Analysis of flutter vibration response of large wind turbine blades under resonant loads

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Abstract: Based on the finite element method, the structural model of large wind turbine blades is established and the natural frequency and natural vibration mode of the structure are studied. The vibration response of the structure under the resonant load is calculated. The displacement amplitude and phase angle at the tip are obtained with frequency. It is found that under the given resonant load conditions, the maximum displacement amplitude and the maximum phase angle at the tip are within the allowable range of the structure, and the structure does not undergo resonance damage. Through the harmonic response vibration analysis of the wind turbine blade, it can provide an effective theoretical basis for the safe design of the blade.

1. Introduction

Wind power generation is a clean, pollution-free way to generate electricity from renewable sources. With the development of wind power industry, the wind resource conditions and service environment of wind turbine will be expanded, and the demand of efficient and reliable utilization of wind resources will lead the development of wind turbine to show a trend of regionalization. In order to ensure the efficient and reliable operation of the wind turbine, the large scale of the single power and space volume of the modern wind turbine will require higher requirements for wind turbine control, condition monitoring and fault warning, which will guide the wind turbine to develop in an intelligent direction [1]. As a blade of an important part of the wind turbine, the regionalized wind turbine necessarily corresponds to a personalized blade to meet diverse natural conditions and working environment. The intelligent wind turbine has corresponding sensing blades to adapt to the intelligent control and intelligent monitoring of the wind turbine.

KIM S W [2] In this study, the structural performance tests, i.e., static tests and dynamic tests of the composite wind turbine blade, were carried out by using the embedded fiber Bragg grating (FBG) sensors. ZHANG Jianhui [3] The experimental investigation on mechanical properties of the glass fiber laminates was carried out. The major parameters of mechanical properties were obtained, and the influence of the fiber direction in the fabric, the testing direction and the prescription factors on the mechanical properties was analyzed. Shuting Wan [4] et al. The effects of wind shear and the tower shadow contribute to periodic fluctuations in the wind speed and aerodynamic torque. TANG You-gang [5] et al. The floating foundation is designed to support a 1.5 MW wind turbine in 30m water
depth. With consideration of the viscous damping of foundation and heave plates, the amplitude-frequency response characteristics of the foundation are studied. Juchuan Dai\[6\] et al. Aiming at the Megawatt (MW) scale wind turbine, a dynamic analysis and simulation method is presented to research blade loads and dynamic characteristics. Caichao Zhu\[7\] et al. A dynamic model of the drive train of a megawatt wind turbine is proposed in which the blades, the hub, the main shaft, and the speed up gearbox are assumed as flexibilities. Taeyoung Kim\[8\] et al. Unsteady turbulent flow characteristics over a two-blade horizontal wind turbine rotor is analyzed using a large-eddy simulation technique.

The blade is one of the most critical components of the wind turbine. The wind wheel composed of the blade and the hub is an energy capture mechanism that converts wind energy into mechanical energy. At the same time, the blade is also the main load-bearing component of the wind turbine, which plays a key role in the safe operation of the entire wind turbine. Therefore, the vibration response analysis of wind turbine blades is analyzed to predict the dynamic response, which can provide an effective theoretical basis for the design, vibration damage and life estimation of wind turbine blades.

2. Theoretical analysis of resonant load

2.1 Equation of motion under resonant load

As long as a set of generalized coordinates \( q_1, q_2, \ldots, q_N \) is used to represent the total kinetic energy \( T \), the total potential energy \( V \) and the total virtual work \( \delta W_{nc} \), the equation of motion of the multi-degree-of-freedom system can be directly derived from the variational form of dynamics, namely the Hamilton principle \[9\]. Expressed in mathematical form as follows:

\[
T = T(q_1, q_2, \ldots, q_N, \dot{q}_1, \dot{q}_2, \ldots, \dot{q}_N) \tag{1}
\]

\[
V = V(q_1, q_2, \ldots, q_N) \tag{2}
\]

\[
\delta W_{nc} = Q_1 \delta q_1 + Q_2 \delta q_2 + \ldots + Q_N \delta q_N \tag{3}
\]

In the formula: \( Q_1, Q_2, \ldots, Q_N \) is a generalized force function corresponding to the coordinate, \( q_1, q_2, \ldots, q_N \), respectively.

The kinetic Hamilton variational representation, the difference between kinetic energy, potential energy, and non-conservative force has zero time variation for any \( t_1 \) to \( t_2 \) time interval:

\[
\int_{t_1}^{t_2} \delta[T(t) - V(t)]dt + \int_{t_1}^{t_2} \delta W_{nc}(t) dt = 0 \tag{4}
\]

Bring equations (1), (2), and (3) into equation (4) and complete the variation to obtain the Lagrange equation of motion:

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial \dot{q}_i} = Q_i \tag{5}
\]

2.2 Approximate analysis of resonant load response

For the general dynamic reaction, once the mode and frequency are determined, the vibration mode superposition analysis of the distributed parameter system is completely equivalent to the vibration mode analysis of the discrete system. The basic operation of the mode superposition analysis is to transform the geometric displacement coordinates into a mode copy or normal coordinates \[10\]. This transformation can be expressed as:

\[
v(x, t) = \sum_{n=1}^{m} \phi_n(x, \gamma_n(t)) \tag{6}
\]

We need to use (6) to form Among a normal variation of the \( N \) coupled equations to obtain \( N \) uncoupled equations:

\[
\ddot{Y}_n(t) + 2\xi_n \omega_n \dot{Y}_n(t) + \omega_n^2 Y_n(t) = P_n(t) / M_n \tag{7}
\]
Among them:  \[ M_n = \phi_n^T m \phi_n ; \quad P_n(t) = \phi_n^T p_n(t) \]

Solving the eigenvalue problem of (7) can obtain the mode shape \( \phi_n \) \((n=1,2,\ldots)\) and the frequency of the response \( \omega_n \). Now, the total response of a multi-degree-of-freedom system can be obtained by solving \( N \) uncoupled mode equations and superimposing their effects:

\[
Y_n(t) = \frac{1}{M_\omega \omega_n} \int_0^t P_n(\tau) \exp \left[ -\xi_n \omega_n (t - \tau) \right] \sin \omega_D (t - \tau) d\tau \tag{8}
\]

3. Establishment of finite element model of wind turbine blade

The geometry of the wind turbine blade is a complex three-dimensional space structure, which is composed of a number of characteristic airfoil curves, each of which has a certain twist angle with respect to the pulping axis. It is difficult to directly use finite element software modeling. This paper uses the blade structure analysis module in the "Blade Design for Windows" CAD software to model and preprocess the blade. The established blade surface skin model file is generated into IGES format and imported into the finite element software ANSYS for mesh division. For the shape of the blade itself and the characteristics of the FRP material, the shell unit is used, and the aerodynamic layout is given along the exhibition direction. Each airfoil section is divided into 13 sections; along the chord direction, the upper and lower skins are divided into 6 different layers according to the structural change result according to the structural design result, and the blade finite element mesh is generated as shown in Figure 1.

![Figure 1](image-url)

Figure 1   Finite element model

4. Numerical calculation and result analysis

4.1 Modal calculation and analysis

The dynamic problem of wind turbine blades is mainly to study resonance and stability. When the frequency of external excitation force is the same as the natural frequency of the system, the system will resonate, and the resonance will cause serious damage to the blades and units of the wind turbine. Therefore, to prevent the occurrence of resonance, the natural frequency of the system should be avoided by the frequency of the external excitation force, and the modal analysis\textsuperscript{10} is the basis and core of the structural dynamics analysis, and the natural frequency of the wind turbine blade can be calculated. Through the finite element calculation, the first 6 natural frequencies and the inherent vibration type are extracted. The results are shown in Table 1 and Figure 2-7:

| Order | First       | Second      | Third       | Fourth      | Fifth       | Sixth       | Seventh     | Eighth      |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Frequency | 1.3467    | 3.0891     | 3.8560     | 7.6663     | 9.2597     | 13.920      | 19.564     | 22.838     |
The numerical solution of the blade waving frequency and the pendulum frequency is compared with the test value and the theoretical value. As shown in Figures 8 and 9, the natural frequency calculated by the numerical comparison with the theoretical value and the test shows that the low-order frequency is highly consistent. The finite element model is built to meet the calculation requirements.

4.2 Calculation and analysis of resonant load
The wind pressure is the pressure of the wind received by the plane perpendicular to the direction of the airflow. The wind pressure is equivalent according to the wind-pressure relationship obtained by the Bernoulli equation and applied to the blade.

The variation of the displacement along the Y direction from the leaf roots at 31.5, 34.5, 37.5m, and 40.5m is shown in (a), (b), (c), and (d). As (a) is shown, at a frequency of 6.95 Hz, the displacement reaches a maximum value of 0.127 m; (b) the graph shows that at a frequency of 6.95 Hz, the displacement reaches a maximum value of -0.114 m; (c) the graph shows that at a frequency of 6.95 Hz, the displacement reaches a maximum value of -0.209 m. (d) the graph shows that at a frequency of 6.95 Hz, the displacement reaches a maximum value of 0.75 m; it can be seen from the change of the overall displacement that the farther away from the blade root, the greater the vibration displacement.
5. Conclusion
Dynamics is an important indicator of wind turbine blade design reference. In this paper, the finite element model of the blade of wind turbine is established according to the related materials, and the vibration response of the blade under random wind load is studied. The equivalent resonant load is applied to the blade and solved by the finite element software ANSYS. The natural characteristics and vibration response of the blade under resonant load are obtained.

1. The first 6 natural frequencies and natural modes of the blade are calculated, and no destructive resonance occurs at the main frequency (0 to 30) Hz.

2. Through the resonance analysis, the variation of the displacement amplitude at different positions of the blade with frequency is obtained, and the maximum response value appears in the low frequency range, and all are within the acceptable range. The vibration characteristics of the structure under the reaction resonance load, find the resonance frequency, avoid the resonance failure of the structure in the design process, and provide a theoretical basis for the rational design and fatigue analysis of the structure.

References
[1] LIU Deshun, DAI Juchuan, HU Yanping, etal.Status and development trends of modern large-scale wind turbines[J].China Mechanical Engineering,2013,24(1):125-135.
[2] KIM S W, KIM E H, RIM M S, etal. Structural performance tests of down scaled composite wind turbine blade using embedded fiber bragg grating sensors[J]. International Journal of Aeronautical and Space Sciences, 2011, 12(4):346-353.
[3] ZHANG Jianhui, YANG Shaochong, SU Shengxi, etal. Experimental investigation on mechanical properties of glass fiber laminates for wind turbine blade[J]. Acta Materiae Compositae Sinica, 2011,28(5):234-239.
[4] Shuting Wan,Lifeng Cheng,Xiaoling Sheng.Numerical analysis of the spatial distribution of equivalent wind speeds in large-scale wind turbines[J].Mechanical Science and Technology.2017,31(2):965-974.
[5] TANG You-gang,SONG Kai,WANG Bin.Experiment Study of Dynamics Response for Wind Turbine System of Floating Foundation[J].China Ocean Eng.2015,29(6):835-846.
[6] Juchuan Dai,Wei Hu,Xiangbin Shen.Load and dynamic characteristic analysis of wind turbine
[6] Flexible blades[J]. Journal of Mechanical Science and Technology. 2017, 31(4): 1569-1580.

[7] Caichao Zhu, Shuang Chen, Hua Iju Liu et al. Dynamic analysis of the drive train of a wind turbine based upon the measured load spectrum[J]. Journal of Mechanical Science and Technology. 2014, 28(6): 2033-2040.

[8] Taeyoung Kim, Donghyun. Large-eddy simulation analysis of turbulent flow over a two-blade horizontal wind turbine rotor[J]. Journal of Mechanical Science and Technology. 2016, 30(11): 4989-4996.

[9] R.W. Clough, J. Penzien. Structural Dynamics[M]. Higher Education Publisher of Beijing, 2006.

[10] Xucheng Wang. Finite Element Method[M]. Tsing-Hua University Publisher of Beijing, 2003.