DESIGN OPTIMIZATION AND MECHANICAL SIMULATION ABOUT GRP BLADES OF THE VERTICAL AXIS WIND-DRIVEN GENERATOR

Weijie Wang¹, Jianhui Zhang², Xuezeng Zhao¹, Yuenjiang Zhang¹, Nan Liu¹
1. Harbin Institution of Technology, Harbin 150001, China
2. Heilongjiang Research Institute of Electric Power Exploration and Design, Harbin 150078, China
zyj374068371@126.com

ABSTRACT
In this paper, a specific type of vertical-axis wind turbine is discussed. For the complex structure of this specific vertical-axis wind turbine, the structures of certain parts are optimized and improved. Size of bolts that connect the root of the blade with the vertical shaft is designed. Also, the improved structure is proved reasonable using Solidworks Simulation. Through the optimization and improvement of structure, the blade of the discussed vertical-axis wind turbine becomes simpler and lighter. As a result, the transportation and installation costs of blade are reduced.

KEY WORDS
Wind power, vertical-axis, optimal design, fiberglass blade

1. Introduction
With the energy crisis becoming worse, wind power, being of green, has been gradually rising in the world. The current mainstream of wind turbine is horizontal-axis wind turbine, which suffers lots of problems where there's need of greater power generation. These problems are such as difficulty of blade processing, the poor stability of vertical shaft and high cost of blade lifting result from the blade being too long and the vertical shaft being too high. Thus, researchers turn to vertical-axis wind turbine. However, vertical-axis wind turbine has no uniform theoretical system. Instead, different analysis methods are given for different vertical-axis wind turbines [1].

The original wind turbine model built in Solidworks in a two-dimension drawings provided by manufacturer is found with redundant structure, difficulties in transporting and assembling, and high cost, thus needs optimization. We reselect the size of the bolts connecting the root of the blade with the vertical shaft. This paper sets out to optimize the structure of the original wind turbine.

2. Optimization of the overall configuration of the blades
2.1 Optimization of the frame structure of the blades
The GRP blades connect to the frame, and then through the frame connect to the vertical shaft. Figure 1 and figure 2 are beam sectional views of the rear frame before and after optimization.

Figure 1. A cross-sectional view of the framework before optimization

Figure 2. A cross-sectional view of the framework after optimization

From figure 1, it can be seen that before optimization, the blade frame structure uses fiberglass blades extending outward and packaging the square tube. One square tube is connected to another by welding. An aluminum plate is attached to the outer surface of the frame, to connect the vertical shaft [2]. This craft would bring about a lot of defects:
1. The material of square tube is Q235 steel of great heaviness which will aggravate the difficulties in hoisting and assembling.
2. The square tube cross-section is adopted, thus the inner surface of the steel pipe cannot be processed with anti-rust, anti-corrosion treatment.
3. As figure 3 shows, the square tubes are connected to each other by welding, which results in deformation of the connecting pieces, leaving a residual stress due to the high temperatures. Besides, it is not easy for weldment to maintain as it’s not detachable.

4. Pasting another board outside of the framework only to connect the pieces can lead to high cost and weight causing transport difficulties.

Therefore, by focusing on the several shortcomings in the original blade frame, some work is done to optimize it into the new structure as is shown in figure 2. The cross-section is in the form of groove and bolt hole locations are reserved in leaves. Finally, the internal and external connections are strengthened by steel plate at the reserved position. The optimization points are as follows:

1. The frame material is changed from Q235 steel to 2018 aluminum alloy, which not only makes the frame lighter, but also tensile compressive strength higher than Q235 steel.

2. Channel is adopted so that the resistance to wind direction bending and shear capacity do not decline, yet the weight on the gravity direction reduces. In addition, the channel section form will allow anti-rust and anti-corrosion processes to be treated on both the internal and external surfaces conveniently.

3. The connections between the frame beams are changed from welding to riveting, as is shown in Figure 4, which makes the processing easier. Furthermore, caulking strength is smaller than the welding strength, and this would allow a certain extent of flexural deformation.

4. The outer link paste board around the framework is removed to reduce weight, costs, and transportation difficulties. Steel sheet is used at the location of the bolt holes to increase the strength to meet the requirements.

2.2 Optimization of accessory structure of the blades

In addition to the optimization of framework of cross-sectional shape and form of connection, some other subsidiary structures are also optimized. Figure 5 and Figure 6 display the connection form between the blades before and after optimization.

As can be seen from the comparison of figure 5 and figure 6, after the optimization, the blades are connected to each other with wire cable, making the wind turbine a whole. The wire cable bears a certain amount of preload. The wire connecting can guarantee that each blade receives strength evenly, that the vibrations generated by the rotation decreases, that the kingpin stability strengthens, and that the chances of impairing the root bolts reduces remarkably [3]. When the stress the blades bear increases, the elastic deformation of the wire cable can reduce the impact, acting as a buffer against the vibration. The internal structures of the wind turbine
blades before and after optimization are shown in figure 7 and figure 8.

Figure 7. The internal structure of the wind turbine blades before optimization

Figure 8. The internal structure of the wind turbine blades after optimization

Before optimization the material of the framework is Q235, its tensile compressive strength being 375-500Mpa, yield limit 235Mpa, and density 7800kg/m³. After optimization the material of the framework is aluminum alloy 2018, its tension intensity being 420.507Mpa, yield limit 317.104Mpa, and density 2800kg/m³. After optimization, the mass of the frame material is smaller and truss structure is not necessary to strengthen the framework on the direction of gravity. Besides, material yield limit increases moderately and its mechanical properties improve. A wire cable sets inside the frame can meet the strength requirements, and other problems such as structural redundancy and low efficiency of assembly can be effectively solved [2].

Wire cable is used to connect inside of the frame. Since the deformation of the blade root and the deformation of the blade tip (as figure 9 shows, L0 < L1), the rope L1 tends to elongate after deformation. It generates tension internally so that the blade tip shrink back, to ease the deformation caused by weight. When the flexible deformation decreases, the damage on the spot where roots and vertical shaft disc contact decreases accordingly.

The structures of the blade connecting with ear plate before and after optimization are shown in Figure 10 and Figure 11.

Figure 9. The schematic diagram of deformable framework

Figure 10. The structure of the blade connecting with ear plate before optimization

Figure 11. The structure of the blade connecting with ear plate after optimization

Comparing figure 10 and figure 11, before optimization, ear plate is not used but just fix the guide plate directly to the framework, which increases the difficulty in the assembly in the actual operation. After optimization, an ear plate is added, making assembly and disassembly of the deflector easier. There are two connecting holes in the ear plates, making the connecting wire cable be in the same plane and the inclination of the force does not occur. At the same time, the three
connections are not in the same hole, so the stress on one bolt reduces, and its chances to be damaged reduce. Bolts will not tilt because of uneven forces.

2.3 Comparative analysis of the blades of the whole structure before and after optimization

Through the above analysis, using Solidworks draw assembly drawings of the optimized structure. Assembly drawings before structure optimization and after structure optimization blade are as shown in figure 12 and figure 13.

![Figure 12. Assembly drawings before optimization](image)

![Figure 13. Assembly drawings after optimization](image)

Figure 12 is based on 2-d drawings provided by the factory, built in the Solidworks assembly drawings of blades before optimization, and figure 13 is assembly drawings after optimization. Through the comparative analysis, optimal assembly later is more simple and more convenient to assemble than before. This will save a lot of time for actual production installation, improving production efficiency.

3. Design and selection of the blade root bolt

After optimization, the structure and stress of the blades are changed. We need to redesign bolt group connected with disc blade root. Bolts are arranged as shown in figure 14.

![Figure 14. The arrangement of bolts](image)

Use 10 hex head bolts to connect blade root and the vertical shaft in one way, as shown in figure 14. Using this way is because this kind of connection mode is simple and compact. Blade force is as shown in figure 15. We are according to the wind speed of 20 m/s (8 grade wind) and speed of 0.2 r/s (angular velocity of 1.256 rad/s) to carry on the design. According to the manual, power $P$ of 8 grade wind is 50.5596 kw and force of the wind $F_w$ is 12000N. Thickness of FRP blade is 6 mm and blade quality (including aluminum alloy frame) is 674.2 kg calculated by Solidworks. Assume that the point of centrifugal force and gravity application is the highest point. Quality and angular velocity calculated by centrifugal force size is 2446N. The force is equivalent to bolt connection [5]. As the blades at the top and bottom are connected to the vertical shaft, top and bottom of each bear half of the total force, as shown in figure 15 [6].

![Figure 15. Blade force diagram](image)
As is shown in figure 16, the load acting on the blade, gravity and centrifugal force are equivalent to bolt connection. Below we will conduct design of the bolt group.

(1) Analysis of the characteristics of bolt load. Solve the X, Y, Z direction of the force and torque values respectively [5].

**Force and torque value in the X direction:**

\[
F_x = \frac{F_w}{2} = 6000N
\]  
\[
M_x = \frac{1}{2}(M_g - M_c) = \frac{1}{2}(G - F_c)l = 9881N
\]

\(F_w\)—— wind power
\(M_g\)—— moment by gravity
\(M_c\)—— moment by centrifugal force
\(l\)—— the coordinate of the highest point \(y\) (m), \(l = 4.6m\).

**Force and torque value in the Y direction:**

\[
F_y = \frac{F_c}{2} = 1223N
\]  
\[
M_y = \frac{1}{2}Gh = 6742N\text{cm}
\]

\(h\)—— the coordinate of the highest point \(x\) (m), \(h = 2m\).

**Force and torque value in the Z direction:**

\[
F_z = \frac{G}{2} = 3371N
\]  
\[
M_z = \frac{1}{2}(P - F_c, h) = 18904N\text{cm}
\]

\(P\)—— the electricity power of the wind turbine when the wind grade is 8(W).

\(w\)—— the angular velocity of the wind turbine(rad/s)

(2) The calculation of largest stress of the bolt. With 10 bolts under tension \(F_z\), average assigned to each bolt is

\[
F_1 = \frac{F_z}{10} = 337.1N
\]

Axial force generated by the gravity of 10 bolts makes 5 bolts side by side along the \(x\) axis are squeezed, and the other 5 bolts are by pulling force [5].

\[
F_2 = \frac{M_z}{10l} = \frac{6742}{10 \times 0.08} = 8427.5N
\]  

\(l\)—— vertical distance from the bolt to \(y\) axis (m)

Pulling force generated by \(M_z\), let the bolts in the positive direction of \(y\) axis tensile, and bolts in the negative direction of \(y\) axis under pressure. In this moment the biggest bolt stress under tension is

\[
F_1' = R_{max} = \frac{9881 \times 0.2}{4 \times (0.1^2 + 0.2^2)} = 9881N
\]

\(r\)—— the vertical distance from the bolt number \(i\) to \(x\) axis (m)

To sum up, the bolt bearing the biggest tension is in the top right corner in figure 16, force of which is

\[
F_1' = F_1 + F_2' + F_3' = 18645.6N
\]

(3) To determine the prestressing force of each bolt. Prestressing force generated by the friction force needs to overcome \(F_x\) and \(F_y\) and \(M_z\). The solving process of prestressing force \(F'\) to overcome \(F_x\) and \(F_y\) is as follows

\[
f(10F_1') - \frac{C_m}{C_B + C_m}F_x \geq K_f \sqrt{F_x^2 + F_y^2}
\]

\(f\) is joint friction coefficient. \(f = 0.5\). \(\frac{C_m}{C_B + C_m} = 0.7\).

\(K_f\) is safety factor. \(K_f = 1\). Put them into the above formula, the result can be calculated.

\[
F'_1 \geq 970.7
\]

The computation formula of prestressing force overcoming the \(M_z\) is as follows

\[
F'_2 = \frac{K_fM_z}{\sum_{i=1}^{10} d_i}
\]

\(d_i\) is the distance from the bolt number \(i\) to the origin.

The result of the calculations is as follows

\[
F'_2 = 29083N
\]

To sum up, we can calculate the total bolts prestressing force [7].

\[
F' = F'_1 + F'_2 = 30053.7N
\]

(4) The calculation of the bolt diameter. The force \(F_{max}\) of the bolt by biggest stress is

\[
F_{max} = F' + \frac{C_B}{C_m + C_m}F
\]

To \(F'\) and \(F\), considering the influence of the \(F_1\), lose one when we are calculating the influence of gravity. Put relative stiffness of bolts, namely \(\frac{c_g}{c_g + c_m} = 0.3\), in the above formula, and we can calculate result, namely \(F_{max} = 35546.25N\). This paper chooses a magnitude of 8.8 bolts. Preliminary selection is the bolt M24. In the case of changing load, safety factor is taken for \(S = 6.8\). The allowable stress of the bolt is
\[
[\sigma] = \frac{\sigma_0}{S} = \frac{800 \times 0.8}{6.8} = 94.18\text{Mpa} \quad (17)
\]

The bolt diameter is
\[
d = \sqrt{\frac{4 \times 1.3 F_{\text{max}}}{\pi [\sigma]}} = 24.994\text{mm} \quad (18)
\]

In fact, 8 grade wind will adjust the guide plate, so we can select M26.

4. The mechanical simulation analysis of the blades

The results of simulation for blades are shown in figure 17 and figure 18 [8] [9].

According to the figure 17, the part bearing the biggest stress is the root of bolt hole, the maximum stress on the framework is 282.45Mpa, and the biggest stress on the FRP blade is 451Mpa. Therefore, we need to increase the thickness of the root of the glass fiber reinforced plastic blade where the bolt holes are with steel and then link the root to the vertical shaft disk. This can avoid damaging glass fiber reinforced plastic material around the bolts [10].

![Figure 17. Stress results](image1)

Figure 17. Stress results

According to figure 18, we know that the maximal displacement is in the lower right corner of the blade. This is the result of joint action of the pressure of the wind and its own gravity. The maximal displacement value is 34.4mm.

![Figure 18. Results of the displacement](image2)

Figure 18. Results of the displacement

Frame material is selected into 2018 aluminum alloy, the yield limit of which is 317.104 Mpa and tension strength limit is 420.507 Mpa. The yield limit of glass fiber reinforced plastic material is 551.485 Mpa and tension strength limit is 861.695 Mpa. Comparing with the results of simulation, materials selected by this paper and the design of the bolt holes are reasonable [11].

5. Conclusion

The vertical shaft wind turbine blades structure and blade frame materials are optimized to improve in this paper. We designed size of the blade root bolts through the calculation. Through optimization of the integral structure blades this article makes the blade structure tend to be lightweight and simplified, and makes mechanical simulation analysis of optimized blade structure with the software Solidworks Simulation. We have verified that the result after the optimization is reasonable and feasible.

References