Study on the structural strength of MW scale wind turbine’s main shaft

Sheng Lu¹ᵃ, Zhixiang Chen²ᵇ, Qinkai Zhou³ᶜ, Yang Zhao⁴ᵈ⁺
¹State Key Laboratory for Strength and Vibration of Mechanical Structures Xi’an Jiaotong University, Xi’an, China
²School of Advanced Manufacturing Engineering Chongqing University of Posts and Telecommunications Chongqing, China
³School of Information and Electronics Beijing Institute of Technology Beijing, China
⁴School of Advanced Manufacturing Engineering, Chongqing University of Posts and Telecommunications, Chongqing, China
[^e-mail: Vincent.kkchen@foxmail.com, ^d⁺e-mail: zhaoyang@cqupt.edu.cn]

Abstract—The main shaft of the wind turbine is an important supporting component of the wind turbine and its performance directly affects the safety of turbine. The structural strength of the main shaft under the 7 ultimate load conditions is checked according to the working load data. The results show that the maximum working stress 182 MPa occurred in Mx (max) load conditions is less than the permissible stress. For the maximum limit working conditions, this paper proposes a method to change the diameter of the end of the main shaft to reduce the working stress. The results show that there is an approximate linear relationship between the diameter of the inner hole at the end of the main shaft and the maximum working stress. On the premise of keeping the quality unchanged, the maximum working stress can be effectively reduced by reducing the diameter of the inner hole, which improves the structural strength of the casting main shaft.

1. INTRODUCTION

The manufacturing of wind turbine occupies an important position in the whole wind power industry chain. The main components of wind turbine, such as main shaft, blade and other transmission components, account for about 70% of the cost. Therefore, improving the performance of the main components and further reducing the cost is the premise of realizing the rapid development of wind power. Wind turbine’s main shaft system is one of the important driving parts connected rotor and gear box. Once the main shaft is damaged, it cannot be removed for maintenance. And according to the wind power industry standard, its designed service life is more than 20 years [1]. The casting main shaft with low production cost has a good application prospect. Therefore, in the design process, it is particularly necessary to check and calculate the structural strength of the casting main shaft.
2. Static strength analysis

2.1. Overview of wind turbine main shaft
In this paper, the main shaft of a MW scale doubly-fed wind generator set is taken as the research object. And SolidWorks software is used to build geometric models of the cast main shaft [2], and it is shown in Figure 1.

![Figure 1. Geometric model of main shaft of wind turbine.](image)

2.2. Finite element meshing
In order to improve the calculation efficiency, the structures such as bolt holes, rounds and threads on the main shaft are simplified. In Hypermesh14.0, a 20-node second-order solid element SOLID186 was used to mesh [3]. The mesh was properly encrypted in key parts of the main axis such as transition fillets and shoulders. And we can get that the number of finite element meshes is 1126637 and the number of nodes is 827108. The finite element model of main shaft system is shown in Figure 2.

![Figure 2. Finite element model of casting main shaft of wind turbine.](image)

2.3. Material properties
The material of the main shaft of the wind turbine is QT400, and its material properties are shown in Table 1.

| Component   | Material | Young's modulus (GPa) | Poisson's ratio | Density (kg·m⁻³) | Yield Strength (MPa) |
|-------------|----------|-----------------------|-----------------|-------------------|----------------------|
| Main-shaft  | QT400    | 169                   | 0.28            | 7200              | 220                  |

2.4. Boundary conditions and loads

2.4.1. Load boundary conditions: The loads in the static analysis of the main shaft include the weight of 56t and the load from the hub fixed coordinate system [4]. The hub coordinate system and the physical meaning of it is shown in Figure 3. And ultimate load of wind turbine main shaft under 7 groups of working conditions are shown in Table 2.
TABLE 2. ULTIMATE LOAD OF WIND TURBINE MAIN SHAFT UNDER 7 GROUPS OF WORKING CONDITIONS.

| Load  | $M_x$ (kNm) | $M_y$ (kNm) | $M_z$ (kNm) | $M_{yz}$ (kNm) | $F_x$ (kN) | $F_y$ (kN) | $F_z$ (kN) | $F_{yz}$ (kN) |
|-------|-------------|-------------|-------------|---------------|------------|------------|------------|---------------|
| $M_x$ | max         | 6935        | -2534       | 786           | 2653       | 135        | -12        | -1352         | 1352         |
|       | min         | -3212       | -3533       | -1337         | 3778       | 220        | 74         | -1325         | 1327         |
| $M_y$ | max         | 3605        | 12739       | -3506         | 13213      | 344        | -165       | -1061         | 1074         |
|       | min         | 883         | -14474      | -2254         | 14649      | -275       | 118        | -1232         | 1238         |
| $M_z$ | max         | 1954        | -15         | 12421         | 12421      | 179        | -50        | -1037         | 1039         |
|       | min         | 4413        | 2174        | -10721        | 10940      | 341        | 9.7        | -1057         | 1057         |
| $M_{yz}$ | max     | 890         | -14451      | -2518         | 14669      | -269       | 119        | -1231         | 12364        |

2.4.2. Constrained boundary conditions: According to the wind turbine structure and the actual working conditions, the bottom plane of the main frame is bolted to the bearing seat, so it is simplified as a fixed constraint. The contact settings between components of the main shaft system are shown in Table III.

TABLE 3. CONTACT SETTINGS FOR SPINDLE SYSTEM.

| Target         | Contact          | Contact type   | Friction coefficient |
|----------------|------------------|----------------|----------------------|
| Hub            | Main shaft       | Bonded         | -                    |
| Distance ring  | Main shaft       | Bonded         | -                    |
| Bearing        | Distance ring    | Standard       | 0.2                  |
| Distance ring  | Main shaft       | Bonded         | -                    |
| Bearing        | Main shaft       | Bonded         | -                    |
| Bearing        | bearing seat     | Bonded         | -                    |
2.5. Material properties

According to the finite element model established above, the strength of the cast main shaft under 16 groups of limit load conditions was checked with software ANSYS [5]. The maximum stress occurred in Mx (max) maximum load conditions, and the location of maximum stress is shown in Figure 4. The main shaft of this unit adopts ductile iron material QT400, and the yield limit of the material $\sigma_y$ is equal to 220MPa. According to the requirements of strength analysis in the German Lloyd (GL) certification specification, the local material safety factor $\gamma_m$ of the metal components in all load conditions groups is 1.1 [6], so the permissible stress of the casting main shaft material is:

$$[\sigma] = \frac{\sigma_y}{\gamma_m} = 200\text{MPa}$$  \hspace{1cm} (1)

The maximum stress obtained by calculation is within the permissible stress range, so the cast main shaft meets the requirement of static strength.

![Figure 4. Stress distribution of main shaft under Mx (max) condition before improvement.](image)

$$\sigma_{\text{max}} = 70.006d + 157.35$$  \hspace{1cm} (2)

$$M_{\text{total}} = m_0 + m_{\text{increase}} = -7027.2d + 23500$$  \hspace{1cm} (3)

![Figure 5. The relation diagram of equivalent stress, mass and inner diameter of main shaft tail end.](image)
From the static strength analysis results in Figure 5, we know that the middle section of the main shaft stress is low, can reduce the mass of the section of the main shaft, to ensure the quality of the same. Similarly, there is a linear relationship between the maximum stress and mass of the main shaft in the middle section, and the fitted curve is shown in Figure 6, And the expressions were as follows:

\[ \sigma_{\text{max}} = 0.7518m_{\text{reduced}} + 47.596 \]  
\[ \sigma_{\text{max}} = -0.0097m_{\text{increased}} + 181.62 \]

If we want the mass of the spindle to be the same as the original model, we have \( m_{\text{increased}} = m_{\text{reduced}} \).

With simultaneous equations (2) ~ (5), we can obtain the optimal diameter of the inner hole at the end of the main shaft to be 0.163 m. After the main shaft is modified, the static strength analysis results are shown in Figure 7. And the modified main shaft still meets the requirement of static strength.

4. CONCLUSIONS
In this paper, the finite element model of the main shaft of the wind turbine is established, and 7 groups of limit working conditions are checked. When the limit load Mx (max) is applied on the main shaft, the maximum equivalent stress of the spindle is approximately linear with the inner diameter of end of main shaft. On the premise of not changing the quality requirements, by properly reducing the inner diameter of the tail of the main shaft, the maximum stress value of the main shaft can be reduced. And the local strength of the main shaft is improved.
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