Fatigue Analysis of Hybrid Wind Turbine Towers

Yuan Wei [1, 2], Yingjie Li [1], Zhaoqi Wu [2, *], Jinyu Chen [1], Shaofei Jiang [2], Xianbiao Xiao [1]

[1]State Grid Fujian Electric Power Research Institute, Fuzhou 350007, China
[2]College of Civil Engineering, Fuzhou University, Fuzhou 350108, China

Abstract. Fatigue analysis of hybrid wind turbine towers between cut in wind speed and cut out wind speed are demonstrated. Nominal stress method and miner liner accumulated damage theory are adopted. Through the analysis of the results, comparative research on effect of parameters of aspect ratio, height ratio and unequal legs for fatigue properties of hybrid wind turbine towers. The results show that the optimal range of aspect ratio of hybrid towers is 1/6~1/4, the optimal range of height ratio of hybrid towers is 0.60~0.67. Fatigue analysis of hybrid towers, should select the right junction of leeward towers and the S-N curve from EN 1993-1-9.The effect of unequal legs for fatigue properties of hybrid towers can be neglected.

Keywords: Wind power generation, Hybrid tower, Fatigue property, Design load spectrum, Finite element analysis.

1. Introduction

The global energy crisis and environmental problems have promoted the large-scale development and utilization of renewable energy such as wind energy. As the supporting structure of the whole wind turbine system, the safety property of wind turbine tower is very important. The current design service life of wind turbine is generally 20 years. During the whole design service life, the wind turbine tower needs to bear up to 107 cycles of random loads, which is very easy to cause fatigue failure. Therefore, fatigue analysis of the wind turbine tower has very important practical engineering significance [1]. Kvittem et al. [2] considered the combined effect of wind turbine load and wave load, and analyzed the fatigue property of 5MW offshore wind turbine tower and platform using the nominal stress method. Long et al. [3] analyzed the fatigue property of 5MW three-limb and four-limb lattice offshore fan towers by frequency domain method. Yao et al. [4] took the 5MW cylindrical fan tower as the prototype, combined with the statistical data of wind speed distribution in Penghu, Taiwan, the fatigue analysis of the tower is carried out using Weibull probability model. Liu et al. [1] studied the fatigue property of 2MW single pile fan support structure by using spectrum fatigue analysis method on the premise of considering the combined action of wind turbine load and wave load.

Literatures [5] and [6] put forward a hybrid tower system suitable for complex terrain such as mountain areas, in which the upper part is a cylindrical tower and the lower part is a lattice tower. The feasibility and engineering applicability of the hybrid tower were preliminarily verified by analyzing the basic mechanical properties of the hybrid tower with different parameters. Compared with the cylindrical tower, the hybrid tower has the advantages of higher material utilization rate, less steel consumption, more convenient production, transportation, installation and maintenance, lower requirements for foundation, smaller excavation amount of foundation pit, which is conducive to vegetation protection and prevention of water and soil loss. It can effectively expand the construction scope of wind farms while meeting the development trend of large-scale wind turbines. However, because the hybrid tower is composed of two types of towers with different stiffness, its overall stiffness is nonuniform. Compared with the traditional tower type, the hybrid tower is more prone to stress concentration, especially at the transition section of the two types of towers, which is very unfavorable for the fatigue property of the hybrid tower. Therefore, based on the tower parameter models given in reference [6], this paper analyzes the fatigue property of hybrid tower under wind load by using the nominal stress method and Miner linear fatigue cumulative damage theory.

2. Analysis methods

Based on S-N curves of materials and Miner linear cumulative fatigue damage theory, the fatigue properties of hybrid wind turbine towers were analyzed by using nominal stress method. Referring to relevant analysis methods in literatures [7] and [8], the occurrence duration and cycle times of hybrid tower under each working condition within the design service life are determined according to the wind speed cumulative distribution

* Corresponding author: zhaoqi_wu@fzu.edu.cn

theory; Secondly, the static analysis of the hybrid tower under various working conditions is carried out to determine the fatigue risk points and select the cyclic stress level under typical working conditions, and the design load spectrum of the tower is given; Thirdly, the appropriate S-N curve is selected to calculate the fatigue damage under different design loads; Finally, according to Miner linear fatigue cumulative damage theory, the fatigue damage under different working conditions is linearly superimposed to obtain the fatigue cumulative damage of the hybrid tower within the design service life.

(1) Design load spectrum of hybrid tower

Wind turbines are often in different wind speed conditions. As a random variable, the wind speed is generally calculated and analyzed by spectral analysis or probability statistics, and the frequency of a certain wind condition in a year is determined according to the annual average wind speed distribution of wind farm. In the world, the wind speed probability distribution model widely used is two-parameter Weibull distribution, and wind turbine manufacturers often choose the Weibull distribution of wind speed with shape parameter 2 as the design basis [9]. The physical meaning of Weibull distribution function p(v) reflected in the distribution of wind conditions is the wind speed frequency curve, which is characterized by scale parameter c and shape parameter k. The probability density function of wind speed is [10]:

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

Where, v is the incoming wind speed, m/s; k is the shape factor, dimensionless; c is the scale factor, m/s.

The physical meaning of Weibull cumulative distribution function P(v) reflected in the distribution of wind conditions is the duration or probability that the wind speed v is less than or equal to the given wind speed v′:

$$P(v)=1-\exp\left[-\left(\frac{v}{c}\right)^{k}\right]=\int_{0}^{v'}p(v)dv \tag{2}$$

If the whole working wind speed is divided into several sections, the annual cumulative hours of a certain wind speed section are:

$$T_i=8760P(v)\Big|_{v_i-\Delta/2}^{v_i+\Delta/2} \tag{3}$$

Where, Δ is the width of wind speed range.

When Δ=2m/s, c=10m/s, k=2.0, that is, the wind speed distribution adopted Weibull distribution with shape parameter 2, and the annual average wind speed was 10m/s. The cumulative times of different wind speeds in a wind farm under normal power generation conditions within 20 years were calculated. According to the load conditions of hybrid towers under various wind speed conditions, the fatigue risk points and the cyclic stress levels of hybrid towers under various wind speed conditions were found out through the mechanical analysis of hybrid towers, and the design load spectrums of hybrid towers were obtained by combining the number of cycles under various wind speed conditions. Due to the limitation of space, the design load spectrum of hybrid tower with representative parameters was given, as shown in Table 1.

Table 1. Design load spectrum of hybrid tower (D/H=1/6, h_2/H=0.67)

Wind speed v_i (m/s)	Hours/1 year	Hours/20 years	Design load S_i (MPa)	Number of cycles n_i ($\times10^7$)
3	951.7	19034.7	25.904	0.146
5	1353.1	27062.7	27.704	0.207
7	1492.6	29851.3	32.206	0.229
9	1396.5	27929.2	42.302	0.214
11	1147.1	22942.7	54.992	0.176
13	841.6	16831.3	70.272	0.129
15	556.7	11134.6	88.136	0.085
17	334.1	6682.3	108.578	0.051
19	182.6	3652.6	131.596	0.028
21	91.8	1823.6	157.187	0.014
23	41.7	833.2	185.348	0.006
25	17.4	349.0	216.080	0.003
Total	8406.4	168127.2	—	1.288

(2) Numerical model establishment

In order to reduce the modeling works of hybrid towers and reflect the actual situations of hybrid towers, the auxiliary components that have little impact on the structure properties of the towers were ignored, and the complex parts were properly simplified. The simplified contents of hybrid tower modeling mainly included that the tower bottom was simplified as a space cantilever beam structure rigidly connected to the foundation without considering the influence of the foundation and the door opening; auxiliary components such as ladders, rest platforms and so on of the tower were not considered; the bolt and welding residual stress on the flange were not considered, and at the change of wall thickness, only the gradual shape of the tower after welding was simulated; The impeller, engine room and hub on the top of the hybrid tower were simplified as a concentrated mass point on the top of the tower. The mass point was located at the center of gravity of the three components, its mass was the sum of the masses of the three components, and the mass eccentricity and moment of inertia were considered [11]. The total height of the hybrid tower model established was 60m. The mass of the wind turbine rotor and the engine room was 18000kg and 40000kg respectively. The distance between their mass centers and the central axis of the tower was 1.5m, and the height of the wind turbine center was 62m. The materials of cylindrical tower and lattice tower were Q345B. In the hybrid tower model, SHELL93 element was used for the cylindrical tower, BEAM188 element was used for the lattice tower, and MASS21 element was used for the concentrated mass at the top of the tower. The cylindrical tower was divided into 12 equal parts along the height and 36 equal parts along the circumference of the section. The column of lattice tower was divided into 18 equal parts along the height direction, the cross member was divided into 6 equal parts, and the diagonal member was divided into 12 equal parts. The concentrated mass on the top of the hybrid tower was rigidly connected with each node on the top of the tower. The hybrid tower was rigidly connected with the foundation. The finite element model of the

 https://doi.org/10.1051/e3sconf/202341601035

hybrid tower is shown in Fig. 1, where, W is the bottom width of hybrid tower; H is the total height of hybrid tower; h_1 is the height of cylindrical tower; h_2 is the height of lattice tower.

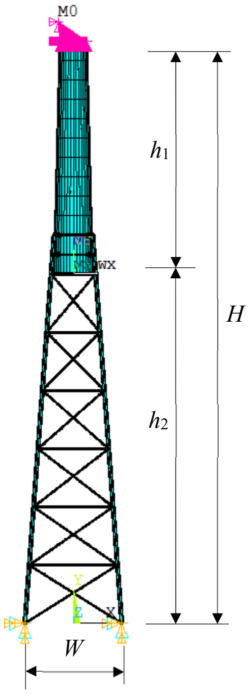

Fig. 1 Finite element model of hybrid tower

3. Analysis results

In the process of fatigue analysis of wind turbine hybrid tower by using nominal stress method, it is necessary to determine the S-N curves of materials, but the manufacturer of 1.5MW cylindrical tower referred to in this paper did not provide detailed material property test data. Therefore, the S-N curves provided by EN 1993-1-9 [12], GB 50017-2003 [13] and ANSI/AISC 360-10 [14] were used to conservatively estimate the fatigue property of hybrid tower. The fatigue analysis module of ANSYS finite element software was used to analyze the fatigue properties of hybrid towers with different aspect ratios (W/H), height ratios (h_2/H) and types of unequal legs.

(1) Aspect ratio

The fatigue properties of hybrid tower models with different aspect ratios W/H (1/10, 1/9, 1/8, 1/7, 1/6, 1/5.5, 1/5, 1/4) were analyzed. According to the static analysis of the towers, the connection between the two types of towers was the fatigue risk point. The member and connection categories selected in the three specifications were 2 (GB 50017-2003), 140 (EN 1993-1-9) and A (ANSI/AISC 360-10). The fatigue cumulative damage indexes D of hybrid towers with different aspect ratios are shown in Fig. 2. It can be seen that the fatigue cumulative damage indexes of the hybrid towers under the same size basically decrease with the increase of the aspect ratio, and the fatigue properties of the towers are improved. When the aspect ratio is 1/8~1/4, the cumulative fatigue damage indexes of the towers are basically less than 1, meeting the design requirements. When the aspect ratio is 1/10~1/7, the cumulative fatigue damage indexes of the towers with different aspect ratios change greatly, and the fatigue properties of the towers are sensitive to the change of aspect ratio. When the aspect ratio is 1/6~1/4, the cumulative fatigue damage indexes of the towers with different aspect ratios change slightly, and the fatigue properties of the towers are not sensitive to the change of aspect ratio. This is mainly due to the different choices of fatigue risk points, resulting in the different sensitivities of the fatigue properties of the towers to the aspect ratio. Therefore, in order to facilitate the design and selection of hybrid towers, the fatigue properties of hybrid towers with different aspect ratios are not likely to change significantly. At this time, the aspect ratio of hybrid towers should be 1/6~1/4.

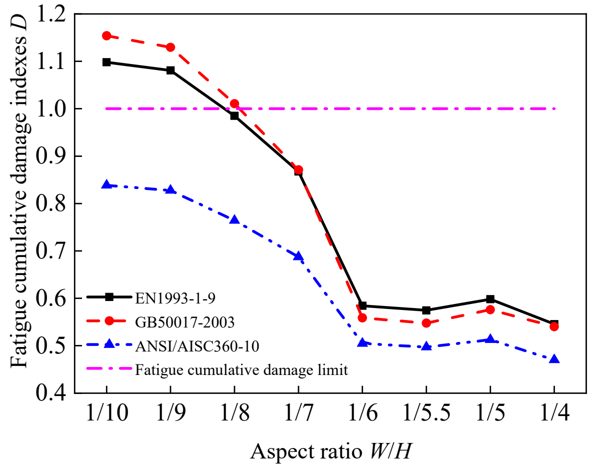

Fig. 2 Fatigue cumulative damages of hybrid towers with different aspect ratios

(2) Height ratio

Based on the aspect ratio 1/6, the fatigue properties of hybrid tower models with different height ratios h_2/H (0.43, 0.47, 0.5, 0.53, 0.57, 0.6, 0.63, 0.67) were analyzed. According to the static analysis of the towers, the connection between the two types of towers was the fatigue risk point. The member and connection categories selected in the three specifications were 2 (GB 50017-2003), 140 (EN 1993-1-9) and A (ANSI/AISC 360-10). The fatigue cumulative damage indexes D of hybrid towers with different height ratios are shown in Fig. 3. It can be seen that the fatigue cumulative damage indexes of the hybrid towers under the same size basically decrease with the increase of the height ratio, and the fatigue properties of the towers are improved. When the height ratio is 0.60~0.67, the cumulative fatigue damage indexes of the towers are basically less than 1, meeting the design requirements. When the height ratio is 0.43~0.57, the cumulative fatigue damage indexes of the towers with different height ratios change greatly, and the fatigue properties of the towers are sensitive to the change of height ratio. When the height ratio is 0.60~0.67, the cumulative fatigue damage indexes of the towers with different aspect ratios change slightly, and the fatigue properties of the towers are not sensitive to the change of height ratio. This is mainly due to the different choices of fatigue risk points, resulting in the different sensitivities of the fatigue properties of the towers to the height ratio. Therefore, in order to facilitate the design and selection of hybrid towers, the fatigue properties of hybrid towers with different height ratios are not likely to change significantly. At this time, the height ratio of hybrid towers should be 0.60~0.67.

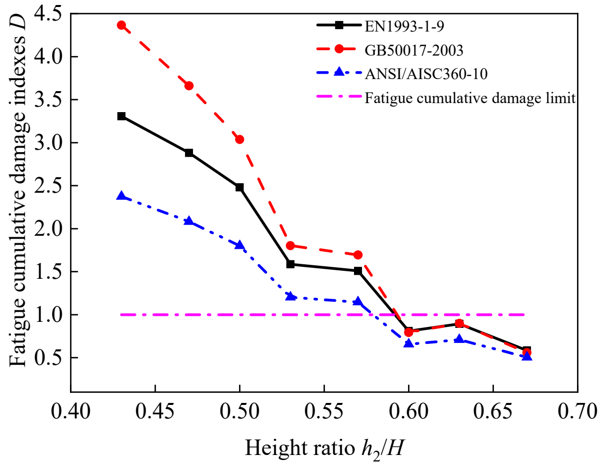

Fig. 3 Cumulative fatigue damage of hybrid tower with different height ratio

(3) Unequal legs

On the basis of the optimal design scheme of hybrid tower with aspect ratio 1/6 and height ratio 0.67, and considering the symmetry of hybrid tower, different types of unequal legs of hybrid tower models were established, such as short front and long back (SFLB), long front and short back (LFSB), and short left and long right (SLLR). The height difference between the long and short legs of the tower model is 0m, 1m, 2m, 3m, 4m and 5m, and the fatigue analysis was carried out respectively. According to the static analysis of the towers, the connection between the two types of towers was the fatigue risk point. The member and connection categories selected in the three specifications were 2 (GB 50017-2003), 140 (EN 1993-1-9) and A (ANSI/AISC 360-10). The fatigue cumulative damage indexes D of hybrid towers with different unequal legs are shown in Fig. 4. It can be seen that the fatigue cumulative damage indexes of the hybrid towers with short front and long back, long front and short back basically increase with the increase of the height difference of the tower legs, but the increase is very small and can be ignored. The fatigue cumulative damage indexes of the hybrid towers with short left and long right basically decrease with the increase of the height difference of the tower legs, and the fatigue properties of the towers are improved. The cumulative fatigue damage indexes of the different types of unequal legs of hybrid towers are basically less than 1, meeting the design requirements.

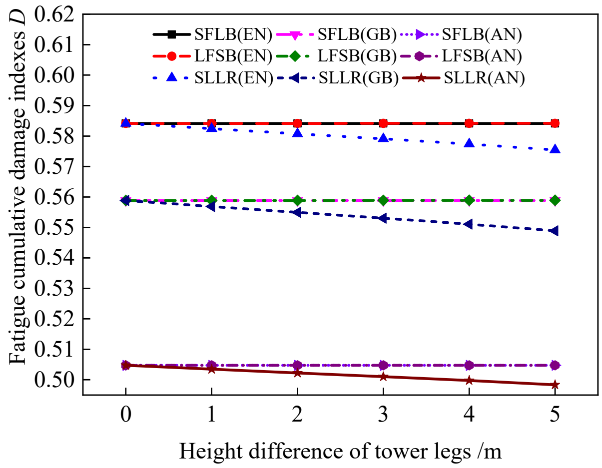

Fig. 4 Cumulative fatigue damage of hybrid tower with unequal legs

4. Conclusions

1) Considering the fatigue properties of hybrid towers with different aspect ratios and height ratios, the height ratio can be taken as 0.60~0.67, and the aspect ratio can be taken as 1/6~1/4 to facilitate the design and selection of hybrid towers.
2) In the case of complex terrain conditions, the length of tower legs varies at the bottom of the hybrid tower. The unequal legs have no significant influence on the fatigue property of the hybrid tower, so the influence of the unequal legs on the fatigue property of the hybrid tower can be ignored.
3) Within the selection range of aspect ratio, height ratio and unequal legs of hybrid towers, the cumulative damage results of hybrid towers obtained by using S-N curves of different specifications from low to high are ANSI/AISC 360-10, GB 50017-2003 and EN 1993-1-9. Considering the number of S-N curves, component and connection categories and evaluation results, it is recommended to use the S-N curves given in EN 1993-1-9 for fatigue property analysis of hybrid towers.
4) The connections of two types of hybrid towers are the places where fatigue damage is easy to occur. The effective structural form of the connection part is designed to minimize the stress concentration, and if necessary, measures such as grinding the weld are taken to improve the fatigue life of hybrid towers.

Acknowledgments

This research was supported by the State Grid Fujian Electric Power Co., Ltd. Technology Project (Grant No. 52130422002Z).

References

1. Liu C, LI LB. Spectral fatigue analysis of a support structure for offshore wind turbines [J]. Renewable Energy Resources, 2016, 34(2): 255-260.
2. Kvittem MI, Moan T. Time domain analysis procedures for fatigue assessment of a semi-submersible wind turbine [J]. Marine Structures, 2015(40): 38-59.
3. Long H, Moe G. Preliminary design of bottom-fixed lattice offshore wind turbine towers in the fatigue limit state by the frequency domain method [J]. Journal of Offshore Mechanics and Arctic Engineering, 2012(134): 1-10.
4. Yao H, Wu WF, Chang YC. Reliability analysis of wind turbine towers [J]. Procedia Engineering, 2014(79): 218-224.
5. He MS, Chen Q, Wang L, et al. Transition Connection Method of Hybrid Wind Power Tower [P]. China Patent, 2014103546065, 2014-07-24.
6. Wei Y. Research on basic mechanical properties of hybrid wind turbine towers [D]. Fuzhou University, 2016.
7. Liu ZQ, Wang MQ, Zhu YM. Fatigue strength analysis of offshore oil platform mooring chain based on miner cumulative damage theory [J]. Marine Technology, 2011(4): 19-21.
8. Zhang TT. Optimization, Dynamic Behavior and Fatigue of Vertical-axis wind turbine [D]. Shanghai Jiao Tong University, 2009.
9. Li H, Sun HB, Zhang F. Review of wind speed distribution models in wind farms [J]. Advanced Technology of Electrical Engineering and Energy, 2014, 33(8): 62-66.
10. Ding M, Wu YH, Zhang LJ. Study on the algorithm to the probabilistic distribution parameters of wind speed in wind farms [J]. Proceedings of the CSEE, 2005, 25(10): 107-110.
11. Zhu XH, Huang FL, Zhang LG. Modal and buckling analysis for the tower of large wind turbine [J]. Journal of Railway Science and Engineering, 2010, 07(6): 86-89.
12. DIN EN 1993-1-9. Eurocode 3: Design of steel structures Part 1-9: Fatigue. European committee for standardization, Brussels, 2005.
13. GB 50017-2003. Code for design of steel structures [S]. Beijing: China Planning Press, 2003.
14. ANSI/AISC 360-10. Specification for structural steel buildings. American institute of steel construction, Chicago, 2010.