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Optimization design in Wind Turbine Blade Based on Specific Wind Characteristics

Yuqiao Zheng
College of Mechano-Electronic Engineering
Lanzhou Univ. of Tech.China
Lanzhou , China
zhengyuqiao2012@sohu.com

Yongyong Cao
College of Mechano-Electronic Engineering
Lanzhou Univ. of Tech.China
Lanzhou , China
caoyy_5794@163.com

Rongzhen Zhao
College of Mechano-Electronic Engineering
Lanzhou Univ. of Tech.China
Lanzhou , China
zhaorongzhen@lut.cn

***Abstract*—The highest possible power output under specified atmospheric conditions plays a key role in designing a wind turbine blade, in this paper, the maximum likelihood estimation method was used to compute the hub height wind speed (65m)mathematical model based on the observation data of Hexi Corridor wind at 10m height, taking 40m blade as an example, the model is established by Blade Element Momentum Theory, at the same time the tip loss is taking into account, each section of the chord, twist angle of wind energy utilization coefficient, skin ply and girder cap layer thickness parameters were optimized, the aerodynamic performance and stress distribution are given out, the results showed that the optimized: the optimized blade wind energy utilization coefficient is greatly improved and the quality of the blade is reduced significantly, it is suitable for wind characteristics of the blade design condition performance supper than that of general blade, it provides a theoretical basis for the blade design.**

***Keywords*——the wind; maximum likelihood estimation; aerodynamic performance; wind energy utilization coefficient; optimization model**

I. INTRODUCTION

Blade is one of the key components in the wind turbine. The wind turbine can transfer wind energy to mechanical energy in a rotor consisting of two or more blades and hub. Blade plays a key role in the safe operation of wind turbine. When designing reliable quality and superior performance blade, the actual operation status of wind turbine must be taken into account. The regional design and research of blade is the future development trend [1-2].Currently, the blade design specifications are mainly based on international standard IEC61400-1, Germany (GL rules), and the relevant wind power standards in China [3-4]. However, the wind resources situation is different between China and other countries. When selecting wind speed model, we usually reference the wind observation height of weather station which is 10m, however, the installation height of wind turbine hub is 50m to 70m, or even higher. This leads to the input source of load can not meet the requirements of some software and make the result of wind load calculation inaccuracy. The Hexi corridor which located in the northwest of China is the unique wind resource accumulation zone in China or even all over the world, and the wind resources of Hexi have its own geographic features. There are only two types of wind—the east wind and the west wind in Hexi corridor , so the wind turbine blade run in the frequent changing yaw angle situation. This seriously affects the reliability of wind turbine operation [5]. The reports of how to apply international standard to calculate regional wind resource characteristics and the regional design of blade are few in China. So the design of wind turbine blade in specific situation is one of problems that engineering application and research urgent to solve [6-7].The wind turbine blade optimization design method which based on wind characteristics in Hexi area is presented in this paper based on a aerodynamic theory. This method takes wind energy utilization coefficient and girder structure parameters as the optimization goal, and through the genetic algorithm to construct the whole blade optimal solution. Then get the blade optimal solution with better pneumatic and structure performance. Providing a reference for optimization and design of regional high-performance blade.

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II. WIND SPEED MODEL

The characteristics of wind are randomness、fluctuation and intermittent. When evaluating wind resources at a certain area not only depend on wind speed data, but also should master its stable statistical features in a long time. The probability distribution of wind speed is an important form of wind statistical properties. There are a lot of wind speed fitting models of probability distribution of wind speed, but among them two-parameter Weibull and Rayleigh distribution are widely considered to be a powerful tool to describe wind speed statistical properties[8].

When using two-parameter Weibull model to fit the wind speed distribution, the probability density function can be expressed as:

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

Where:

- v is wind speed
- $f(v)$ is the appearance probability of wind speed v
- k is shape parameter, dimensionless

- c is scale parameter

$$\bar{v} = c\Gamma\left(1/k\right) \quad (2)$$

Where :

- $\Gamma\ (\cdot)$ is the Gamma function .

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \quad (3)$$

When c=1, wind speed distribution is standard Weibull distribution. When 0<k<1, the mode of distribution is 0, $f(v)$is the decreasing function of wind speed v. When k=1, $f(v)$ becomes exponential distribution. When k=3.5, $f(v)$ very close to normal distribution. The bigger the k, shows that the smaller change of the average wind speed in a certain period of time; the smaller the k, shows that the bigger change of wind speed range.

Particularly, when k=2, the distribution is specifically known as Rayleigh distribution, there is only one parameter c in it; the wind speed probability density function can be expressed as:

$$f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] \quad (4)$$

A. Parameter Estimation Method

In order to establish mathematical model of wind speed of characteristics of regional wind resources, we must solve the problem of high accuracy parameter estimation. Weibull distribution is a common function of wind speed distribution of wind field. There is a lot of methods to calculate the parameter k and c in Weibull model; we use maximum likelihood estimation method [9-10] to calculate the shape parameter k and the scale parameter c in Weibull model in this paper.

According to the Weibull probability density function of wind speed distribution, structure maximum likelihood function as follows:

$$L(k,c) = \prod_{i=1}^{n} f(v_i) = \prod_{i=1}^{n} \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} \exp\left[-\left(\frac{v_i}{c}\right)^k\right] \quad (5)$$

The natural logarithm of above formula can be expressed as:

$$H(k,c) = \ln\left[L(k,c)\right] = \sum_{i=1}^{n}\left[(k-1)\ln(v_i) - \left(\frac{v_i}{c}\right)^k + \ln k - k\ln c\right] \quad (6)$$

The maximum likelihood estimate of k and c (in the above equation) can be obtained by solving equation (5) and (6).

$$H_1 = \frac{\partial H(k,c)}{\partial k} = \sum_{i=1}^{n}\left[\frac{1}{k} + \ln(v_i) - \ln c - \left(\frac{v_i}{k}\right) k \ln\left(\frac{v_i}{c}\right)\right] = 0 \quad (7)$$

$$H_2 = \frac{\partial H(k,c)}{\partial c} = \sum_{i=1}^{n}\left[\frac{k}{c}\left(\frac{v_i}{k}\right)k - \left(\frac{k}{c}\right)\right] = 0 \quad (8)$$

Where:

- $$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln v_i}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right)^{-1} \quad (9)$$

- $$c = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^k\right)^{\frac{1}{k}} \quad (10)$$

B. Wind Speed Distribution at the Height of Hub

When analyzing the characteristics of the wind energy resources, it is difficult to infer the characteristics of wind energy resources accurately at the height of hub (65m) according to the wind energy resources at the height of 10m. Many areas lack of measured data of wind speed of different height; so we usually use long-term observation data of wind at the height of 10m when calculation, the accuracy of result is not high. Therefore, it is necessary to make the statistical result [5] of wind energy resources at 10m outward expansion to the height of hub (65m) in Hexi region. When analyzing wind speed distribution at 65m, we get the wind speed data at 65m which calculated from data of wind speed at the standard height by using formula (4), then use maximum likelihood estimation method to get the wind speed probability density function which is shown in Fig.1.

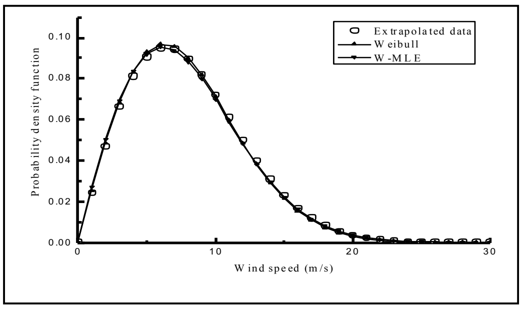

Fig.1 Wind Speed Probability Density Function at the Height of Hub

III. Calculation of Blade Aerodynamic Parameter

Wind turbine blade aerodynamic performance is determined by the power, thrust, torque and its corresponding coefficient [11-12].When calculating the aerodynamic performance, firstly, the axial inducible factor a and circumferential inducible factor b are calculated according to momentum blade element theory; Secondly, the air velocity triangle of blade element and the normal force dF_n and tangential force dF_t that effect on blade element are obtained; Thirdly, axial force dT and torque dM which effect on each blade element are calculated too; Finally, along the blade spanwise integration , the axial force T , torque M and shaft power P that effect on whole turbine are also calculated. Lift force and resistance are shown in figure 2:

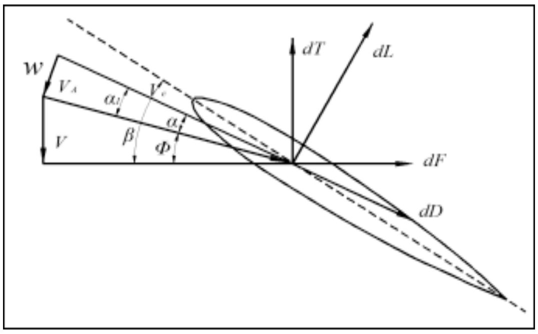

Fig. 2 Figure of Lift Force and Resistance

$$\begin{aligned} &\sin\phi \approx \phi \\ &F = 1; C_d = 0; a_0 = 0 \\ &C_l = 2\pi a \end{aligned} \tag{11}$$

Axial inducible factor calculation amendment is:

$$a = \frac{1}{4}\left[2 + \pi\lambda_r\sigma' + \sqrt{4 - 4\pi\lambda_r^2\sigma'(8\beta + \pi\sigma')}\right] \tag{12}$$

Initializing inducible factor a and b, the axial inducible factor that calculated by initial value can reduce iteration time. In flow angle is [13]:

$$\tan\phi = \frac{U_\infty(1-a)}{\Omega r(1-a')} \tag{13}$$

Angle of attack is:

$$a = \phi - \beta \tag{14}$$

Where:

- $$C_T = \frac{\sigma'(1-a)^2(C_l\cos\phi + C_d\sin\phi)}{\sin^2\phi} \tag{15}$$

Because the force on blade element which at the tip of blade have exerted a far-reaching influence on the aerodynamic performance of whole wind turbine blade, so the tip loss should not be ignored. If considering the Prandtl tip loss correction factor, tip loss coefficient F can be defined as:

$$F = \frac{2}{\pi}\cdot\arccos\left[\exp\left(-\frac{B}{2}\cdot\frac{(R-r)}{R\sin\varphi}\right)\right] \tag{16}$$

Then, the contribution that each blade element contribute to total wind energy utilization coefficient is:

$$\mathrm{d}C_p = \frac{8}{\lambda_0^2}b(1-a)F\lambda^3\mathrm{d}\lambda \tag{17}$$

IV. Sample Analysis

The known conditions: blade length−40m; airfoil profile−NACA63-XXX series; rated wind speed−11m/s; cut-in wind speed−3m/s;cut-out wind speed−25/s(10minutes mean value).Use genetic algorithm to optimize the calculation(taking chord length, torsional angle, front layer thickness as the design variables and taking wind energy utilization coefficient and girder structure parameters as the optimization goal).

TABLE. 1 BLADE DESIGN BASIC PARAMETERS

Rated power	blade length	The ratec Speed	at the Height of Hub	λ	The rated Wide speed
1500 KW	40.5m	17.2m/s	65m	8.5	10m/s

The chord length distribution (before and after optimization) is shown in Fig.3.The optimized blade chord length distribution along the spanwise present a nonlinear characteristics which can be seen from the figure on the whole, each chord length of blade element is greater than the initial blade, and the optimized blade chord length distribution is more smooth especially at the middle of the blade. However, the chord length of blade root and blade tip less than the initial blade; this is because it develops toward to the trend of increasing blade area in the optimization process (considering wind resource characteristics of Hexi in calculation and taking maximum wind energy utilization coefficient as the objective function).

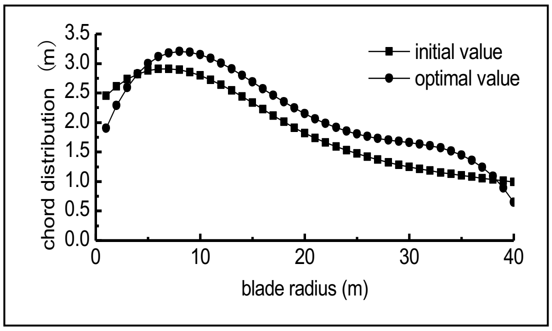

Fig. 3 Comparison of Chord length Optimization

The torsional angle distribution after optimization is shown in Fig.4.We can see from the picture, torsional angle distribution presents nonlinear characteristics, and the entirety has the trend of increasing under the condition of torsional angle optimal value rigidity. The torsional angle value reach the maximum at r/R=0.2 after optimization, however its maximum value at r/R=0.25 before optimization. The maximum value of optimized blade torsional angle is more close to the blade root, and the distribution of torsional angle is more smooth. The main reason leads to increase chord length of blade root is the torsional angle of blade root is greater than initial blade which consider the regional wind load effects, and it benefits to reduce the load of blade root, then increase the service life of blade.

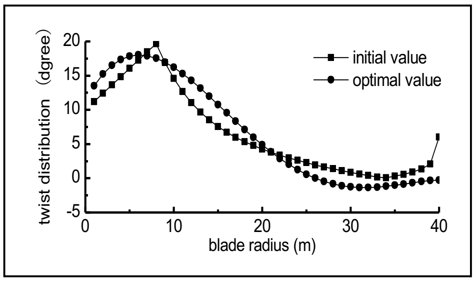

Fig. 4 Torsional Angle Optimization

We can see from figure 5, low wind speed area torque coefficient declined slightly, and high wind speed torque coefficient increased after optimization. It illustrates that probability of occurrence of wind speed is bigger at high wind speed area, so we can improve the high wind speed area wind energy utilization. The optimized wind turbine blade under the condition of low wind speed, wind rotor is able to obtain large torque. So wind turbine can reach the rated speed faster, then increases its annual electricity output.

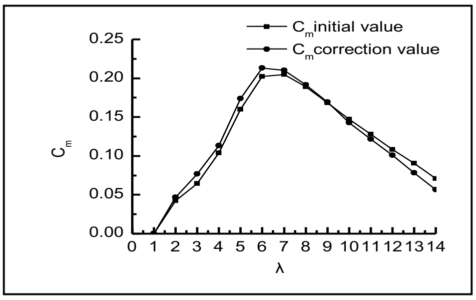

Fig. 5 C_M—λ Characteristic curve

Curve of thrust coefficient changing with blade tip speed (before and after optimization) is shown in figure 6. We can see from the figure, wind rotor thrust coefficient increases with the increases of blade tip speed, it means that the axial thrust that wind rotor effected increases with the increases of blade tip speed. The thrust on optimized blade slightly smaller than the original wind rotor thrust when tip speed ratio (high wind speed) at the range of 4 to 7.5, and it is beneficial to reduce the whole wind turbine load. When wind turbine operation (tip speed ratio greater than 8.5), the thrust coefficient increased significantly after optimization. But this does not substantially increases the whole wind turbine load, and wind turbine can reduce the load through varying propeller, stalling and other measures.

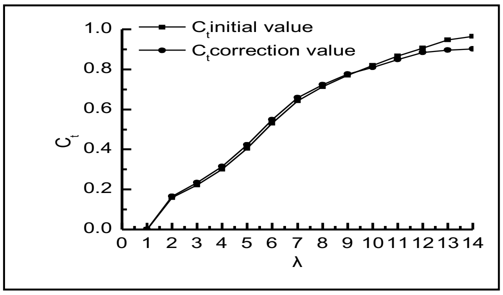

Fig. 6 C_T-λ Characteristic curve

Curve of power coefficient changing with blade tip speed ratio (before and after optimization) is shown in figure7. We can see that the power coefficient is significantly greater than the initial blade when tip speed ratio at the range of 6 to 12, and this is mainly caused by different blade shape parameters. Blade has the highest wind energy utilization coefficient when tip speed ratio at the range of 8 to 10 (before optimization), and its maximum value is 0.485. Moreover, the maximum value of wind energy utilization coefficient is 0.42, and the Betz limit is 0.593; there is a big gap between them. The reason of it is that the wind energy utilization at blade root is not high when calculating wind energy utilization coefficient of blade. The wind energy utilization mainly concentrated at 0.2R to R along the spanwise, that is shows the range of wind energy utilization of blade is wider after optimization, the aerodynamic performance of blade improved, and its aerodynamic efficiency is higher.

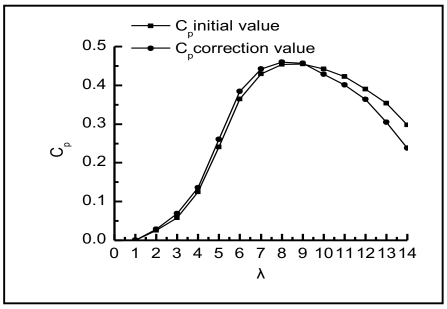

Fig.7 C_P-λ Characteristic curve

The power curve of wind rotor overall change is small when using wind speed distribution at 10m and 65m respectively, we can see it from figure 8. Wind rotor power slightly more than 10 m height observation data when wind rotor at the height of hub and wind speed v<10*m/s*; wind rotor power was constant at 1.5MW when wind speed v>10*m/s*, this is because when wind turbine reached rated wind speed, it uses measure of adjusting pitch angle to ensure constant output, then consistent with actual operation power.

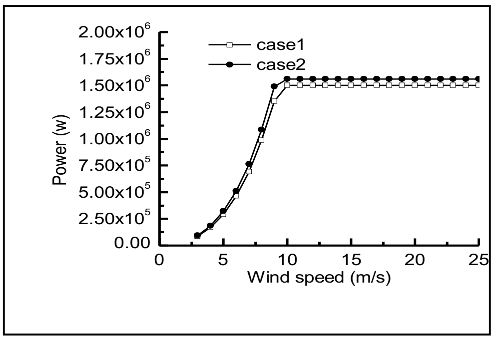

Fig. 8 power comparison (before and after optimization)

Aerodynamic force directly affects the layer structure of the blade. Main girder cap layer thickness distribution under different wind speed (at the height of 10m and 65m) is shown in figure 9. We can see from the figure that the main girder cap layer thickness distribution presents nonlinear characteristics; the main girder cap layer that use actual wind load to calculate at the height of 65m is increased near blade root under rigid condition. Blade girder is the main bearing part , the optimized girder cap layer thickness decreases at 0.2R-0.5*R*, and girder cap layer thickness increases to satisfy the requirement of blade overall rigidity at 1/2-*R* .

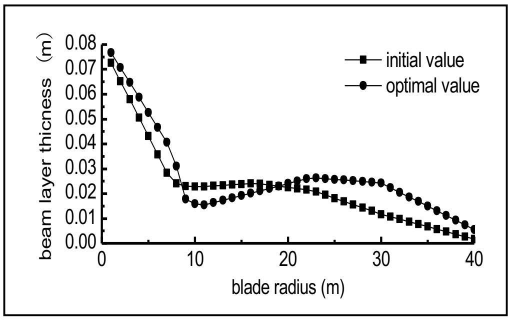

Fig. 9girder cap layer thickness comparison (before and after optimization)

Curve of blade mass linear density under wind load influence of two working conditions is shown in Figure 10. The figure shows that the optimized blade section mass linear density decreases near blade root. However, blade root is the accumulation area of blade mass; so this reduce blade overall mass, and reduce the blade manufacturing cost.

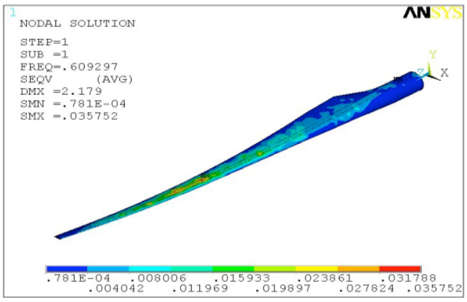

Fig.10 stress distribution

Further, blade stress is analyzed. Through analyzing figure 10, blade main bending strain zone is located at girder which is located at 1/3-2/3 of blade along the spanwise, blade stress is big at the part of girder cap, and its minimum value is located near the blade tip. So changing the girder cap layer is one of the most effective measures to improve blade stress, and its maximum stress at blade root conform to the GL standard. Therefore, stress analysis result that under the regional wind resources characteristics is believable.

V. CONCLUSIONS

Based on characteristics of the wind resource in Hexi area, optimization research and design of blade which adapt to the wind resource characteristics flexibly is carried out, and get the following conclusions by analyzing the optimization results:

a) In this paper, based on 10m level long-term observation data of wind speed in Hexi corridor, use maximum likelihood estimation to establish mathematical model at the height of hub in Hexi corridor, and calculate the shape parameter and scale parameter of Weibull model, then provide a theoretical basis for the accurate model of wind speed of regional wind resources characteristics.

b) Based on the theory of blade element momentum, the aerodynamic mathematical model is established. The chord length、torsional angle and thrust coefficient of each blade element are greatly improved, and the quality of blade is significantly reduced after optimization. The chord length and torsional angle at blade root do not appear extremely distortion of geometric shape. The chord length of blade root and blade tip are less than initial blade, the maximum torsional angle is closer to the blade root, and the distribution of the torsional angle is more smooth after optimization. All these above will bring great convenience to blade production and blade manufacturing process; When tip speed ratio at the range of 4-7.5, the thrust on blade decreases, then the load on wind turbine decreases.

c) Based on the calculation of aerodynamic force, the blade, skin layer, and main girder cap layer thickness are optimized. Compared with initial blade, the optimized blade torsional angle at blade root is significantly greater than the initial blade, and this will reduces the load of blade root, then increases the service life of blade. Finally, the stress analysis of optimized blade is done, and the main stress position of blade is pointed out. The research of this paper provides important guiding significance for subsequent wind turbine blade structure design and optimization.

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