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Detection of tower bolt looseness and its influence of wind level

Enjun Wu[1], Hongjun Chen[1], Weida Liao[1], Wenfeng Qu[1], Chong Huo[1], Zhengzhao Liang[1], Xiangzhao Huang[1], Zhenrong Li[1], Hang Li[1], Bin He[1], and Tao Yang[2]

[1]State Power Investment Group Xuwen Wind Power Co., Ltd., Zhanjiang 524000, Guangdong Province, China
[2]Huazhong University of Science and Technology, Wuhan 430074, Hubei Province, China

Abstract. Taking the wind turbine tower as the research object, based on the finite element software, a simplified beam-shell hybrid element model was first established; through the simulation, the phase difference between the loose position and the unloose position was compared to verify the feasibility of the phase difference detection method; Secondly, the influence of the number of loose bolts, the position of loosening, and the magnitude of the wind force on the phase of the flange bolt connection structure and the response characteristics of the system are analyzed. The research results show that the number of loose bolts, the position of loosening, and the magnitude of the wind have certain effects on the phase difference and response characteristics of the flange. With the increase in the number of loose bolts, the connection stiffness of the bolt connection continues to decrease. The linear characteristic is enhanced; the closer the loosening is to the excitation force loading position, the greater the detected phase difference; as the wind increases, the phase of the upper flange of the tower changes, and the phase of the lower flange remains unchanged, and the wind is on the flange The disc connection strength has little effect.

1 Introduction

The wind turbine includes five parts: blades, hub, main shaft, nacelle and tower, among which all the weight of the wind turbine is borne by the tower. In general, the height of a large wind turbine energy exceeds. 50m, wherein the tower accounts for the total weight amount than the value exceeds. 50% [1], the disc flange connection force at the very poor. And because the tower is in a windy environment for a long time, it will produce alternately falling vortices around, making the tower generate periodic pulsating pressure in the cross-flow and downstream directions [2]. As a results, the fastening bolts are easy to loosen, and in severe cases, it will resulting in wind turbine collapse accident. Uneven settlement or looseness of the foundation, abnormal inclination and bending of the tower, and fatigue failure of the tower flange bolts are three common reasons that endanger the safety of the tower[3]. The issue of uneven foundations is also involved in the construction field, and the relevant literature is relatively abundant. [4,5], there are also many studies on the inclination of the tower [6].

It can be seen from the literature that there are few studies on the phase difference of flange bolt connections, and there are fewer studies on the effect of wind on the loosening of wind turbine tower bolts. Most of the research focuses on the modal analysis and structure of the tower. Analysis of mechanical properties [7,8]. In this paper, finite element analysis is used to study the phase of bolt loosening and the strength of flange bolt connection through different amounts of loosening, different positions and different wind speeds, which provide a basis for monitoring the loosening of tower bolts.

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

$$M\ddot{x}(t)+Cx(t)+Kx(t)=F^{w}(t)+F^{s}(t) \tag{1}$$

In the formula, M, C and K are the mass, damping and restoring force (stiffness) coefficients of the single degree of freedom system respectively; $F^w(t)$ is the wind-induced excitation, F^s(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. [9] treated the overall sloshing load as:

$$F^{s}(t)=F_{a}\cos(\omega t-\varphi) \tag{2}$$

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

* Corresponding author: hust_yt@hust.edu.cn

$$F^s(t)=\frac{F_a}{A}\cos(\varphi)x(t)-\frac{F_a}{A\omega}\sin(\varphi)\dot{x}(t) \tag{3}$$

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

$$M\ddot{x}(t)+\left[C+\frac{F_a}{A\omega}sin(\varphi)\right]\dot{x}(t)+\left[K-\frac{F_a}{A}cos(\varphi)\right]x(t)=F^w(t) \tag{4}$$

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:

$$C_s=\frac{F_a}{A\omega}\sin(\varphi),\ K_s=\frac{F_a}{A}\cos(\varphi) \tag{5}$$

3 Model establishment

The tower model is established based on ANSYS software. It is composed of 4 short cones separated by 3 flanges. The material parameters are set as follows: Elastic modulus E =210 GPa, Poisson's ratio v=0.3 and density ρ= 7800 kg/m^3.

Table 1. Tower structure size (m)

		describe	value
height			77.26
base		diameter	4.2
Lower flange plate	Upper flange	diameter	4.047
	Lower flange	diameter	4.047
Middle flange plate	Upper flange	diameter	3.821
	Lower flange	diameter	3.821
Upper flange plate	Upper flange	diameter	3.482
	Lower flange	diameter	3.482
Top		diameter	3

This article mainly studies the characteristics of flange fastening bolts in different situations. Because the tower model is built according to the actual size, its large size makes the calculation efficiency low. In order to effectively use computer resources and improve the calculation efficiency, only the tower is selected. The bottom flange is the research object, and the beam - shell hybrid element finite element model of the flange is established, as shown in Fig. 1.

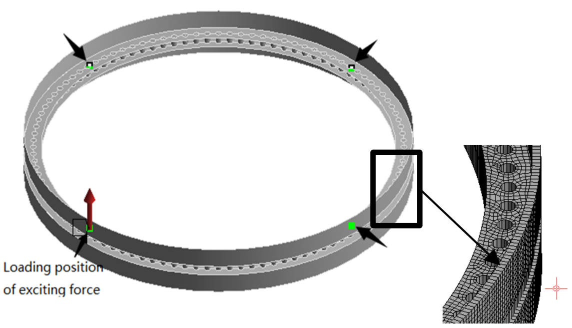

Fig. 1. Flange structure diagram

4 Response characteristics of wind turbine flange

This section analyzes the structure bolted flange along the upper flange uniform. 4 transverse strips excitation response characteristic in the member. Firstly, the phase difference and system response characteristics of different bolt numbers are solved; secondly, the phase change of bolts at different positions under the same loosening number is studied; finally, the influence of different wind levels on flange phase and system response characteristics is analyzed. Uniformly distributed along the flange. 4 transverse excitation, loading position as in Fig. 2.

Table 2. Upper flange excitation setting

Frequency Spacing	Range Minimum	Range Maximum	Solution Intervars
Linear	30Hz	50Hz	20

4.1. Analysis of the number and location of loosening

This section analyzes the system response curve of the tower flange under several conditions and the influence of the amount and position of the looseness on the phase difference between the upper and lower flanges. In the simulation, the when the number is smaller than the loose bolts 7. when a phase difference in stability 180°; If loose exceeds 7 months time, the upper and lower flanges substantially no retardation; and when number exceeds loose. 10 after one between the upper and lower flanges and retardation occurs and increases with an increase in loose. 10 loosened, the three different positions of their position for the research phase, one is the excitation force is applied in the center position, a second position of the exciting force is loaded loose edges, the third species is loosening of the bolts away from the loading position, as in Fig. 2 shown.

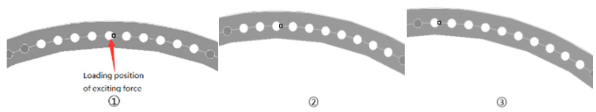

Fig. 2. loose positions

Fig. 2 at a first loosening the phase difference between the upper and lower flanges have 86.4°, The second loose, the phase difference is reduced 54°, The third case, the phase difference continues to decrease to 43.2 °, therefore, the closer the loosening center is to the place where the excitation force is loaded, the higher the detection accuracy. Because the place where the excitation force is loaded is where the load is applied, the surrounding structure is more sensitive to forced vibration.

In order to verify the model, a test bench as shown in Fig. 3 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.

Fig. 3. Actual object

Table 3. Number of loose bolts and phase difference

Number of loose bolts	Measuring phase difference (degrees)
5	39
10	63
15	92
20	152

Fig. 4 is a loose bolts were 25%, 50% and 100%, the system frequency response curve at different excitation. Under the same excitation frequency, as the bolt looseness increases, the nonlinearity of the system response gradually increases. This is because the greater the number of looseness, the smaller the stiffness of the bolt connection interface and the stiffness fluctuations. Under the same excitation frequency, the amplitude of the doubled frequency will increase with the increase of the loosening quantity. This is because the overall stiffness of the system decreases with the increase of the loosening quantity.

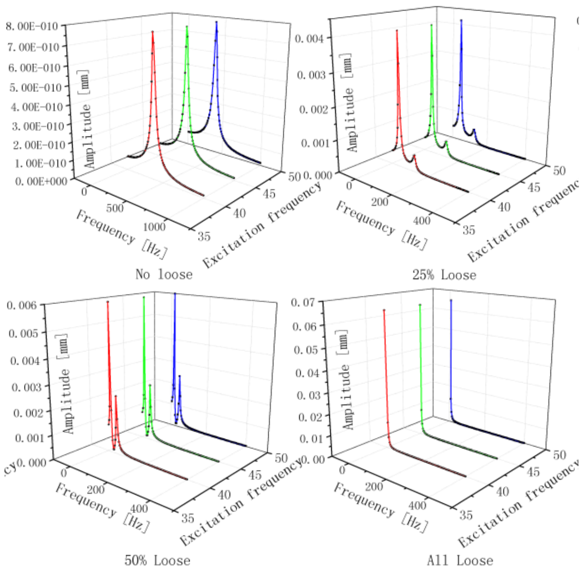

Fig. 4. Three dimensional spectrum of different bolt looseness

4.2. Influence of wind level

Wind-induced vibration is divided into buffeting, vortex-induced vibration and self-excited vibration according to the nature of response. Vortex- induced vibration mainly occurs in slender structures. In nature, there are many places where two sides of the object will periodically fall off the two sides of the object, the rotation direction is opposite, the regular arrangement of the double row line vortex, these vortices form the Karman vortex street after nonlinear action, make the structure surface pressure change periodically. Wind turbine tower barrel due perennial strong wind farm is located, and often height / diameter is large, easy to form Karman vortex street, this section of the study 25% of loose bolts, different wind velocity at the phase difference change.

Roscoe (Roshko) Experimental study shows that the frequency of vortex shedding, the vortex shedding frequency f and the flow velocity u is proportional, with the cylinder diameter D is inversely proportional

$$f = \frac{Sr \times u}{D} \tag{6}$$

Wherein Sr is described unsteady vortex shedding number of Strouhal, is an important characteristic parameter of the fluid flow around the relationship between it and the Reynolds number is approximately as

$$Sr = \frac{fD}{u} = 0.198\left(1 - \frac{19.7}{Re}\right) \tag{7}$$

The calculation formula of Reynolds number is:

$$Re = \frac{uD}{v} \tag{8}$$

u is the wind speed, m/s; D is the diameter of the lower flange of the tower, m; ν is the air kinematic viscosity, Pa·s.

In this paper, D = 4.047m, and the air kinematic viscosity at 20 ℃ is 1.81×10 -5 Pa·s

Tower surface pressure calculation formula [10]

$$w_0 = \frac{1}{2} \times 0.0125e^{-0.0001z} \times v^2 \tag{9}$$

In the formula: w_0 is the basic wind pressure converted from wind speed, kPa; z is the altitude above sea level, taken as 1000m; v is the maximum wind speed, m/s.

From the formula 7 can be seen that when Re is large enough, Sr more constant approaches 0.198, in fact, when Re > 1 000 when the Strouhal number is approximately constant, in order to simplify the calculation, taking Sr = 0.198.

Table 4. Calculation results

wind speed （m·s^{-1}）	Re	Preasure （MPa）	Vortex frequency （Hz）	phase difference
13.9-17.1	3.82E+06	1.65E-03	0.971831	82.8
17.2-20.7	4.63E+06	2.42E-03	1.227576	86.4
20.8-24.4	5.46E+06	3.37E-03	1.446998	90
24.5-28.4	6.35E+06	4.56E-03	1.754386	97.2
28.5-32.6	7.29E+06	6.01E-03	2.054114	104.4
32.7-36.9	8.25E+06	7.70E-03	2.461824	111.6
37-41.4	9.26E+06	9.69E-03	2.864344	118.8

41.5-46.1	1.03E+07	1.20E-02	3.189523	126
46.2-50.9	1.14E+07	1.47E-02	3.521621	129.6
51-56	1.25E+07	1.77E-02	4.012849	136.8

In harmonic response analysis, the loading frequency is the vortex frequency in Table 4, and the amplitude is sinusoidal excitation of wall pressure in Table 4. Record the corresponding relationship between wind level and wind speed and the Reynolds number, wall pressure and phase difference obtained in Table 4.

It can be seen directly from the table that as the wind increases, the phase difference when the tower bolts are loosened will increase, making the bolt looseness easier to detect. Because the lower flange is closer to the bottom of the tower, the fixed sub-model is closer to the lower flange, and the bolt connection strength is not as good as the drum. Under the influence of wind, the upper flange shakes more severely and the node displacement is greater. And during the simulation process, the phase of the monitoring point at the lower flange also remains unchanged.

Apply an inward sinusoidal excitation $P = P_0\sin(2\pi ft)$ on the surface of the tower, where P_0 is the amplitude of the exciting force, f is the frequency of the exciting force, and t is the loading time. The values of each parameter are: P_0 take table 3 surface pressure of, F taken in table 4 in the vortex off frequency. Fig. 5 (a) shows the displacement versus time curve of a node of the lower flange in 6 cycles under a wind of magnitude 7 and the fast Fourier transform is performed on it to obtain figure 5 (b). Similarly, the sum of wind of 1 and 1 is obtained. Fig. 5 (c) and (d) of the flange connection strength under the wind of level 11 and 14.

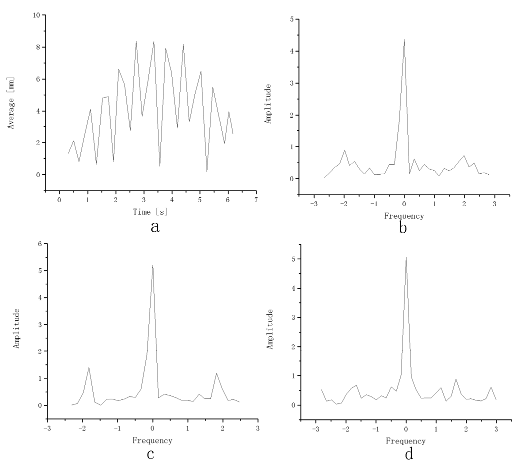

Fig. 5. Displacement-time curve and FFT change

From Fig. 5 (a), (b), (c), it can be seen that under three different wind speeds, the connection strength of the lower flange did not change significantly.

5 Conclusion

In this paper, the finite element analysis method based on Ansys Workbench is used to establish a This article first studies the feasibility of the phase difference detection method on the tower.

With the increase in the number of loose bolts, the system response curve nonlinearity of the growing, large fluctuations stiffness, rigidity of the connection bolt decreasing position, when the quantity exceeds loose bolts. When one, the upper and lower flanges between phase with the loosening of the increase in the growing of.

The closer the bolt loose position is to the load excitation position, the stronger the vibration and the stronger the response, which leads to the increase of the phase difference. Under the same loosening condition, the greater the wind, the higher the phase difference between the upper and lower flanges will increase accordingly, which is conducive to detecting the bolt looseness. It can be seen from the fft curve that the wind has little effect on the strength of the flange connection. It should be noted that resonance occurs when the vortex shedding frequency is equal to the natural frequency.

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