finite element model of the blade.

3.2. Setting material properties and loading constraints

The blade material is glass fiber/epoxy, presoak it in uniaxial direction (uniaxial epoxy fiberglass) and PVC foam board to simplify calculations. The density of uniaxial glass epoxy is 1888 kg/m³, selecting PVC foam board as the core material of the blade, and its density is 83 kg/m³, it can be used to improve the overall rigidity, prevent shell instability and reduce weight. Table 1 shows the mechanical properties of composite materials and PVC.

Where \( E_1 \) is longitudinal elastic modulus, \( E_2 \) is the transverse elastic modulus, \( G_{12} \) is shear modulus, \( v \) is material Poisson’s ratio, \( \rho \) is the density of the material.

| Materials              | \( E_1 \) (Pa) | \( E_2 \) (Pa) | \( G_{12} \) (Pa) | \( v \) | \( \rho \) (kg/m³) |
|------------------------|----------------|----------------|-------------------|-------|------------------|
| Uniaxial epoxy fiberglass | 37.0e+9     | 9.0e+9      | 4.0e+9            | 0.28  | 1888.0           |
| PVC foam board         | 8.3e+7       | 8.3e+7      | 1.0e+6            | 0.38  | 83.0             |

After setting material, it need to select constraints. The constraint of blade root adopt rigid fixing, it means that three directions and six freedom degrees of the blade root are need to be constrained. Simplify the blade as an cantilever model. Assuming each blade moving at flapwise direction which parallel to airfoil chord and at edgewise direction which perpendicular to airfoil chord. The blade loading method is consistent with the test in the finite element analysis software, loading by single
point on flapwise. Concentrated moment that applying on blade tip by calculating torque is 43 kN·m, loading by parallel multi-points at flapwise of each blade element, the average loading force is 56kN at 25 elements.

3.3. The impact on the number of layers
The mechanism to achieve aeroelastic tailoring is mechanical properties with anisotropic of the composite, therefore change the numbers, sequences of layers, ply-up angles and directions are the main method to reinforce strength and stiffness of the composite. Comparing the blade structure characteristics of different numbers of layers with the same thickness through changing the number of plies, designing various ply-up configurations to analysis structural properties of the composite. Using three different configurations of blade ply-up, every time change 5 layers. Thickness of each layer is 3mm. Configuration 1: the number of layers is 10; Configuration 2: the number of layers is 15 layers; Configuration 3: the number of layers is 20. The configurations are shown in Figure 3.

![Figure 3. Ply-up of three configurations.](image)

The nature vibration modes and frequencies of the blade are mainly affected by its structure rigidity and mass, it is necessary to control the blade vibration frequency to avoid resonance of wind turbine. Figure 4 showed the former two vibration mode contours of three configurations, the first step frequency is the first natural frequency at edgewise direction, the second order frequency is the second natural frequency at flapwise direction. The vibration of blades are mainly the first step edgewise and flapwise, because of its large aspect ratio. The maximum deformation occurs at the free end of blade tip, while the minimum deformation occurs at blade root. The first-order vibration mode is mainly at flapwise, the second-order vibration is mainly at edgewise and the gravity influences the bending direction of the blade.
Figure 4. The former two vibration of three configurations.

Table 2 is the results of the frequency and maximum deformations of kinds of configurations. It shows: with the increasing in the number of layers, the frequencies of the blade increases, but the range of change is not large due to the impact of stiffness and mass of the blade, reasonable design for the number of ply-up can achieve stiffness tailoring better; For the three configures, the maximum deformation of first-order is larger than the second-order, the deformation mainly occurs at the first-order, the deformation of the first-order is the maximum for configuration 2, but the deformation of the second-order is the minimum, knowing that the maximum is not only depend on the number of the blade.

|                          | configuration1 | configuration2 | configuration3 |
|--------------------------|----------------|----------------|----------------|
| The first-step frequency (Hz) | 1.47           | 1.49           | 1.58           |
| The maximum deformation of the first-step (m) | 0.85           | 0.93           | 0.67           |
| The second-step frequency (Hz) | 2.97           | 3.23           | 3.08           |
| The maximum deformation of the second-step (m) | 0.61           | 0.50           | 0.56           |
4. Conclusions
It is difficult to calculate the stiffness of section because the ply-up section of composite blades doesn’t in rule. The stiffness of section that calculates by ANSYS program can reflect strength properties of the blade sections reasonably and reliably to complete the stiffness tailoring. It is important to proceed structure analysis in practical application for the wind turbine blade.

It can make the blade designer predict the natural frequency, know the vibration characteristics of the blade, design and control the blade rotary speed in order to avoid resonance of the blade and various components according to modal analysis results. The maximum deformation is at the blade tip and the minimum deformation is at the blade roots. The former two orders is mainly flapwise and edgewise, the impact of flapwise and edgewise on blade vibration is larger than torque vibration, so the vibration frequencies and modes of these two directions should be considered when designing the blade.

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