Wind-induced fatigue analysis of wind turbine steel tower

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Abstract. In this paper, a wind turbine tower with a hub height of 60m is taken as the research object, and its wind-induced fatigue analysis is carried out. First, the general method of wind-induced fatigue analysis of the wind turbine tower is given. The maximum stress time history curve of the tower is calculated by the time history analysis method. The stress amplitude, the mean value and the cycle times of the stress time history are counted by the rain-flow counting method. Finally, the fatigue life of tower is calculated by linear damage theory. According to the study, the fatigue life of the wind turbine is greater than that of the design service life, and it can meet the requirements of the design. The influence of wind load on the fatigue damage of the tower is different from the wind load of different wind speed and wind direction.

1. Introduction

Wind turbines are susceptible to fatigue damage due to the long-term wind load dynamics. In recent years, domestic and foreign scholars have studied wind-induced fatigue damage of wind turbine tower structures. The time domain analysis method based on rain-flow counting method and Miner criterion is the main method of structural wind induced fatigue analysis, which calculates the stress time history at key points by numerical time history analysis based on finite element model. The fatigue damage of the structure is evaluated by rain-flow counting method and linear cumulative damage Miner criterion. Ke Shitang et al [1] applied this method to consider the influence of tower-blade coupling effect, and calculated the wind-induced fatigue life of a 5MW wind turbine blade and tower; Xu Guoyang [2] established a finite element model of the tower for the 1.5MW horizontal-axis wind turbine, and calculated the load spectrum and fatigue life of the tower by using the time domain analysis method. Liu Shengxiang [3] studied the dynamic response and fatigue damage of offshore wind turbine towers under the combined action of aerodynamic loads and sea wave loads. Since the flange joint is usually the weak part of the tower, the fatigue fracture damage of the flange bolt is one of the main damages of the tower. Therefore, some scholars have used the time domain analysis method to study the wind-induced fatigue damage of the wind turbine tower connecting bolt [4-6]. Although the time domain analysis method has high precision, it requires a lot of computational workload. In order to overcome this deficiency, a time-frequency hybrid method based on frequency domain analysis and rain-flow counting method have proposed in recent years to calculate wind-induced fatigue damage of structures. Firstly, the power spectrum density function of key stress is calculated by frequency domain method based on random vibration analysis, then the stress time history is generated by harmonic
superposition method, and the fatigue damage of structure is evaluated by rain-flow counting method and linear cumulative damage criterion. Some scholars use this method to analyze the fatigue of wind turbine towers. Yeter [8] used the commercial software Ansys to establish a finite element model of a 2MW three-legged offshore wind turbine tower. The random vibration analysis module is used to calculate the transfer function and power spectral density function of the four key points. The stress time-history curve is generated by inverse FFT transform, and the fatigue damage of the wind turbine is evaluated according to the linear cumulative damage criterion; Tibaldi et al. [9] used the multi-body dynamics-based HAWCStab software to obtain multi-dimensional first-order linear ordinary differential equations of motion for wind turbines. The stationary random vibration analysis method is used to calculate the power spectral density function of key stresses. Then the fatigue damage evaluation of the structure is carried out, and compared with the calculation results based on nonlinear finite element time domain analysis, the reliability of the adopted method is verified.

At present, although some researches have been carried out on wind-induced fatigue damage of wind turbine tower structures, it is still insufficient compared with wind-induced fatigue research of blades. This article is based on the Abaqus software platform. the finite element model of the wind turbine tower structure is established. The dynamic response of a wind turbine tower with a height of 60m is calculated under the wind load of different speeds and directions, and the time history curve of the key point stress is obtained. The wind-induced fatigue life of the tower is evaluated by time domain analysis method based on rain-flow counting method and Miner criterion.

2. Wind load formation

The wind load on the tower during the operation of the wind turbine includes the wind load transmitted by the blade to the tower and the wind load received by the tower itself. These two loads are calculated by equations (1) and (2) respectively [10].

\[
F = \frac{1}{2} C_P \rho V^2 (x, y, z, t) \pi R^2
\]

\[
F = \frac{1}{2} C_D \rho V^2 (x, y, z, t) A
\]

where, \( C_P \) is the utilization factor of wind energy; \( R \) is the blade radius of wind turbine; \( \rho \) is the density of air; \( V(x, y, z, t) \) is the transient wind speed; \( A \) is the vertical projection area of the tower; \( C_D \) is the drag coefficient of tower.

The transient wind speed \( V(x, y, z, t) \) equals the sum of the average wind speed \( \bar{V}(z) \) and the fluctuating wind speed \( v(x, y, z, t) \).

\[
V(x, y, z, t) = \bar{V}(z) + v(x, y, z, t)
\]

The value of the average wind speed \( \bar{V}(z) \) varies with the height, and the wind speed at a height of 10 m is used as the reference wind speed, which varies exponentially with height[11].

\[
\bar{V}(z) = \bar{V}_{10} \left( \frac{z}{10} \right)^\alpha
\]

where, \( \bar{V}_{10} \) is the average wind speed at standard height (10m); \( z \) is the point height from the ground; \( \alpha \) is the index of ground roughness.
The fluctuating wind speed portion can be simulated with a set of zero-means Gaussian stationary stochastic processes. Using the Kaimal spectrum provided in EN61400-1[12], and considering the spatial correlation of fluctuating wind speed at any two points in space. A set of fluctuating wind speeds can be generated by harmonic superposition. Substituting them into equations (1) and (2) gives the wind load time history of the tower.

3. Probability distribution of wind direction and wind speed
In the natural world, the wind speed and wind direction have a certain randomness. The probability of each wind direction is different and the wind speed is also uncertain. The extent of fatigue damage depends on the speed of the wind. However, the probability of a large wind speed is generally less than the probability of a small wind in actual cases. Therefore, the influence of the wind speed and wind direction probability distribution on wind-induced fatigue must be considered in the actual fatigue damage of the wind turbine tower. In general, the probability of occurrence of different average wind speeds is subject to the Weibull distribution, whose probability density function [14] is formula (5).

$$P(v) = \frac{K}{A} \left(\frac{v}{A}\right)^{K-1} \exp\left[-\left(\frac{v}{A}\right)^{K}\right]$$

(5)

where, $K$ is the distribution shape parameter of Weibull; $A$ is the characteristic life parameter; $v$ is the average of wind.

For a region, the wind may come from any direction, which have different effects on the calculation of wind-induced fatigue of the wind turbine tower. The probability of each wind direction appearing in the wind field can be determined according to the wind direction rose diagram of the area.

4. Wind-induced fatigue calculation method
Considering the randomness of wind direction and wind speed, the fatigue damage of the tower under wind load with different wind direction and wind speed in $T$ time is the formula (6).

$$D_{i,j} = D(\theta_i, \bar{v}_j) \cdot p(\theta_i) \cdot p(\bar{v}_j)$$

(6)

where, $D(\theta_i, \bar{v}_j)$ is the fatigue damage of the tower under the direction $\theta_i$ of wind load $\bar{v}_j$; $p(\theta_i)$ is the probability of direction $\theta_i$, and can be determined by the wind direction rose diagram of the region; $p(\bar{v}_j)$ is the probability of the average wind speed $\bar{v}_j$ is calculated by equation (5).

The total fatigue damage of the tower to the wind load of different wind direction and wind speed is the formula (7).

$$D = \sum_{i,j=1}^{m,n} D_{i,j}$$

(7)

In the calculation of equation (6), the key is the determination of $D(\theta_i, \bar{v}_j)$, which can be calculated by Miner linear fatigue cumulative damage criterion.

$$D(\theta_i, \bar{v}_j) = \sum_{k=1}^{m} \frac{n_k}{N_k}$$

(8)
where, \( m \) is the number of load blocks; \( n_k \) is the actual number of cycles in which the stress amplitude is \( \Delta \sigma_k \) under the \( \vec{V}_j \)-class wind load in the \( \theta_i \) direction, and \( N_k \) is the number of cycles in which the fatigue failure occurs when the stress amplitude is \( \Delta \sigma_k \).

In the formula (8), the \( n_k \) can be obtained by statistical calculation of the stress time history of the key points by the rain-flow counting method, and the \( N_k \) can be obtained by using the fatigue curve of the tower material. The general expression of the fatigue curve is the formula (9).

\[
N_k = C \cdot \Delta \sigma_k^{-\beta}
\]  

(9)

where, \( \beta \), \( C \) are material constants, which can be obtained by fatigue testing of materials and related design specifications.

The formula (9) is used to express the law of symmetric cyclically variable stress, which is applicable only when the average value of the stress applied to the structure is zero, but the average value of the stress on the structure is not equal to zero in general, which also affects the fatigue damage of the structure. Therefore, it is necessary to convert the stress amplitude and use the Goodman conversion formula to process the stress amplitude. The conversion formula is as follows [15].

\[
\Delta \sigma_a = \Delta \sigma_{a0} \left(1 - \frac{\sigma_m}{\sigma_u}\right)
\]

(10)

where, \( \Delta \sigma_a \) is the stress amplitude when the average stress is not equal to zero; \( \Delta \sigma_{a0} \) is the stress amplitude when the average stress is equal to zero; \( \sigma_m \) is the average stress; \( \sigma_u \) is the ultimate strength of the material.

In order to simplify the calculation, the variable amplitude stress cycle can usually be converted into a constant amplitude stress cycle. According to the principle of damage equivalent, the conversion formula used is as follows [16].

\[
\Delta \sigma = \left[ \sum_{k=1}^{m} n_k (\Delta \sigma_k)^{\beta} \right]^{1/\beta}
\]

(11)

Using equations (8) - (11), the calculation can be simplified to

\[
D(\theta_i, \vec{v}_j) = \frac{(\Delta \sigma_j)^{\beta} \sum_{k=1}^{m} n_k}{C}
\]

(12)

5. Case analysis

The wind turbine hub of this study is 60m high. The tower is a cone-shaped steel thin shell. The outer diameter is linearly reduced from 3.8m at the bottom to 2.3m at the top. The thickness of the shell is 35mm at the whole height. The steel elastic modulus is 210GPa, the Poisson's ratio is 0.2, and the density is 7850 kg/m3. According to the Steel Structure Design Code [16], the type of tower steel in the fatigue calculation is 2 types. According to the specifications, the accurate value of \( \beta \) and \( C \) can be found. The blade cross-section is a hollow rectangular section with a blade cross-section height of 2 m, a width of 0.8 m, a length of 30 m and a blade thickness of 15 mm. The blade has a modulus of elasticity of 65GPa, a Poisson's ratio of 0.2, and a density of 2100 kg/m3. The mass of the cabin is
50000kg; the mass of the hub is 20,000kg, and the deviation distance between the tower and the blade is 5m.

The finite element model for this wind turbine tower was created using ABAQUS software. The cylindrical tower is simulated via thin shell element S4R. The blade is simulated via elastic element Beam31. To model the interaction between the blade and the tower, the blade and tower are connected via a beam element with large stiffness. The cabin and hub are simulated via concentrated mass elements placed at the tower top and the blade connection center. The finite element model for the structure is shown in figure 1.

![Wind turbine finite element model](image1)

According to the probability statistics of the wind speed at 10m height in the area where the wind turbine tower is located, the Weibull distribution model in equation (7) K takes 1.88, A takes 3.92. The average wind speed is divided into 10 grades, which are 1 m/s, 2 m/s, 3 m/s, 4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s and 10 m/s, and the probability distribution map of each grade wind speed is shown in figure 2. The wind direction is divided into eight directions: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. The distribution of each wind direction is shown in the wind direction rose diagram shown in figure 3. According to the wind speed probability map and the wind direction rose diagram, the
probability of different wind speeds and wind directions during the design and use of the wind turbine tower can be obtained as shown in Table 1. Considering the arrangement of different wind speeds and different wind directions, a total of 80 power calculations for wind turbines are required. Figure 4 shows the point of action of the wind load, where the load at the top of the tower is the wind load transmitted by the blade to the tower.

**Figure 3. Wind rose diagram**

**Figure 4. The point of action of the wind load**

| Wind direction | 0° | 45° | 90° | 135° | 180° | 225° | 270° | 315° |
|----------------|----|-----|-----|------|------|------|------|------|
| v=1m/s         | 0.466 | 0.593 | 1.312 | 3.213 | 2.230 | 1.082 | 0.719 | 0.385 |
| v=2m/s         | 0.746 | 0.949 | 2.099 | 5.141 | 3.568 | 1.731 | 1.150 | 0.616 |
| v=3m/s         | 0.863 | 1.097 | 2.427 | 5.944 | 4.125 | 2.001 | 1.330 | 0.712 |
| v=4m/s         | 0.956 | 1.216 | 2.689 | 6.587 | 4.571 | 2.218 | 1.474 | 0.789 |
| v=5m/s         | 0.793 | 1.008 | 2.230 | 5.462 | 3.791 | 1.839 | 1.222 | 0.654 |
| v=6m/s         | 0.420 | 0.534 | 1.181 | 2.892 | 2.007 | 0.974 | 0.647 | 0.346 |
| v=7m/s         | 0.233 | 0.297 | 0.656 | 1.607 | 1.115 | 0.541 | 0.360 | 0.192 |
| v=8m/s         | 0.117 | 0.148 | 0.328 | 0.803 | 0.557 | 0.270 | 0.180 | 0.096 |
| v=9m/s         | 0.047 | 0.059 | 0.131 | 0.321 | 0.223 | 0.108 | 0.072 | 0.038 |
| v=10m/s        | 0.023 | 0.030 | 0.066 | 0.161 | 0.111 | 0.054 | 0.036 | 0.019 |

Under the wind load, the wind turbine tower is prone to fatigue damage mainly in the vicinity of the bottom section near the door, the thickness change of the tower and the stress concentration. Through the calculation and analysis, the fatigue life analysis is carried out by selecting the maximum stress near the bottom of the tower door. The dynamic time history analysis method is used to calculate the Mises stress time history of the point under different wind speed and wind direction combination. When the wind direction is 0 degree, the wind speed is 8m/s. The Mises stress time history curve at this point is shown in figure 5. By inputting the stress time history into the rain-flow counting method programmed by MATLAB software, the average stress, stress amplitude and corresponding number of cycles of the stress time history under the working condition can be counted (as shown in figure 6).
Using the wind-induced fatigue calculation method in the previous section, the fatigue damage of the maximum stress point near the bottom of the tower is calculated within 20 years of service life (look at Table 2 and Table 3). It can be seen from the table that the cumulative fatigue damage value is 0.4 in the 20-year service life, and the actual fatigue life is $20 \times \frac{1}{0.4} = 50$ years. The wind loads of different wind speeds and wind directions have different effects on the fatigue damage of the tower. Due to the random distribution of wind speed and wind direction, the fatigue damage of the wind turbine tower increases first and then decreases with the increase of wind speed. When the wind speed is 7 m/s, the fatigue damage of the wind turbine tower is the largest. The wind load of different wind direction has different effects on the fatigue damage of the tower. The fatigue damage caused by the wind direction at 135 degrees is larger than other wind directions.

Table 2. Fatigue damage at the bottom of the wind turbine tower at the maximum wind force of 0 degrees

| Wind speed (m/s) | Equivalent stress amplitude (MPa) | Actual number of cycles | Theoretical cycle number | Probability of occurrence (%) | Fatigue damage |
|-----------------|----------------------------------|-------------------------|--------------------------|-------------------------------|---------------|
| 1               | 1.97                             | 1.29x10^9               | 5.68x10^{13}             | 0.466                         | 1.06x10^-7    |
| 2               | 3.29                             | 8.50x10^8               | 7.36x10^{12}             | 0.746                         | 8.62x10^-7    |
| 3               | 7.60                             | 8.76x10^8               | 2.58x10^{13}             | 0.863                         | 2.93x10^-4    |
| 4               | 13.20                            | 9.41x10^8               | 2.84x10^{10}             | 0.956                         | 3.17x10^-4    |
| 5               | 18.99                            | 1.20x10^9               | 6.62x10^9                | 0.793                         | 1.44x10^-3    |
6. Conclusion

This paper introduces the general method of wind-induced fatigue analysis of wind turbine tower. The dynamic response of a wind turbine tower with a height of 60m is calculated under the wind load of different speeds and directions, and the time history curve of the key point stress is obtained. Finally, the fatigue life of the tower is evaluated according to the linear cumulative damage theory. The calculation and analysis show that:

(1) In the variable amplitude stress spectrum at different wind speeds, when the stress amplitude is small, the number of cycles is large, and the stress spectrum is mainly concentrated on the diagonal of the average stress and amplitude.

(2) The design life of the wind turbine is 20 years, and the actual wind-induced fatigue analysis result is 50 years, which is greater than its design value and meets the design requirements. In the wind-induced fatigue analysis, the stress of the tower is mainly concentrated near the bottom of the tower, which is a key node in wind-induced fatigue analysis.

(3) Due to the randomness of wind speed and wind direction, the fatigue damage of the wind turbine tower increases first and then decreases with the increase of wind speed. When the wind speed is 7m/s and the wind direction is 135 degrees, the fatigue damage of the wind turbine tower is the largest.

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Table 3. Fatigue damage under wind load with different wind speed and wind direction

| Wind speed m/s | 0°   | 45°  | 90°  | 135° | 180° | 225° | 270° | 315° | Sum  |
|----------------|------|------|------|------|------|------|------|------|------|
| 1              | 1.06×10^{-7} | 1.33×10^{-7} | 2.96×10^{-8} | 7.34×10^{-9} | 5.03×10^{-7} | 2.41×10^{-7} | 1.63×10^{-7} | 8.94×10^{-8} | 2.27×10^{-6} |
| 2              | 8.62×10^{-7} | 2.21×10^{-7} | 2.68×10^{-7} | 1.61×10^{-7} | 3.44×10^{-8} | 2.40×10^{-7} | 1.79×10^{-7} | 2.50×10^{-6} | 3.00×10^{-5} |
| 3              | 2.93×10^{-8} | 5.33×10^{-8} | 3.49×10^{-8} | 1.86×10^{-8} | 7.67×10^{-9} | 3.70×10^{-8} | 5.26×10^{-8} | 8.65×10^{-8} | 5.04×10^{-4} |
| 4              | 3.17×10^{-8} | 1.09×10^{-8} | 1.44×10^{-8} | 1.09×10^{-8} | 3.22×10^{-9} | 4.08×10^{-8} | 6.04×10^{-8} | 8.49×10^{-8} | 3.84×10^{-3} |
| 5              | 1.44×10^{-8} | 5.16×10^{-9} | 8.76×10^{-9} | 7.52×10^{-9} | 1.40×10^{-8} | 1.72×10^{-8} | 2.73×10^{-8} | 3.74×10^{-8} | 1.99×10^{-2} |
| 6              | 3.03×10^{-8} | 1.24×10^{-8} | 2.74×10^{-9} | 2.38×10^{-9} | 4.54×10^{-9} | 3.67×10^{-8} | 5.86×10^{-8} | 8.39×10^{-8} | 5.33×10^{-1} |
| 7              | 6.01×10^{-8} | 2.59×10^{-8} | 7.16×10^{-9} | 6.14×10^{-9} | 1.16×10^{-8} | 7.03×10^{-9} | 1.15×10^{-8} | 7.14×10^{-9} | 1.14×10^{-1} |
| 8              | 4.29×10^{-8} | 4.13×10^{-8} | 8.66×10^{-9} | 5.19×10^{-9} | 1.29×10^{-8} | 9.03×10^{-9} | 9.33×10^{-9} | 5.94×10^{-9} | 1.06×10^{-1} |
| 9              | 2.94×10^{-8} | 1.73×10^{-8} | 5.44×10^{-9} | 2.61×10^{-9} | 8.67×10^{-9} | 4.47×10^{-9} | 4.35×10^{-9} | 2.69×10^{-9} | 5.64×10^{-2} |
| 10             | 2.12×10^{-8} | 1.29×10^{-8} | 4.22×10^{-9} | 2.01×10^{-9} | 7.33×10^{-9} | 3.39×10^{-9} | 4.78×10^{-9} | 1.64×10^{-9} | 4.49×10^{-2} |
| Total          | 2.02×10^{-2} | 1.16×10^{-2} | 2.93×10^{-2} | 1.92×10^{-1} | 4.69×10^{-2} | 2.98×10^{-2} | 3.92×10^{-2} | 3.05×10^{-2} | 4.00×10^{-1} |

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