Lightweight Design Of Composite Spinner For Large Wind Turbine

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Abstract: Taking a 5MW wind turbine spinner as the research object and the lightest quality of the structure as target under the condition of ensuring that the comprehensive performance of the structure meets the design requirements, using the combining method of finite element analysis and multidisciplinary structural optimization, applying hierarchical optimization strategy, the optimal mathematical model were established. The lightweight design scheme of spinner was obtained by optimizing the layout of the stiffener and the laminate parameter. The structure analysis results indicate that the optimized spinner model meets the requirements in terms of comprehensive performance, while the quality is greatly reduced. This provides a method for the lightweight design of the spinner and also provides an idea for the optimization design of large composite shell structure composed of multiple parts.

1. Introduction

With the development of wind power technology and the change of relevant national policies in the wind power industry [1], large-scale wind turbines have become a development trend. However, the continuous increase in the quality of the spinner has caused the manufacturing and installation costs of wind turbines to continue to rise, which is contrary to the needs of enterprises to reduce costs and achieve sound development. Therefore, the lightweight of large-scale composite spinner has become a hot topic [2].

Composite materials have the advantages of light weight and high specific strength, and are widely used in all walks of life. The lightweight research of composite material structure has also received general attention. Ye Hui [3] et al. carried out the ply structure design, prototype manufacturing and performance comparison analysis of the composite engine cover, which verified the effectiveness of the simulation design; Chen Jing [4] et al. used genetic algorithms to optimize the layer thickness of the anti-collision beam structure with multiple objectives, and the lightweight effect reached nearly 65%; Yan Li [5] et al. used mathematical planning methods to optimize the design of the manned space environment simulation cabin, which reduced the wall thickness by 1mm and the mass by 1t; Zhao Xiaoyu [6] et al. applied composite material laminated structure mechanics theory combined with stiffness equivalent design method to carry out lightweight design of composite battery box for electric vehicles, while Chen Jing [7] et al. used a multi-objective optimization method to optimize the battery Box for lightweight design. These optimization methods that achieve light weight only by changing the layering parameters of the overall structure are suitable for small and simple shell structures, but for the wind
turbine spinner, which is a typical multi-rib, multi-shell spliced complex large shell structure, it is often impossible to achieve a satisfactory optimization effect, and the current research on the spinner is mostly based on the strength check analysis of the existing structure [8-9].

This paper takes a composite wind deflector of a 5MW wind turbine as an example. From the perspective of the overall structure optimization of the wind deflector, the method of combining finite element analysis and multidisciplinary optimization is used to establish an optimization model and first study the overall stiffener of the wind deflector. For the layout plan, according to the structural load, the regional optimization method of the composite ply structure is studied, and the static strength analysis and verification of the lightweight design are performed.

2. The establishment of finite element model of composite material spinner

2.1 Finite element model of the spinner

The main body of the diversion cover is conical with a length of 6.23 m and a maximum outer diameter of 6 m. The geometric model is shown in figure 1a. The spinner is a large-scale shell structure, so a four-node and six-degree-of-freedom 2D element is used for modeling, and the parts are assembled with bonded always (bonded always) instead of bolted connections. The finite element model of the spinner is shown in figure 1b.

![Geometric model of spinner](image1)
![Finite element model of spinner](image2)

Figure 1. Model of spinner

2.2 Composite layer

There are mainly four types of composite glass fibers used in the composite spinner, namely CSM300, MF1250, CCM1380, MF800, and their respective performance parameters are shown in table 1.

| Parameter | CSM300 | MF1250 | CCM1380 | MF800 |
|-----------|--------|--------|---------|-------|
| $E_1$/MPa | 13590  | 19910  | 11570   | 21690 |
| $E_2$/MPa | 13590  | 19090  | 10500   | 20720 |
| Poisson's ratio | 0.27   | 0.24   | 0.28    | 0.13  |
| G/MPa     | 4850   | 5520   | 3800    | 4320  |
| $X_c$/MPa | 168.4  | 253.3  | 151.5   | 449.4 |
| $Y_c$/MPa | 173.4  | 394.1  | 213.8   | 468.4 |
| $S$/MPa | 74.1   | 58.5   | 45.5    | 54.3  |
| t/mm | 0.4 | 1.2 | 2 | 0.8 |
| Density /kg/m³ | 1634 | 1758 | 1468 | 1804 |

Based on these glass fibers, the strength of the laminate in the main direction in the plane is determined by controlling the lay angle, lay thickness and lay sequence. Table 2 shows the original ply structure plan of the mask and stiffeners of the spinner. The $0^\circ$ layup direction of the composite fiber of the finite element model is defined as follows: the $0^\circ$ layup direction of the main cover of the deflector is
from back to forward along the axial direction, and the 0° layup direction of the three blade mounting hole walls is clockwise in the circumferential direction, and the specific setting is shown in figure 2.

Table 2. Laminate details of nacelle cover

| Area  | Material | Amount | Thickness | Angle          |
|-------|----------|--------|-----------|----------------|
|       | MF1250   | 4      | 4.8       | 0°/±45°/90°    |
|       | CCM1380  | 1      | 2.0       | 0°             |
| Stiffener |       |        |           |                |
| MF1250 | 4        | 4.8    | 0°/±45°/90° |                |
| MF800  | 1        | 0.8    | 0°        |                |
| MF1250 | 1        | 1.2    | 0°/90°    |                |
| CSM300 | 1        | 0.4    | 0°        |                |
| MF1250 | 2        | 2.4    | 0°/90°    |                |
| CCM1380| 1        | 2.0    | 90°       |                |
| MF1250 | 4        | 4.8    | 0°/±45°/90° |                |

a. Skin                          b. Wall of blade mounting hole

Figure 2. Fiber 0 degree lay direction

2.3 Load cases

According to the GL2010 specification, the calculation and analysis loads of the spinner mainly include: static load, live load, snow load and wind load. Static load refers to the self-weight load of the spinner; live load refers to the load when the operator is walking on the top or inside of the spinner; wind load mainly refers to the load formed by the wind from different directions acting on the dome, and the wind load is calculated as follows [10]:

\[
P_{wk} = \frac{1}{2} \rho \omega v_{wind}^2 \cdot C_w
\]

In the formula: \( \rho \) is the air density, taken as 1.225kg/m³; \( v_{wind} \) is the limit wind speed, and the limit wind speed is 70m/s once in 50 years in the Category I wind area.; \( C_w \) is the load distribution coefficient, the windward surface is 0.8, the wind direction parallel surface is 0.6, and the leeward surface is 0.5.

This paper mainly studies the structural optimization method of the composite spinner. Therefore, four working conditions that have a greater impact on the static strength of the overall structure of the diversion cover are selected for analysis and calculation, namely: load case 1-top walking condition, load case 2-bottom walking condition, load case 2-bottom walking condition, load case 3-forward wind, load case 4-lateral wind.

3. Optimization of rib layout

3.1 Establishment of topography optimization model

The topography optimization is adopted to redesign the layout of the ribs of the spinner to improve the rigidity of the overall structure and reduce deformation. The design space is composed of the displacement vectors of some nodes in the finite element model of the diversion cover. Based on the periodic symmetric structure of the spinner, one third of the design area of the stiffener is selected as the design space; the goal of the optimal design is to minimize the weighted strain energy of each working condition.
of the overall structure of the diversion cover; the constraint condition is that the dispersion coefficient of the rib is not more than 20% and the original rib cross-sectional size requirement.

The optimized mathematical model is as follows:

$$\begin{align*}
\text{min } C_w &= \sum_{i=1}^{l} \omega_i C_i \\
\text{s.t.} \\
\text{Beadfrac} &\leq 20\% \\
\text{Min Width} &\geq 40 \text{ mm} \\
\text{Draw Heigh} &\leq 60 \text{ mm} \\
\text{Draw Angle} &= 70^\circ
\end{align*}$$

(2)

Where: $l$ is the total number of load cases; $\omega_i$ is the strain energy weight of the $i$-th case; $C_i$ is the strain energy of the $i$-th case; Beadfrac is the stiffener dispersion coefficient; MinWidth is the minimum rib width; Draw Heigh is the maximum rib height; Draw Angle is the tangled corner.

### 3.2 The strain energy weight ratio distribution of each working condition

It can be seen from equation (2) that the strain energy weight ratio of the load case has a direct impact on the objective function, so it is necessary to consider how to allocate the weight ratio to make the calculation result optimal. The weight ratio distribution schemes commonly used in solving engineering problems include orthogonal experiment to determine weight ratio, analytic hierarchy process to determine weight ratio, and proxy model-based optimal weight ratio search. The latter has better results than the previous two algorithms. Excellent [11].

Compared with Latin Hypercube Sampling (LHS), Hamersley Sequential Sampling (HSS) can search the sampling space more uniformly, and it also has better uniformity in multi-dimensional problems [12]. Therefore, the Hamersley sequence sampling method is selected, and the weight ratios of the four working conditions are used as samples for sampling, and the number of samples is 30. Substituting 30 sets of sample data into the model for calculation, and obtaining the objective function value of each set of sample data to form a sample matrix.

The surrogate model created by the radial basis function (RBS) has a strong ability to approximate complex nonlinear functions, and it can also take into account the calculation accuracy and efficiency [13]. Therefore, the radial basis function is used to construct the surrogate model. The function model is such as As shown in formula (3), 25 sets of sample data are used to construct the model, and 5 sets of samples are used for model verification. After testing, the cross-check matrix determination coefficient of the proxy model is 0.986, and the test matrix certainty coefficient is 0.992. The global response surface method (GRSM) is used to find the optimal strain energy weight ratio distribution scheme, which has the characteristics of high efficiency and global optimization. The optimal solution for the weighted strain energy distribution of each load case after search iterations is 0.250, 0.245, 0.063, 0.442, and the predicted objective function value is $3.99 \times 10^5$.

$$f(x) = \sum_{i=1}^{N} \lambda_i \phi(\|x - x_i\|) + \sum_{j=1}^{N} c_j p_j(x)$$

(3)

Where: $N$ is the number of sample points; $\lambda_i$ is the coefficient determined by the difference; $\phi$ is the function of the radial distance $r = \|x - x_i\|$, and CS21 (Wu's Compactly Supported (2,1)) basis function is selected here, as shown in formula (4) [14]; $c_j$ is the coefficient to be determined; $p_j(x)$ is the low-order polynomial function.

$$\phi(r) = (1 - r)^4 + (4 + 16r + 12r^2 + 3r^3)$$

(4)
3.3 Topography optimization calculation results

The obtained optimal weight ratio distribution scheme is substituted into the finite element model for calculation, and the final result is obtained after 38 steps of iterative calculation. The final value of the objective function is $3.92 \times 10^5$, which is 1.75% different from the surrogate model, indicating that the accuracy of the surrogate model is guaranteed. The iterative process of the objective function is shown in figure 3a, and the topography optimization result is shown in figure 3b. The topography optimization belongs to the conceptual design, and the result is generally not directly used as the final design plan. It needs to be improved in combination with the production process, cost and structural function requirements. The final rib distribution plan is shown in figure 3c and figure 3d. Compared with the original stiffener plan, the surface area of the stiffener is reduced by 27.39%.

Figure 3. Topography optimization calculation results

With the help of ANSYS software, the layout plan of the ribs before and after optimization is analyzed and compared. After calculation and analysis, the optimized stiffener layout scheme has a significant increase in structural rigidity, which is mainly reflected in the significant reduction of the maximum displacement under all load cases, with a reduction rate of over 41%. Among them, the maximum displacement of the top walking condition reduces the most, reaching 59%, and displacement cloud is shown in figure 4.

Figure 4. Maximum displacement
4. Research on optimization of pavement structure
The mechanical properties of composite laminates are closely related to the layup angle, layup thickness and layup sequence of composite fibers. The research of composite material layer structure is mainly through comprehensive consideration of the force characteristics, structural characteristics, composite fiber layup principles, and processing and manufacturing characteristics of different areas of the spinner, and determine the optimal layup parameters for different areas of the spinner to achieve structural lightweight. At the same time, the overall structural strength performance of the optimized scheme meets the requirements of the GL2010 specification. The optimization of the composite material ply structure of the spinner is divided into three stages. The first stage is regional division. According to the structural force characteristics, ignoring the boundary constraints of each cover, the entire deflector mask structure is divided into several Area, the layup parameters in each area are the same; the second stage is to optimize the number of layups, to determine the number of layup layers of the composite fiber in each area at the corresponding laying angle; the third stage is to optimize the layup sequence to determine the optimal order of layering in each area.

4.1 Regional division
In order to give full play to the material performance, according to the load characteristics of different areas, combined with the actual situation of production and manufacturing, the design area of the entire deflector mask is divided. With the help of composite material free size optimization method to divide each area, the composite fibers used in the three masks of CSM300, MF1250 and CCM1380 are set to 4 super layers according to the laying direction of 0°, ±45°, and 90°. The thickness of the layer is a design variable, the minimum flexibility is the goal, and the volume fraction is not more than 30% as the constraint for size optimization. At the same time, considering the principle of composite fiber layup, the fiber thickness in the ±45° layup direction is constrained to be consistent, and combined with the periodic symmetry structure of the deflector, the optimization result is set to be periodic symmetry.

After 31 optimization iterations, the comprehensive thickness distribution results of each super layer are shown in figure 5a. It can be seen that thicker areas appear near flange mount and the roots of the three blade hole walls. The thicker area is basically the same as the area where the tensile and compressive strain extremes are high in the previous verification calculation. According to the calculation results, the spinner mask is divided into 5 areas, and the stiffener is used as one area. The division result is shown in figure 5b.

4.2 Optimization of the number of layers
The optimization of the number of layers is to optimize the thickness of each super layer. Because the fiber thickness of the composite material is constant, the discrete variable of the number of layers contained in each super layer is selected as the design variable. The traditional optimization method is to set the thickness of the super layer as a continuous variable, and then use it as a design variable for optimization. After the thickness is determined, the number of layers is rounded up. Compared with the traditional method, the method used is more direct. Because the artificial rounding process is reduced,
and the optimized solution is the final solution, the method used is more straightforward and simple than the traditional method.

Keeping the number of layers of CSM300, MF800 and CCM1380 consistent with the original plan as one layer, the layer angle is set as the design variable, and the number of layers on the $0^\circ$, $\pm 45^\circ$, and $90^\circ$ directions of MF1250 is used as the design variable. The design variables are all discrete variables. The design goal is to minimize the overall mass, and the constraints are limited to the maximum tensile strain not exceeding 0.35%, and the maximum extrusion strain not exceeding $|\pm 0.25|$. Generally, the tensile and compressive strengths of GFRP materials in the main direction of the material are not equal. For this reason, the tensor polynomial failure criterion proposed by the Tsai-Wu criterion is used as the limitation of composite material failure. The failure criterion formula is shown in equation (5):

$$F.I. = F_1 \sigma_x^2 + F_2 \sigma_y^2 + 2F_4 \sigma_x \sigma_y + F_6 \tau_{xy}^2 + F_7 \sigma_x^2 + F_8 \sigma_y^2 < 1$$

Where: $F.I.$ is the failure factor; $\sigma_x$ is the stress in the fiber plane parallel to the fiber direction; $\sigma_y$ is the stress in the fiber plane perpendicular to the fiber direction; $\tau_{xy}$ is the principal stress intensity tensor coefficient [15].

The optimized mathematical model is as follows:

$$\min Mass = m(t_i, a_j)$$

$$s.t. : g_k(t_i, a_j) - g_k^U \leq 0, \quad k = 1, ..., N$$

$$a_j = 0^\circ, 90^\circ, \quad j = 1, ..., M$$

Where: $t_i$ is the number of layers in each super layer of MF1250 in each area; $a_j$ is the angle of CCM1380, CSM300 or MF800 layer in each area; $g_k(t_i, a_j)$ is the $k$-th constraint function; $g_k^U$ is the upper limit of the $k$-th constraint.

The global optimal solution obtained after 47 steps of the GRSM algorithm search iteration is shown in table 3.

| Area | MF1250/piece | CCM1380/° | CSM300/° | MF800/° | Thickness/mm |
|------|--------------|-----------|----------|---------|--------------|
| Zone 1 | 1 | 1 | 90 | 0 | 3.6 |
| Zone 2 | 1 | 1 | 1 | 90 | 0 | 6 |
| Zone 3 | 1 | 1 | 0 | 90 | 3.6 |
| Zone 4 | 1 | 1 | 1 | 90 | 0 | 6 |
| Zone 5 | 1 | 1 | 90 | 0 | 3.6 |
| Stiffener | 3 | 0 | 90 | 6.4 |

### 4.3 Optimization of Laying Sequence

In order to determine the layup sequence of composite fibers in each area, an optimization model is established to find the optimal solution that meets the requirements. The optimization model is as follows:

Objective: Maximize the stiffness of the overall structure;

Variable: Laying sequence of composite fiber in each area;

Constraints: ① Design constraints: the maximum tensile strain does not exceed 0.35%, the maximum extrusion strain does not exceed $|\pm 0.25|$, and the failure factor of the Tsai-Wu criterion is not greater than 1; ② Manufacturing constraints: the same kind of composite fiber layup in the same direction in the same shell must be continuous to avoid splitting due to different partitions.
The final optimization results are shown in figure 6. The optimization result shows the layering parameters of each part of the cover in different zones, which is also the final decision of the composite layer structure.

5. Comparison of optimization results

With the help of ANSYS software, the static strength of the optimized spinner structure is calculated and compared with the original structure. The comparative analysis load cases adopt the load cases described in section 2.3. The strain reserve coefficient of the spinner under each load case before and after optimization is shown in figure 7a, and the quality change is shown in figure 7b. The largest change in the strain settlement results before and after optimization is load case 3, and the strain calculation results before and after optimization are shown in figure 8 and figure 9. The safety reserve coefficient of the unoptimized spinner ranges from 2.60 to 2.91, which is much larger than the allowable coefficient 1, indicating that the structure cannot fully utilize the material performance, causing material performance redundancy. The finite element model calculation shows that the original structure mass reaches 2.45 tons, and the manufacturing, transportation, and installation costs are relatively high. Finite element model calculations show that the overall structural mass of the optimized model structure is reduced to 1.02 tons, and the safety reserve coefficient ranges from 1.13-1.68, which still meets the permit requirements.

Figure 6. Final layup plan

a. Strain comparison results

b. Quality comparison results

Figure 7. Comparison of results before and after optimization
a. Load case 3 tensile strain  
b. Load case 3 compressive strain  
Figure 8. Strain before optimization

6. Conclusion
The design method of topography optimization is adopted to find the optimal stiffeners layout plan, and the weighted strain energy distribution problem in the optimization model is solved by constructing a proxy model and combining with a global search algorithm. The optimized layout of stiffeners reduces the surface area of the stiffeners by 27.39%, and also increasing the stiffness of the structure, so that the maximum displacement of each load case is significantly reduced by more than 41%.

In the optimization design process of the composite material structure of the large complex shell composed of multiple parts, the optimization method effectively solves the composite material optimization problem of the multi-part structure. This method first ignores the boundary constraints of the parts, and then uniformly partitions optimization according to the overall force of the structure, and finally determines the specific composite fiber layup sequence of a single part.

The optimized spinner can fully utilize the material properties, and reduce the weight by 58% while ensuring that the comprehensive performance meets the design requirements.

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References
[1] National Energy Administration. (2019) Interpretation of “Notice on actively promoting work related to wind power and PV power generation without subsidized parity”[J]. Solar Energy, 297(01): 9-10.
[2] Liu S L, Wang M X, Cheng S Y. (2018) Comprehensive research on the current situation and development trend of wind power generation[J]. China new communication, (8): 233.
[3] Ye H, Liu C, Yan K K. (2020) Application of fiber reinforced composite in auto-body panel [J]. Journal of Jilin University(Engineering and Technology Edition), 50(2): 417-425.
[4] Chen J., Tang A T., Tian K., et al. (2020) Lightweight design of carbon fiber composite anti-collision beam [J]. Automotive Engineering, 42(3):390-395.

[5] Yan L., Ma A J., Xu S H., et al. (2017) Optimization Design of Manned Space Environment Simulation Chamber Based on OptiStruct [J]. Space Medicine & Medical Engineering, 4(4): 283-286.

[6] Zhao X Y, Zhang S R. (2018) Lightweight Design Method for Electric Vehicle Battery Boxes Made by Composite Materials [J]. China Mechanical Engineering, 29(09): 1044-1049.

[7] Chen J., Peng B, Wang D F, et al. (2020) Lightweight Design of Carbon Fiber Reinforced Composite Battery Box [J]. Automotive Engineering, 42(2): 257-263.

[8] Zhou Z L, Wu B M, He Z Y, et al. (2009) Design and calculation of strength and rigidity of 3MW diversion hood for wind power with new 3D sandwich structure composite material [J]. Journal of Materials Engineering, (S2): 317-318.

[9] He Y L, Wang Z, Yang D S. (2013) Structural strength analysis for composite hub cover of wind turbine [J]. Mechanical Science and Technology for Aerospace Engineering, 32(04): 528-532.

[10] Germanischer Lloyd WindEnergie Gmb H. (2010) Guideline for the Certification of Wind Turbines [S]. Germanischer Lloyd, Hamburg.

[11] Qiu R B, Lei F, Chen Y, et al. (2016) Research on the method of multicase topology optimization of frame structure based on the weight ratio [J]. Journal of Engineering Design, 23(05): 444-452.

[12] Chirdpong, Preechakul, Soorathep et al. (2009) Modified genetic algorithm with sampling techniques for chemical engineering optimization [J]. Journal of Industrial and Engineering Chemistry, 15(1): 110-118.

[13] Chen G D, Han X. (2014) Multiobjective optimization method based on metamodel and its applications in vehicle body design [J]. Journal of Mechanical Engineering, 50(9): 70.

[14] Wu Z. Compactly supported positive definite radial functions [J]. (1995) Advances in Computational Mathematics, 4(1): 283-292.

[15] Yang Z Y, Song L. (2017) Structural design of composite submersible based on ANSYS ACP [J]. FRP / composite, (4): 24-28.