

Study on Determination Method of Fatigue Testing Load for Wind Turbine Blade

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Abstract. In this paper, the load calculation method of the fatigue test was studied for the wind turbine blade under uniaxial loading. The characteristics of wind load and blade equivalent load were analyzed. The fatigue property and damage theory of blade material were studied. The fatigue load for 2MW blade was calculated by Bladed, and the stress calculated by ANSYS. Goodman modified exponential function S-N curve and linear cumulative damage rule were used to calculate the fatigue load of wind turbine blades. It lays the foundation for the design and experiment of wind turbine blade fatigue loading system.

1. Introduction

As an important component of the wind turbine, the wind turbine blade is subjected to the changing wind load in the actual operation of the wind farm. Because of the bad climate environment and the Long time operation of blade, people pay much attention to wind blade fatigue life [1-2]. The analysis and calculation of the load is the basis for the subsequent design and test, which affects the dynamic characteristics of the blade structure and the analysis and calculation of fatigue. The failure analysis of the blade is divided into two parts: prediction analysis and test detection. The analysis can be used to control the fatigue of the blade, and provide guidance for the test. Fatigue analysis and prediction is still not accurate enough. Fatigue loading test is an important way to study the fatigue failure of blade. Wind turbine blade fatigue evaluation involves many uncertain factors, but more and more attention has been paid to [3]. In order to cause the blade to be subjected to sufficient fatigue damage in a reasonable test period, the test load is usually greater than the design load to speed up the testing process [4]. The finite element analysis and the blade vibration test method are combined to analyze the fatigue of the wind turbine blade [5]. This paper analyzes the characteristics of wind load and the equivalent load of blade, and studies the fatigue property and damage theory. According to the uniaxial constant amplitude loading, the load of wind turbine blade fatigue is calculated.

2. Wind turbine blade load analysis

Wind turbine blade is composed of airfoil with different sections. The section of the blade root is round and thick, and the middle part is the aerodynamic airfoil, which gradually thinning to the tip direction. In order to ensure that the blade as light as possible, the general use of hollow interior configuration, according to the structure is divided into: stiffened plate - bearing structure, shell - pneumatic structure and blade root - connection structure. Wind turbine blades are subject to time-varying loads from the outside, including aerodynamic force, centrifugal force and gravity. Usually along the blade is divided into many micro segments, each segment is called a leaf. The leaf as a two-



dimensional cascade, and assuming that there is no interference between the force of blade's role in blade force on only related to momentum change swept the ring gas. Usually, the blade is taken as the research object to carry on the stress analysis. For a specific load condition, the air load of the blade is simplified as a plurality of concentrated force loads along the spanwise direction of the blade, as shown in Figure 1. The force acting on the blade is obtained by integrating the force acting on the blade and the blade. The bending moment produced by normal force are M_y , and M_x ,

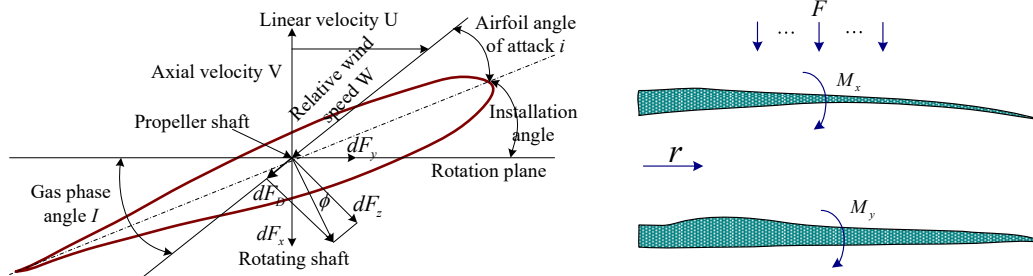


Figure 1. Blade load analysis and simplification of blade section.

The flapping direction of shear F_y , the shear direction of shear F_x , the blade root vibration moment M_x and the flapping moment M_y can be expressed as:

$$F_x = \frac{1}{2} \int_{r_0}^R \rho v_0^2 B c C_n dr, F_y = \frac{1}{2} \int_{r_0}^R \rho v_0^2 B c C_t dr \quad (1)$$

$$M_x = \int_{r_0}^R r dF_x, M_y = \int_{r_0}^R r dF_y$$

Because of the gravity of the blade, the gravity changes periodically with the azimuth of the blade. The gravity load causes the blade to produce a moment M_{xG} in the direction of vibration. In order to facilitate the calculation of the gravity load, it is necessary to calculate the density and area of the blade. The blade rotates, the centrifugal force is produced, and the action point is located at the center of gravity of the blade section, and the component of the centrifugal force moment in x, y direction is respectively M_{xp} and M_{yp} . The wind wheel rotation caused by centrifugal force on the blade is always outward along the blade, when acting on the blade flapping moment direction make flexible blade from wind wheel rotating plane, the centrifugal force on the blade can reduce the blade deviation in moment of wave direction is generated.

$$\begin{cases} M_{xG} = -\cos \phi \int_{r_0}^R (r - r_0) \rho_0 A_0 g dr \\ M_{xp} = \int_{r_0}^R (r - r_0) \rho_0 \omega^2 A_0 Y_G(r) dr \\ M_{yp} = \int_{r_0}^R [X_G(r) - Y_G(r_0)] \rho_0 \omega^2 A_0 r dr \end{cases} \quad (2)$$

Where ϕ is the rotating blade azimuth angle, ρ_0 and A_0 are the density and area of blade small segment period after conversion.

3. Fatigue property and damage theory of blade material

The selection of the correct S-N curve is the precondition for the fatigue life analysis of the blade, and the fatigue loading characteristics are evaluated by defining the maximum stress σ_{\max} , the minimum stress σ_{\min} , the stress amplitude σ_a and the mean stress σ_m . There is no clear limit of fatigue for leaf glass fiber reinforced plastics. It is usually used to estimate the stress value of the cycle number $5 \times 10^4 - 10^7$ as the fatigue limit. The relationship between the stress and fatigue life of glass fiber reinforced plastics, in the stress ratio $R = \sigma_{\min} / \sigma_{\max} = -1$, in the S-lgN coordinates on a straight line:

$$\sigma_i + B \lg N_i = \sigma_b \quad (3)$$

Where σ_b is the static strength of the material, B/σ_b is 0.1 approximation, σ_i and N_i are the corresponding stress levels and the number of cycles at failure.

The S-N curves of glass fiber reinforced plastic blades were obtained under the condition of cyclic $R = -1$. After the rain flow counting algorithm, the asymmetric cyclic loading spectrum is obtained, and the

conditional fatigue limit can be obtained according to the modified Goodman curve equation under the specified cycle life:

$$\sigma_a = \sigma_{-1} \cdot (1 - \sigma_m / \sigma_b) \quad (4)$$

Where σ_a is the stress amplitude, σ_{-1} is the conditional fatigue limit, σ_m is the average stress.

The fatigue performance of the blade is based on the fatigue curve S-N of glass fiber reinforced plastics, and the Goodman stress limit diagram is given according to the GL, and the theoretical limit of fatigue limit is obtained by R , which is known as the stress ratio N .

$$N = \left[\frac{R_{k,t} + |R_{k,c}| - |2\gamma_{Ma} S_{k,M} - R_{k,t} + |R_{k,c}|}{2S_{k,A} (\gamma_{Mb} / C_{lb})} \right]^m \quad (5)$$

Where $S_{k,A}$ is the dangerous section of the stress amplitude, $S_{k,M}$ is the dangerous section of the mean stress, $R_{k,t}$ is the tensile strength characteristics of short term structural elements, $R_{k,c}$ is the short-term compressive strength characteristics of structural components, $R_{k,A}$ is the maximum stress amplitude, and $R_{k,A} = (R_{k,t} + |R_{k,c}|) / 2$; γ_{Ma} is the local material safety, γ_{Mb} is the local material safety factor; m is the slope parameter of S-N curve.

To quantitatively study the effects of fatigue, this paper defined in a stress level of R_i , and the corresponding number of blade load n_i . Single load damage degree is d_i . A strain of the allowable load cycle number is N_i . The fatigue failure is defined as $d_i = 1 / N_i$. The fatigue damage value D of the fatigue load design point can be calculated according to the Miner linear damage theory.

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_i} = 1 \quad (6)$$

4. Fatigue damage calculation

In the actual operation of the blade fatigue load spectrum is very complex, must use the actual operation situation of simplified and accelerated method of equivalent simulation of blade in a relatively short period of time, the blade applied equivalent damage fatigue load equivalent damage and service life in the leaves of the same. According to the analysis of fatigue strength, fatigue safety margin selection section as the minimum fatigue test verification section. In order to make the test time can not be too long, but also to avoid too few times because the test can not reflect the true situation, the general test number of $N = 2 \times 10^6 \sim 1 \times 10^7$ times. Test frequency and blade natural frequency are similar, and the maximum damage location is as fatigue calculation concerns. In order to facilitate the interaction between calculation and test, the leaves of the outer section of the maximum strain damage for fatigue calculation concerns.

According to the fatigue load calculated by Bladed and the stress calculated by ANSYS, Goodman modified exponential function S-N curve and linear cumulative damage rule are selected. The fatigue load calculation method for a certain type of 2MW blade is studied under uniaxial constant amplitude loading. The blade length 56.6m is applied to simulate the blade's working condition at the root of the blade, and the blade finite element model is established. At the tip of the blade, the strain values of each section of the blade finite element model are calculated by using the three directions of the load and the vibration. Strain and fatigue load fatigue loads calculated using Bladed software under the blade value of every section, theoretical calculation of fatigue damage of glass fiber composite materials based on the calculation and drawing the maximum coefficient of each section of the blade fatigue damage by using Matlab software, The maximum coefficient of fatigue damage is shown in Figure 2. According to the evaluation of the maximum coefficient of action, the fatigue test range in the direction of swing is confirmed to be $L = 13\text{m}$ to $L = 38\text{m}$, and the fatigue test range is $L = 4\text{m}$ to $L = 27\text{m}$. According to the calculation results of blade fatigue damage, the blade section girder cap 23m part most prone to fatigue failure of the specific location, determine the location of dangerous points of blade fatigue test of dangerous section (which is the fatigue load design point) at the same time, the direction of fiber strain the outermost layer of the location of the fatigue test load as the design reference value.

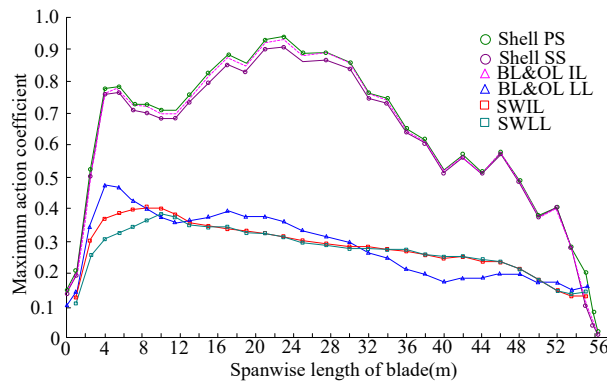


Figure 2. Maximum coefficient of fatigue damage.

5. Blade fatigue test load calculation

After determining the design points of fatigue load, it is necessary to calculate the fiber orientation strain value of the blade under the action of the unit bending moment in order to design the fatigue load. Finite element software is used to calculate the strain value ε of the fatigue load design point under the action of unit bending moment. The dynamic strain amplitude $S_{k,A}$ under the cyclic loading is calculated by calculating the strain value under the unit load multiplied by the load amplitude. Then the unit load under the locomotive load are worth to strain under cyclic load strain mean $S_{k,M}$. The blade was reinforced epoxy matrix, m value was 10. By using the formula of fatigue life of glass fiber composites, the fatigue life of fatigue load design points under the action of fatigue load M_y is obtained N . The cycle number of the fatigue test is 2×10^6 in the direction of the swing and the direction of vibration. Equation (5) transformed into:

$$S_{k,A} = \left[\frac{R_{k,t} + |R_{k,c}| - |2\gamma_{Ma} S_{k,M} - R_{k,t} + |R_{k,c}|}{2 \cdot (\gamma_{Mb}) \cdot N^{\frac{1}{10}}} \right] \quad (7)$$

The parameters in the equation (7) are calculated as shown in table1:

Table 1. Data of fatigue life calculation

$R_{k,t}$	$R_{k,c}$	γ_{Ma}	$2(\gamma_{Mb} / C_{lb})$	m
0.02	-0.016	2.205	3.594	10

Due to the actual wind turbine blade in the wind field, the fatigue load is variable amplitude load spectrum, and the actual test process applied to the fatigue load is equivalent to the constant amplitude fatigue load. Therefore, it is necessary to convert the variable amplitude fatigue load into equal amplitude fatigue loading. According to the theory of fatigue damage, it can be known that there is a certain proportion between strain amplitude $S_{k,A}$ and strain mean $S_{k,M}$:

$$\frac{S_{k,A}}{S_{k,M}} = \frac{1-R}{1+R} \quad (8)$$

Where R represents the load ratio.

The value of R is considered in the case of the weight and the weight of the blade in the fatigue test. Then according to equation (8) can be calculated from the mean strain blade corresponding amplitude under fatigue load, at the same time using equation (7) can be calculated from the strain amplitude fatigue loading:

$$S_{k,M} = \frac{|R_{k,c}|}{\frac{1-R}{1+R} (\gamma_{Mb} / C_{lb})^{1/m} - \gamma_{Ma}} \quad (9)$$

According to the requirements of the test specification and the position of the blade fatigue risk section, the 25m section of the fatigue test load is selected. Considering the dispersion coefficient of the blade and the uncertainty of the fatigue formula, it is necessary to consider the load factor of the fatigue test on the actual calculation of the fatigue test load. F_{df} is the initial load. The load of the fatigue test is $F_{target} = F_{df} \cdot \gamma_{nf} \cdot \gamma_{sf} \cdot \gamma_{ef}$, and the static load amplitude is calculated by using the test load coefficient in listing table 2.

Table 2. Load factor of fatigue test

Test load factor	Numerical value
Local coefficient of difference between blades γ_{sf}	1.1
Uncertainty of fatigue formula γ_{nf}	1.04
Local failure factor γ_{ef}	1.15

The fatigue life of the blade is $N_{ref}=1 \times 10^7$, and the damage equivalent load is the value of the cycle number. The cyclic range of each load component is calculated to calculate the damage equivalent load of the target test cycle, and then the cyclic range is multiplied by the load factor of the fatigue test to obtain the target load. When setting the cycle number of 2×10^6 , the calculated results of the load of the fatigue test target are shown in table 3. The shear strain induced by the shear force accounts for only a small proportion of the whole structural damage. Therefore, the test design will focus on the bending moment, for the same reason, the load of the *FZP* and *MZP* groups are also ignored.

Table 3. Fatigue test load

Radi(m)	FYP (kN)	FYP (kN)	MXP (kN·m)	MYP(kN·m)
0.00	213.18	507.72	8597.29	5644.29
7.00	178.77	341.85	5846.19	4416.43
13.00	172.58	268.92	4068.02	3452.52
25.00	146.56	158.46	1742.18	87.47
34.00	109.56	93.58	841.15	41.96
42.00	69.18	46.09	328.13	15.67
50.00	27.14	13.71	57.73	4.01

6. Conclusion

The characteristics of wind load and blade equivalent load are analyzed. According to the Miner linear fatigue cumulative damage theory and damage equivalent principle, the fatigue performance curve of FRP is calculated. Based on the Bladed simulation, the fatigue load matrix of a 2MW blade is obtained. Based on the theory of fatigue damage analysis and finite element software, the fatigue damage value of the fatigue load design point is determined, and the static load parameters are obtained.

Acknowledgments

This work is supported by the Jiangxi Province Key Laboratory of Precision Drive & Control project (PLPDC-KFKT-201622).

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