Finite element model of bolt looseness of wind turbine tower

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Abstract. Flange bolt looseness is one of the common problems of wind turbine tower, and is the main factor leading to the collapse of wind turbine tower. In this paper, based on ANSYS Based on the finite element analysis method of workbench, the local finite element vibration analysis model of tower drum is established and verified by experiments. Based on this model, the influence of bolt looseness number, wind strength and wind direction on the phase difference between the upper and lower flange plates is studied. The results show that the flange plate with certain bolt looseness ratio is at the top and bottom. The absolute value of the phase difference between the plates is obviously larger than that when the bolts are tightened. Therefore, the phase difference between the upper and lower flanges can be used as the basis for judging the looseness of the bolts in the tower flange.

1. Introduction

In recent years, with the proposal of sustainable development policies, China’s wind power industry has developed rapidly and has now become the world’s largest wind power generation capacity and the fastest growing market [1]. As of 2019, the domestic installed wind power capacity is about 221GW, which has one third of the world’s wind power capacity[2,3]. However, wind turbine collapse accidents frequently occur in China and around the world [4-6]. In these collapse accidents, the loosening of the wind turbine tower bolts is a major cause. In China the domestic research on wind turbines mainly focuses on the research of its aerodynamic performance [7,8]. There are few researches in the field of detection and monitoring of the bolt connection status of wind turbine towers in China or abroad [9-11].

The loosening of the tower flange bolts will cause the connection of the upper and lower flanges to become loose. Due to the uneven stress on the flanges, deformation and fracture are prone to occur at the loose position, resulting in a decrease in the stability of the tower. When the wind turbine fails, the tower is more likely to collapse. It can be seen that the bolt condition monitoring is helpful to prevent the wind turbine from collapsing. Zhao Jianjun et al. [12] designed a system composed of high-speed AD sampling module, FPGA system module and PC host computer to determine the phase difference of the vibration functions of two adjacent workpieces, thereby judging the connection status of the workpieces. He Xianlong et al. [13] conducted a large number of tests on 6 towers with loose flange bolts, and found that even if a small number of bolts were loosened, the phase difference was obviously abrupt, and the first-order phase difference was obtained. Nowadays, the method of
detecting bolt looseness is mainly to judge the torque manually, which is a heavy workload, time-consuming and laborious.

This article introduces a phase difference detection method. First, use ANSYS finite element software to model and simulate the flange model, and design and build a flange model experimental platform to verify the feasibility of the method. On this basis, complete modeling of the wind turbine tower is based on the sub-model. The phase difference variation law of the flange under different bolt loosening conditions is studied.

2. Model establishment and verification

Taking a certain bolt connection plane as the dividing line, the upper part is regarded as a whole, and the lower part is regarded as a whole. If the bolts are loosened, it can be simplified as the whole caused by adding a structural sloshing overall load to the structure subjected to the environmental load. Motion, the structure motion equation can be expressed as

\[ M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F''(t) + F'(t) \]  

In the formula, \( M, C \) and \( K \) are the mass, damping and restoring force (stiffness) coefficients of the single degree of freedom system respectively; \( F'(t) \) is the wind-induced excitation, \( F''(t) \) is the upper structure sloshing process, the upper structure acts on the lower part. The overall sloshing load.

When the structure is excited by the external simple harmonic \( x(t) = A\cos(\omega t) \), Faltinsen et al. [14] treated the overall sloshing load as:

\[ F'(t) = \frac{F_a}{A}\cos(\omega t - \varphi) \]  

Among them: \( \varphi \) is the phase difference of the sloshing overall load lagging the structure motion, and \( \omega \) is the original frequency of the harmonic excitation. The formula (2) can be transformed into:

\[ F'(t) = \frac{F_a}{A}\cos(\varphi)\dot{x}(t) - \frac{F_a}{A\omega}\sin(\varphi)\ddot{x}(t) \]  

Putting (3) into the structural motion equation (1), we can get:

\[ M\ddot{x}(t) + \left[ C + \frac{F_a}{A\omega}\sin(\varphi) \right]\dot{x}(t) + \left[ K - \frac{F_a}{A}\cos(\varphi) \right]x(t) = F''(t) \]  

It can be seen from the equation of motion after deformation that the effect of the overall sloshing load can be added to the original damping and restoring force (stiffness) coefficients of the structure motion, so that:

\[ C_s = \frac{F_a}{A\omega}\sin(\varphi), \quad K_s = \frac{F_a}{A}\cos(\varphi) \]  

It can be seen from equation (5) that the size of the upper sloshing additional damping \( C_s \) and the additional restoring force (stiffness) coefficient \( K_s \) is determined by the overall upper sloshing load amplitude \( F_a \) and the phase difference \( \varphi \). Therefore, the magnitude of \( F_a \) and \( \varphi \) can be used to determine the tower performs status identification and fault diagnosis.

3. Model establishment and verification

In order to preliminarily verify whether the phase difference between the upper and lower flanges is sensitive to bolt loosening, this paper uses ANSYS finite element software to take the middle and lower tower of a 2MW wind turbine as the object, and compare the phase difference between the upper and lower flanges of the tower when the bolts are loose perform analysis. The geometry of the model is shown in Figure 1(a), and the simulation experiment is performed when the number of loose bolts is 10 (20 in total), that is, the loosening rate is 50%.
In order to verify the model, a test bench as shown in Figure 1(b) was set up in the laboratory, and the flange connection bolts were M16 grade 9.9 high-strength bolts. Use SP1631A type function signal generator to output voltage signal. The voltage signal generates 200Hz excitation frequency at the upper flange position through JKZ-1 type vibration exciter. YZ-6 magnetoelectric vibration speed sensor is used to collect signals and early warning. A data acquisition system developed and written with USB-6251 Ni data acquisition card and C# language is used to acquire signals. The acquisition frequency of the acquisition card is set to 4096 Hz and the sampling length is 4096.

Table 1. Number of loose bolts and phase difference

| Number of loose bolts | Measuring phase difference (degrees) | Simulation phase difference (degrees) | Relative error(%) |
|-----------------------|--------------------------------------|---------------------------------------|-------------------|
| 5                     | 39                                   | 38                                    | 2.56              |
| 10                    | 63                                   | 59                                    | 6.35              |
| 15                    | 92                                   | 85                                    | 7.61              |
| 20                    | 152                                  | 138                                   | 9.21              |

The data measured in each group of experiments are averaged and rounded, and then the data measured in the experiment are compared with the simulation results, as shown in Table 1. It can be seen from Table 1 that when 5 bolts are loose (25% loose), the phase difference is about 39°, and there is a more obvious phase difference. When 10 bolts are loose (50% loose), the phase difference is about 63 °, if all the bolts are loose, the phase difference will increase by 152°. The simulation results of the model are in good agreement with the experimental results, and the maximum error does not exceed 10%, indicating the correctness of the model. The phase difference obtained by the model simulation is relatively small relative to the experimental value. The main reasons should be: 1. The model adopts the beam connection method, the bolt connection is too tight, and the contact stiffness between the thread and the flange is relatively large. 2. When the monitoring point is far away from the loosening center position, the phase difference decays too fast, resulting in a smaller phase difference when the mean value of the phase difference is used as the characteristic value.
4. Full tower model analysis

4.1. Geometry
The entire tower structure has a height of 77m and a bottom diameter of 4.2m. It consists of 32 drums. The average wall thickness of the drum is 22mm. 104 M59 bolts are evenly distributed on the 100mm thick lower flange, 90mm thick. The middle flange is arranged with 108 M51 bolts, and the 70mm thick upper flange is evenly distributed with 98 M48 bolts. In order to reduce the calculation amount, the whole wall structure adopts shell elements, and bolts are replaced by beam elements, as shown in Figure 2.

![Figure 2. Tower model and grid](image)

4.2. Implementation of the sub-model method
The sub-model is a method to study the local part based on the global model. This method can improve the analysis accuracy on the basis of the constant or even reduced number of grids. At present, there are many sub-model application researches in China. In this example, the global model of the tower is directly changed, the processing speed is slow and the solution accuracy is also low, so the sub-model method is considered to analyze part of the structure.

First, you need to run the global model to get a rougher analysis result. The second step is to cut out the local model from the global model. There is no clear judgment basis to ensure that the cutting boundary is correct when establishing the sub-model, and the sub-model method is based on Saint-Venant's theorem [15], and the cutting boundary needs to be far enough away Focus on the center, so you need to determine from the sub-model results whether the model you built is correct. The third step is to use the condition of the corresponding position of the global model as the boundary condition of the sub-model cutting boundary. Finally, the sub-model is analyzed.

The sub-model is selected as the part circled in red in Figure 3, which is located at the lower flange of the tower. The specific structure is shown in Figure 3. The sub-model has 17,518 nodes and 14233 elements.
Figure 3. Sub-model and grid

In the case of ensuring the accuracy of the model, the thread structure is omitted from the model, and the flange structure is encrypted. The number of grid cells divided is 28694, the yield strength of the model material is 250MPa, and the density is 7850Kg/m3. In this paper, the beam element node coupling method [16] is used to apply distal contact between the bolt and the flange simplified as the beam element, and the beam element radius is kept consistent with the bolt radius.

5. The simulation scheme

When no bolts are loosened. In order to facilitate the display of the bolt loose position, the bolts are numbered in clockwise order, as shown in Figure 4.

Figure 4. Sub-model bolt number

In the following simulation process, the two variables of bolt looseness and wind strength are mainly considered to study and analyze the feasibility of the phase difference detection method on the tower, as well as the change of phase difference between the upper and lower flange plates when these two variables change. The loosening of bolts can be divided into four conditions: no loosening and loosening 26, 52, 78 and 104, which are 25%, 50%, 75% and 100% respectively. In order to simplify the process, direct pressure is applied to wind load, and the basic wind pressure can be calculated according to Bernoulli equation:

\[ w_0 = \frac{1}{2} \rho v^2 \]  

Where: \( w_0 \) is the basic wind pressure converted from wind speed, kPa; \( \rho \) is the air density, t/m\(^3\); \( v \) is the maximum wind speed, m/s.

Within a certain accuracy range, from the perspective of simplifying calculations, it is generally believed that air density varies with latitude and altitude. For this reason, the air density can also be approximated by formula (7) according to the local altitude \( z \), m:

\[ \rho = 0.0125e^{-0.0001z} \]  

Therefore, the basic wind pressure calculation formula becomes:

\[ w_0 = \frac{1}{2} \times 0.0125e^{-0.0001z} \times v^2 \]  

The altitude \( z \) is 1000m, and the simulation conditions are shown in Table 2.
Table 2. Simulation conditions

| Condition | Number of loose bolts | Wind speed (m/s) | Wind pressure (Pa) |
|-----------|-----------------------|------------------|-------------------|
| 1         | 0                     | 4                | 90                |
| 2         | 26                    | 4                | 90                |
| 3         | 26                    | 25               | 3700              |
| 4         | 52                    | 5                | 90                |
| 5         | 104                   | 4                | 90                |
| 6         | 104                   | 25               | 3700              |

6. Result analysis
When no bolts are loosened and the tower is at a wind speed of 5m/s, first use Ansys Workbench software to calculate the natural frequency value of the bolt connection sub-model, as shown in Table 3. The simulation uses transverse sinusoidal excitation, and the excitation frequency is 380Hz.

Table 3. Natural frequencies of each order of the model

| Natural frequency /Hz | 1st stage | 2nd stage | 3rd stage |
|-----------------------|-----------|-----------|-----------|
| 382.24                | 382.24    | 391.22    |

Table 4. Setting of excitation frequency of upper flange

| Linear | 0Hz | 380Hz | 20 |
|--------|-----|-------|----|

Figure 4 is the frequency curve under this condition, and the phase at this time is shown in Figure 6.

When 26 bolts are loose, the phase of the monitoring point is shown in Figure 7, and the frequency-amplitude curve at this time is shown in Figure 8.

Figure 5. Frequency curve

Figure 6. Phase diagram
Through the finite element simulation, the average value of the phase difference under various conditions is taken as the characteristic value in this case, and the simulation data is summarized in Table 5.

Table 5. Summary of phase difference

| Condition | Number of loose bolts | Wind speed | Average phase difference (degree) |
|-----------|-----------------------|------------|----------------------------------|
| 1         | 0                     | 5          | 0                                |
| 2         | 26                    | 5          | 34                               |
| 3         | 26                    | 20         | 34                               |
| 4         | 52                    | 5          | 51                               |
| 5         | 104                   | 5          | 90                               |
| 6         | 104                   | 20         | 90                               |

It can be seen from Table 5 that when the bolt is loosened, the phase of the monitoring point changes more or less. The phase difference of the monitoring point close to the center of the loosening can reach 108°, and the phase difference shows a trend of attenuation to the surroundings. The phase difference of the monitoring point close to the non-loose bolt is only 7.2°, and the attenuation in the middle position is faster. It can be seen from Table 6 that when the wind speed increases, the average phase difference of the tower flange does not change significantly, and the phase difference change is not sensitive to the wind intensity.

When the wind speed is 5m/s, 23 bolts are loose and the loose position is downwind, the average value of the phase difference changes less than when it is in the upwind position. Compared with when the loosening position is in the upwind position, the phase difference of most monitoring points remains unchanged, and the change is greater near the loosening center, while the phase difference at the boundary is basically unchanged.

7. Conclusion

In this paper, the finite element analysis method based on Ansys Workbench is used to establish a local finite element vibration analysis model of the tower and verify it through experiments. Based on this, an analysis model of the entire tower is established, and the bolt loosening on the flange is studied. The influence of quantity, wind intensity and wind direction on the phase difference between the upper and lower flanges, the following conclusions are drawn:

1. The absolute value of the phase difference between the upper and lower plates of the flange plate with a certain percentage of bolt looseness is significantly larger than that of the bolt tightening.
Therefore, the phase difference between the upper and lower flanges can be used as the basis for judging the looseness of the flange bolts.

2. When the amount of looseness is the same, the phase difference method is easier to detect when the interval is loose than when the looseness is continuous, which is beneficial to the phase difference detection.

3. In the simulation, it is found that when the wind is stable, the wind intensity and wind direction have little effect on the phase difference. The next step is to consider loading dynamic loads, and then study the phase difference changes caused by bolt loosening under dynamic wind loads.

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