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Vibration analysis of tower of onshore wind turbine

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Abstract: *The tower of onshore wind turbine is the supporting part of the whole machine, and its service is related to the safety state of the whole machine. In order to ensure the safety of the whole machine operation, the vibration analysis of the tower is needed. This paper takes the onshore wind turbine tower as the research object, establishes the 3D model of the onshore wind turbine tower, and uses Ansys Workbench software to carry out the finite element modal analysis of the tower. According to the results of finite element modal analysis, the measured scheme is designed to test the tower, and the measured data onto tower vibration is analyzed by power spectrum. The analysis results can provide some reference to vibration monitoring of wind turbine tower.*

Keywords: *Wind turbine; Tower; Modal analysis; Vibration test*

1. Introduction

Wind power generation is one of the important clean energy sources. Wind turbine is a mechanical and electrical equipment that converts wind energy into electricity directly. Its complex operating conditions and harsh environment bring great challenges to the safe operation of wind turbine. At present, the service time of a large number of onshore wind turbines in the wind power industry is close to or more than half of the design service life. As a supporting structure, the tower safety and reliability is the premise of the safe operation of the whole machine. Therefore, the service quality of the tower has been widely concerned.

When the external load is consistent with the natural frequency of the tower, resonance will cause damage to the tower[0]. Meanwhile, the vibration characteristics of the tower, such as top displacement and first-order natural frequency and other parameters, can provide references for the health monitoring of the tower structure[0]. The modal analysis of the tower structure can realize the vibration state of the tower through the response data of the tower structure, and provide suggestions for operation and maintenance. The modal analysis methods of large structure mainly include theoretical modal analysis, experimental modal analysis and operational modal analysis. Theoretical modal analysis is mainly based on theoretical calculation, but it is difficult to accurately describe the physical parameters and boundary conditions, and can not fully reproduce the complex external load and fatigue damage of wind turbines, but it has great reference significance for the analysis of measured data. Experimental modal analysis can obtain structural dynamic response through experiments, but it is not convenient to apply to large structures. Operational modal analysis is an ideal method to analyze tower vibration by using structural response generated by natural excitation.

In this paper, the land wind turbine tower is taken as the research object, the finite element model is established and the theoretical modal analysis of the tower is carried out, and the natural frequency and modal shape of the tower are mastered by the modal analysis results. Based on the theoretical modal analysis results, the measured scheme is selected to conduct the operational modal analysis of the tower, and the modal analysis results is verified, which can provide reference for tower vibration monitoring of wind turbines.

2. Finite element modal analysis of tower

The relevant parameters of 1.5MW wind turbine tower were taken as references to establish the finite element model[0], and the finite element calculation software Ansys WorkBench was used for theoretical modal analysis. As shown in Figure 1, the finite element model is composed of four components, which are foundation ring, lower tower, middle tower and upper tower, with an overall height of 70m. The tower is made of Q345 structural steel with density of 7850 kg/m^3 and Young's modulus of 2.06×105MPa. The diameter decreases gradually from bottom to top, with the maximum diameter of 4.2m and the minimum

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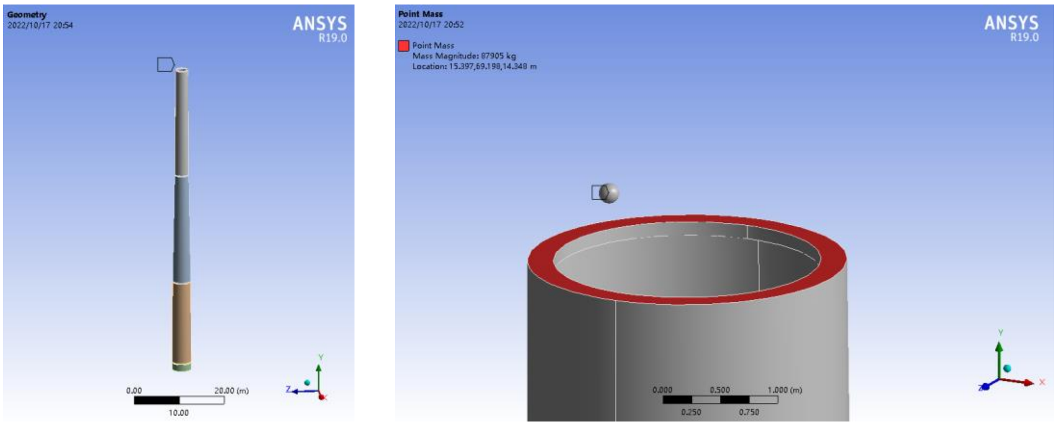
diameter of 2.7m; The maximum wall thickness of the tower is 22mm and the minimum wall thickness is 16mm. The contact of flange surface is set as binding. All components at the top of the tower, such as blades, hub, engine room, etc., adopt a mass point instead. The mass of the mass point is set as the sum of components 87905kg, and the position of the mass point is the position of the centroid of the top member. A fixed constraint was set on the bottom surface of foundation ring to simulate the stable foundation without settlement and inclination. The grid is divided into 917410 nodes and 478083 cells. Figure 2 shows the first three vibration modes of the tower, and the modal vibration frequency is shown in Table 1.



(a) Tower geometry mode *(b) Mass point action model*

Figure 1: Finite element model

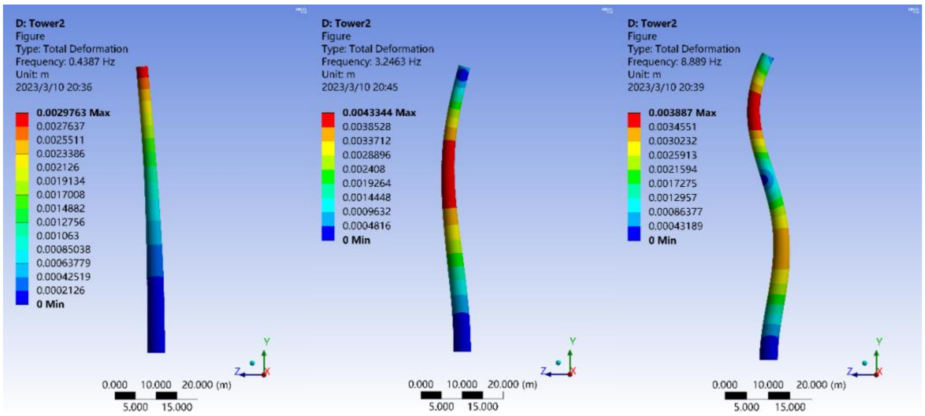


Figure 2: Tower modal analysis.

Table 1: Tower modal frequency.

Modal order of tower	Frequency value (Hz)	Effective modal mass
First order bending modal in X direction	0.4387	61.5%
First order bending modal in Z direction	0.4374	61.46%
Second order bending modal in X direction	3.2463	16.74%
Second order bending modal in Z direction	3.2524	15.82%
Third order bending modal in X direction	8.889	23.23%
Third order bending modal in X direction	9.2882	6.48%

According to the modal analysis results, the first-order vibration frequency of the tower is about 0.43Hz. Since the tower structure is a symmetrical cone, the first-order natural frequencies in the two directions are basically equal. The results of the tower vibration modes show that the maximum displacement point of the first-order mode mode is located at the top of the tower, and the maximum displacement point of the second-order mode mode is 1/2 of the tower height. The maximum displacement position of each order for modal shapes is the most suitable measuring point position. Considering the effective modal masses proportion and construction difficulty, the vibration monitoring and measuring point can choose the first three orders for the tower vibration displacement maximum point position.

Due to mass unbalance and aerodynamic unbalance, the wind turbine of a wind generator will generate an exciting frequency related to the speed. Usually, the exciting frequency generated by such frequency is called 1P, and its frequency doubling is referred to in the same way[0]. Taking a three-blade wind turbine as an example, its vibration frequency may be concentrated on the wind turbine rotation frequency 1P, blade over-paddle frequency 3P and its frequency doubling rate.

Based on the modal analysis results of the wind turbine tower and the conversion to wind turbine speed, the Campbell diagram of the wind turbine tower is drawn by considering only the natural frequency of the tower and the excited frequency of the wind turbine, as shown in Figure 3.

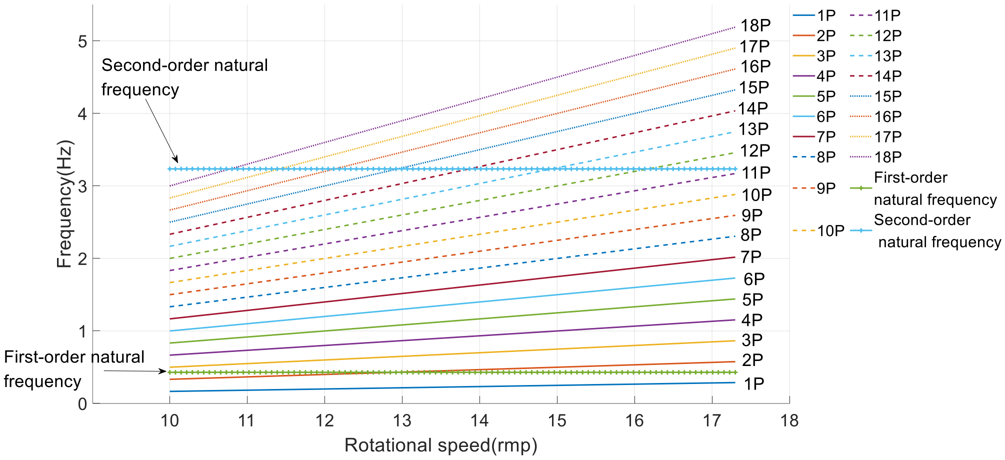


Figure 3: Campbell diagram of tower vibration

The figure shows that the first-order natural vibration frequency is between 1P and 3P, and only intersects with 2P excitation frequency, while the second-order natural frequency intersects with 12P, 15P, 18P and other excitation frequencies. Since the tower vibration energy is mainly concentrated on the low frequency band, it is necessary to pay more attention to the possibility of resonance for the first-order natural frequency and wind wheel rotation frequency 1P and 3P.

3. Tower vibration test and operational modal analysis

Vibration monitoring is a kind of holistic monitoring. It is a cost-effective monitoring method to analyze the state of the tower by using vibration signals stimulated by environmental excitation through a limited number of measuring points. The quality of monitoring signal is restricted by the location of measuring points. Suitable measuring points can provide high signal-to-noise ratio signals for monitoring work. The difficulty of construction and the cost of monitoring to make the number of measuring points in practical engineering very limited.

3.1. Vibration test system

The vibration test data came from a mountain wind farm, and the capacity of the test wind generator was 1.5MW. The monitoring data parameter was vibration displacement, and the measurement point was located on the tower wall of the top platform of the tower, close to the contact position of the engine room and the tower. The signal acquisition system is shown in Figure 4. The vibration displacement data acquisition sensor is installed at the top of the tower. As the position of the maximum first-order modal response, this measurement point can collect vibration data onto the maximum extent. The data acquisition instrument is arranged at the bottom of the tower to facilitate data transmission. Since the tower is a large steel structure, its vibration is mainly low frequency, so the sampling rate is set at 50Hz.

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Figure 4: Test system diagram

3.2. Measured data pre-processing

Dc component is a fixed-value signal in the process of tower vibration signal acquisition. Such errors will lead to misjudgments in signal processing, resulting in a high peak value of 0Hz in the data spectrum diagram. There are two main methods to eliminate DC component: (1) frequency domain de-DC method. The frequency domain signal is obtained by fast Fourier transform from the data, and the data onto 0Hz is set to 0, and then the frequency domain signal is converted back to the time domain signal by fast Fourier inverse transformation. Since the data onto frequency 0 originally belonging to the DC component is eliminated, the DC component is eliminated by restoring the time domain signal. (2) Time domain de-DC method. Dc component is reflected as the change of mean value in time domain signal, so adjusting the mean value of time domain signal to 0 can eliminate DC component and obtain the same Fourier spectrum as that of frequency domain DC removal method. In this paper, the time domain method is used to eliminate the DC component of the signal Compared with eliminating the DC component through frequency domain transformation, this method is also effective and simpler, which is more suitable for real-time monitoring.

The trend component refers to the change of signal mean value caused by the influence of the outside world or the sensor itself in the process of sensor acquisition. The influence of the trend component on vibration signals time-domain waveform is represented as baseline drifts, which is different from that of the DC component on tower vibration signal, which is represented as a fixed value, and the influence of the trend component on signal is a time-varying value. For example, the unstable supply voltage of the sensor causes the mean baseline of the output signal to gradually increase or decrease to time. The influence of this trend term is reflected on the spectrum diagram as the signal energy value of ultra-low frequency region close to 0 frequencies is higher. The elimination of trend item of vibration acceleration and vibration displacement usually uses the method of subtracting trend item fitting data series from original data series. This method can offset most of the influence of trend item on signal analysis. However, due to the fitting accuracy and fitting difficulty of different trend items, the influence of trend item can only be reduced but cannot be completely eliminated theoretically.

The original measured signal is selected, as shown in Figure 5(a). Obvious DC component and trend component can be seen in the figure. The mean value of signal in this section are about 0.0871m, while the trend component shows a gradual decline. The signal after eliminating DC component and trend component through signal preprocessing are shown in Figure 5(b). The mean value of signal after processing is about 0, indicating a more stable signal trend.

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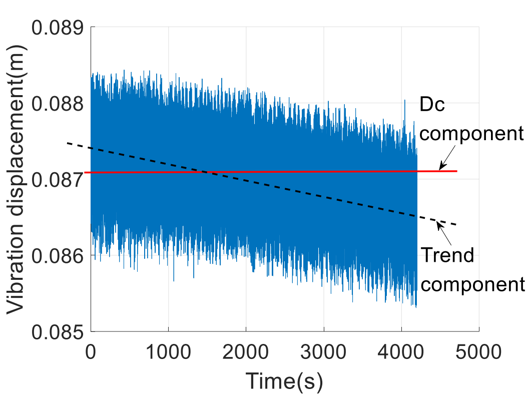
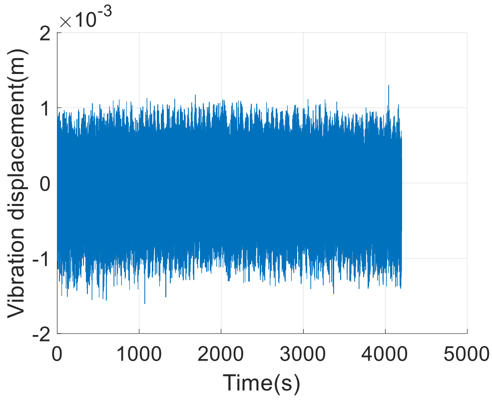


(a) Original signal



(b) The processed signal

Figure 5: Eliminate DC and trend component of signal

3.3. Operational modal analysis

When the natural vibration frequency of wind turbine tower is similar to the harmonic frequency of environmental load or wind turbine rotation, tower resonance will be generated, which will reduce the performance of wind turbine and even lead to shutdown and reduce power generation efficiency[0-0]. According to the finite element analysis results, the first order natural frequency of the tower is about 0.43Hz.Figure6 shows the power spectrum of the measured vibration data onto the tower. The wind turbine rotation frequency of 1P of this model wind turbine corresponds to the frequency band of 0.15-0.288Hz, and the corresponding blade passing through the tower frequency of 3P corresponds to the frequency band of 0.45-0.864Hz. The first order vibration frequency of the tower is the peak point in the figure, and the corresponding frequency is 0.4326Hz, which is close to the natural frequency of the first order tower obtained by the finite element simulation. The error is 1.06%. The error of the main frequency value of the tower vibration obtained by the finite element modal analysis and the vibration frequency picked up by the vibration sensor is small, and it is considered that the signal picked up by the sensor is accurate and effective. It can be used for vibration data analysis and safety monitoring. In order to avoid damage to the tower caused by resonance, the first-order natural frequency of the tower should not overlap with the 1P frequency band or 3P frequency band, and 10% safety margin should be reserved. The first-order natural frequency of the tower is too close to the initial frequency of 3P frequency band, and there is resonance risk. Therefore, the value of the first-order natural frequency should be included in the monitoring range.

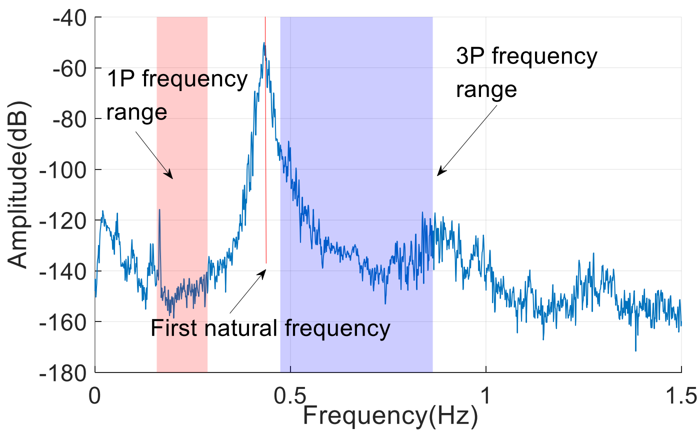


Figure 6: Low frequency tower power spectrum

According to the campell diagram shown in Figure.3, it is known that the 3P excitation frequency of the wind turbine operating at the lowest speed is close to the first-order natural frequency of the tower. The data analysis of the wind turbine operating at low speed is shown in Figure.7. The meaning of the power peak in the figure is that 0.164Hz corresponds to the vibration frequency of 1P wind turbine, 0.43Hz corresponds to the first natural frequency of tower, 0.50Hz corresponds to the 3P frequency, 0.994Hz corresponds to the 6P frequency, 1.330Hz corresponds to the 8P frequency, and 1.647Hz corresponds to the 10P frequency. It is generally believed that for a three-blade wind turbine, the energy generated by wind turbine rotation is concentrated on 1P and 3P frequency. However, the measured data show that even for a three-blade wind turbine, its vibration energy is not completely concentrated on the wind turbine excitation frequency and 3x frequency, but may also be concentrated on 8 or 10x frequency. Because the measuring point is located at the top of the tower and at the second-order mode mode node, it is not sensitive to second-order mode frequency, so there is no peak corresponding to second-order natural frequency in the power module.

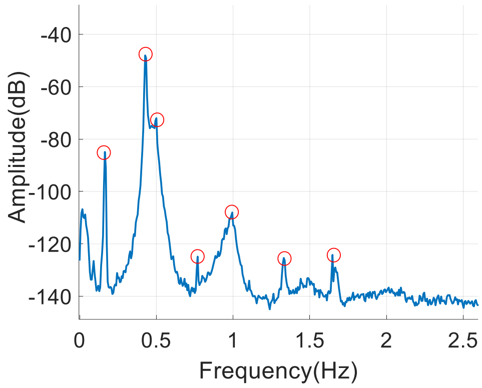


Figure 7: Vibrational displacement power spectral density

As shown in Figure 7, the corresponding frequency of the maximum peak value in the power spectrum is the first-order natural frequency of the tower, and the corresponding frequency point is 0.43Hz, which also indicates that the vibration energy of the tower is concentrated in the low frequency band during the operation of the wind turbine, and in the low frequency band, it is mainly concentrated in the first-order natural frequency, wind wheel rotation excitation frequency and its frequency doubling. As a whole wind turbine, vibration monitoring should not ignore the coupling relationship between the components[9].The first-order natural frequency of the tower is close to the 3P exciting frequency of the lowest speed of the wind turbine. Formula (1) is used to verify whether the first-order natural frequency of the tower has resonance risk.

$$\begin{cases} f_k / f_1 \le 0.95 \\ f_k / f_1 \ge 1.05 \end{cases} \tag{1}$$

Where, f_k is the rotation frequency of the k-order wind wheel, and f_1 is the first-order natural frequency. The calculated vibration frequencies of 1P and 3P wind turbine are 0.383 and 1.163, indicating that there is no resonance risk.

4. Conclusions

In this paper, the tower of land wind turbine is taken as the object, and the finite element modal analysis results show that the first-order bending modal frequency of the tower is about 0.43Hz. Under the condition of uneven mass distribution at the top, the first-order and second-order bending modes of the tower is basically the same as the left-right bending modes. The power spectrum analysis of measured data shows that the modal analysis results of the tower are accurate and reliable. The results of tower vibration test show that the distribution of tower vibration energy in the frequency domain mainly focuses on the first order natural frequency, wind wheel rotation excitation frequency and frequency doubling. The results show that there is no resonance risk to the first-order natural frequency and 1P and 3P frequencies. The conclusion of this paper can provide some reference from vibration safety monitoring of wind turbine tower.

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