

Loads Experiment Research on Key Components of Umbrella Wind Turbine Regulating Mechanism

Daorina Bao^{1,*}, Fan Gao¹, Jiawen Liu¹

¹School of Energy and Power Engineering, Inner Mongolia University of Technology, Hohhot, Inner Mongolia, 010000, China

* Corresponding author

Abstract: Taking the key components of the umbrella wind turbine regulating mechanism as the research object, the main stress concentration parts were determined by numerical simulation, and the strength of the key components was checked. Through the wind tunnel test, the variation of the stress on the key components of the adjustment mechanism with the shrinkage angle of the umbrella wind turbine under the actual operating conditions was tested. The results show that the stress on the connecting rod and the small hub increases first and then decreased with the increase of the shrinkage angle, and both reach the maximum stress under the working condition of 45°. The stress of the large hub decreased with the increase of the shrinkage angle. The safety and reliability of the power regulating mechanism of the umbrella wind turbine was verified by numerical simulation and wind tunnel test, which laid a research foundation for the subsequent structural optimization and improvement of the umbrella wind turbine.

Keywords: Load, Experiment, Umbrella wind turbine, Stress.

1. Introduction

Renewable energy plays an important role in energy conservation with the challenge of the global environment, wind power generation as a clean energy utilization mode is of great significance to alleviate climate change. For the wind turbines, its control mode in the operation process is directly related to the efficiency, safety and power quality of wind power generation. Large wind turbines can maintain constant power output by adjusting converter equipment, paddle and other methods. For traditional small and medium-sized wind turbines is mainly through the stall to control the power growth, but this will lead to the overall efficiency of the wind turbine is low. If the wind speed exceeds the cut-out wind speed, the wind turbine will stop working, causing a waste of wind energy. Therefore, this study proposes an umbrella wind turbine with a power regulating mechanism. When the incoming wind speed is higher than the rated wind speed, the shrinkage angle of the wind wheel of umbrella wind turbine can be adjusted by the power regulating mechanism to control its output power to keep near the rated value; When extreme climatic conditions are encountered, the shrinkage angle of the wind wheel can be adjusted to the maximum state, so that its generator and blades are not damaged by the extreme climate. Because the power regulating mechanism directly affects the operation performance of the umbrella wind turbine, it is of great significance to the safe and stable operation of the umbrella wind turbine by studying the force situation change regularity of the key components with the shrinkage angle change.

Many researchers have studied the power control of traditional small and medium-sized wind turbines and proposed many power control methods for small and medium-sized wind turbines. Pasupulati et al.[1] proposed a new wind turbine with variable blade length, which can extend the blade length at low wind speed, enhance wind energy capture, and shrink the blade at high wind speed to reduce the load of the wind wheel. D.B. Stoyanov et al.[2] proposed the method of tip speed ratio correction to improve

the wind turbine output power decline in the case of ice accumulation. A 5MW NREL wind turbine was numerically simulated in 12 different freezing conditions. The results show that the proposed method can effectively reduce the power loss caused by ice accumulation in cold climate. N.Franchina et al.[3] considered several numerical problems, including domain extension, the category of assigned boundary conditions, spatial and temporal resolution, and numerical accuracy in the equation resolution, the generated flow model is used to do the 2D and 3D simulations of the flow field around the wind turbine, and verifies the conclusions by detailed comparison with the large experimental database available for the considered turbine. B.Dose et al.[4] used two different tower concepts to study downwind wind turbine output performance. The obtained numerical results show that the truss tower causes more severe tower shadowing than the tubular tower, and the recovery of the wake wind speed behind the rotor was also slower. Wei Xie et al.[5] proposed a new foldable blade wind turbine. The experimental results show that the foldable blade can effectively control the power output when wind speed exceed rated value and reduce the wind power by up to 50%. Daorina Bao et al.[6-8] developed side bias drive mechanism between the wind wheel and tail rudder. When the current wind speed exceeds the rated value, through the side bias drive mechanism adjust eccentric distance between generator and tail wing to make the output power of the wind turbine control near the rated power. The gravity reversing side deviation regulation mechanism has been widely used in power regulation and wind speed limit of small wind turbines. Xiongfei Liu et al.[9-11] verified the effectiveness of gravity reversing wind turbines on power control and wind speed limit through mechanism analysis and experimental test.

In this paper, the numerical simulation method was used to study the loads characteristics and obtained the pressure variation cloud chart of the key components of umbrella wind turbine regulating mechanism. The pressure value of the key components determined by experiment. The results of analysis between simulation and experiment will provided

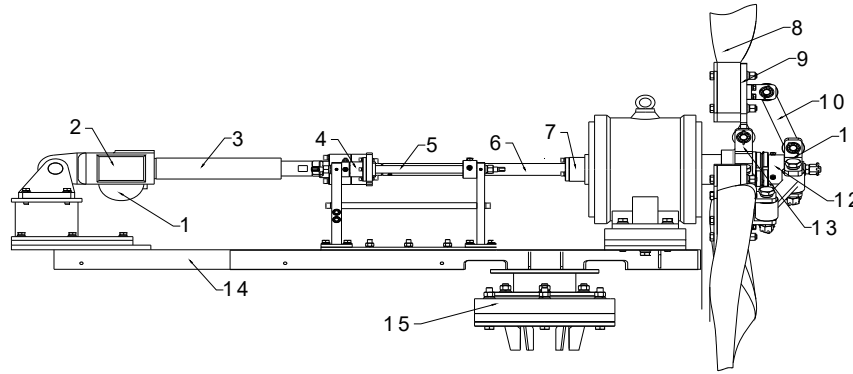
data reference for future umbrella wind turbine design and related work.

2. Umbrella Wind Turbine

2.1. Structure of The Umbrella Wind Turbine

Umbrella-shaped wind turbine is a downwind wind generator, which is mainly driven by servo motor, reducer, electric push rod; Transmission mechanism: pressure bearing, linear optical shaft, guide rod, generator hollow shaft; The blade support is connected to the small hub by connecting rods.

Regulating mechanism: blade, connecting rod, blade support, large hub, small hub, lock nut, engine room base, tower cylinder and other components, as shown in Fig. 1. The electric push rod is connected with the linear optical axis through the pressure bearing; The linear optical axis is connected with the small hub through the hollow shaft of the generator through the guide rod bearing; The blade is connected with the large hub fixed on the hollow shaft of the generator through the blade support; The blade support is connected to the small hub by connecting rods.



1- Servo motor 2- Reducer 3- electric push rod 4- Pressure bearing 5- guide rod 6- Ejector rod 7- Generator hollow shaft 8- blade 9- blade bracket 10- Connecting rod 11- Small hub 12- Lock nut 13- Large hub 14- engine room base 15- Tower barrel

Figure 1. Structure diagram of umbrella wind turbine.

2.2. Action Principle

When the incoming wind speed deviates from the rated wind speed, the servo motor starts to rotate forward and backward, and exerts thrust or tension on the electric push rod through the reducer to achieve the purpose of changing the linear optical axis stroke. The linear optical axis is connected to the blade through the small hub and connecting rod, so the blade can be controlled by the servo motor to do umbrella-shaped closing action to achieve the purpose of changing the blade shrinkage angle. Thus, the sweep area of the wind turbine is changed, and the output power is controlled to ensure the safe operation of the wind turbine. Where, the shrinkage angle γ is the angle between the blade and the plane perpendicular to the incoming wind speed.

3. Numerical Simulation

Due to the umbrella wind turbine power regulation mechanism is very complex, it is difficult to conduct accurate stress analysis of its parts. Numerical simulation method could intuitively and accurately reflect the force situation of the umbrella wind turbine regulation mechanism key components in different shrinkage angle conditions. This obtained the cloud chart of stress concentration parts and provided the foundation for the subsequent load test. Through

the process of 3D model establishment, computing domain construction, grid division and simulation calculation of the umbrella wind turbine, the numerical simulation results of the stress cloud chart in the 220RPM condition of the key components of the regulating mechanism were obtained.

3.1. Connecting Rod

Both ends of the connecting rod have a pin shaft fixed hole, one side is used to connect the small wheel hub, and the other side connects the blade. When the umbrella wind turbine needs to conduct power adjustment, the servo motor pushes the rod reciprocal movement to control the opening and closing action of the blade and change the sweep area of the wind wheel. The force situation of the connecting rod in different shrinkage angle conditions is shown in Fig. 2. As can be seen from the cloud chart, the maximum stress value of the rod is all concentrated on the rod arm near the fixation hole of the side pin shaft of the blade. When the shrinkage angle is 0° , the umbrella wind turbine operates as an ordinary horizontal axis wind turbine and the maximum stress on the connecting rod is 28.067 MPa. When the shrinkage angle is 45° , the maximum stress on the connecting rod is 178.55MPa. When the shrinkage angle is 60° , the maximum stress on the connecting rod is 156.49 MPa. Thus, with the increase of the shrinkage angle, the maximum stress shows first increase and then decrease.

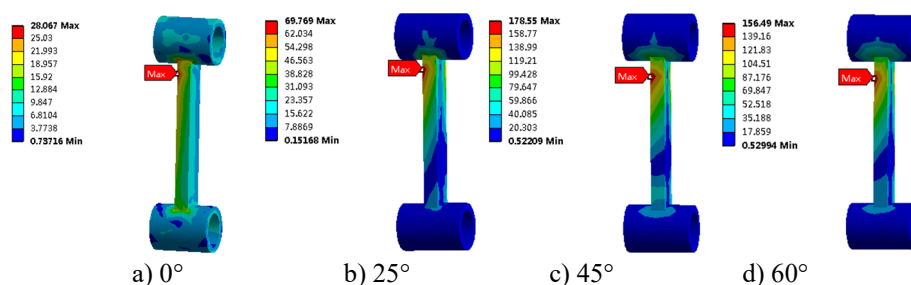


Figure 2. The stress cloud chart of connecting rod in different shrinkage angle.

3.2. Small hub

The small hub is fixed on the top rod, and the servo motor drives the top rod back and forth, and the small hub drives the connecting rod to pull down or push up the blade for realize the adjustment function of the shrinkage angle of the umbrella wind turbine. The force situation of the small hub in different shrinkage angles is shown in Fig. 3. As can be seen from the cloud chart, the maximum stress value of the small hub is concentrated on the fixed arm near the fixed hole of the side

pin shaft. When the shrinkage angle is 0° , the maximum stress of the small hub is 10.865 Mpa. When the shrinkage angle increases to 45° , the maximum stress value of the small hub is 37.059 MPa. Due to the decrease of the wind wheel mass center and the centrifugal force, when the shrinkage angle is 60° , the maximum stress value of the small hub is reduce to 30.689 MPa. Thus, the stress of the small hub is first increasing and then decreasing with the increase of the shrinkage angle.

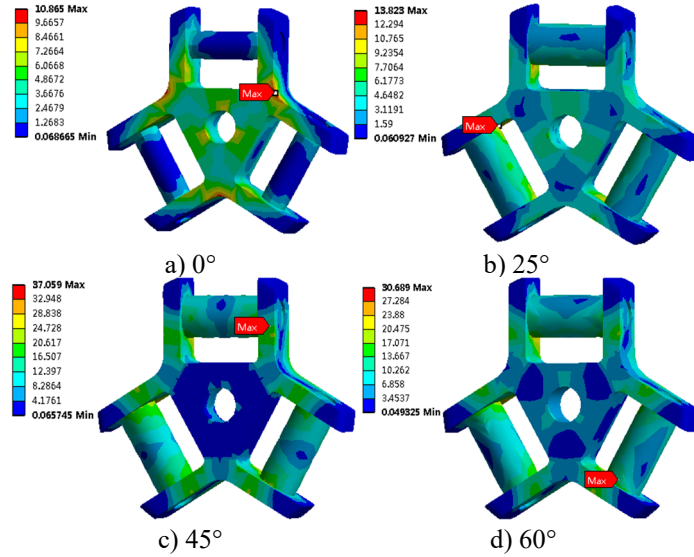


Figure 3. The stress cloud chart of small hub in different shrinkage angle.

3.3. Large hub

The large hub is fixed to the main shaft of the generator to connect the blade and provide the fulcrum for the blade shrinkage. The force situation of the large hub in different shrinkage angles is shown in Fig. 4. As can be seen from the cloud chart, the maximum stress value of the large hub all

appears at the fixed arm of the pin shaft. When the shrinkage angle is 0° , the maximum stress value of the large hub is 57.276Mpa. When the shrinkage angle increases to 60° , the large hub stress value decreases to 24.003Mpa. With the shrinkage angle increases, the trend of change of the large hub stress gradually decreases.

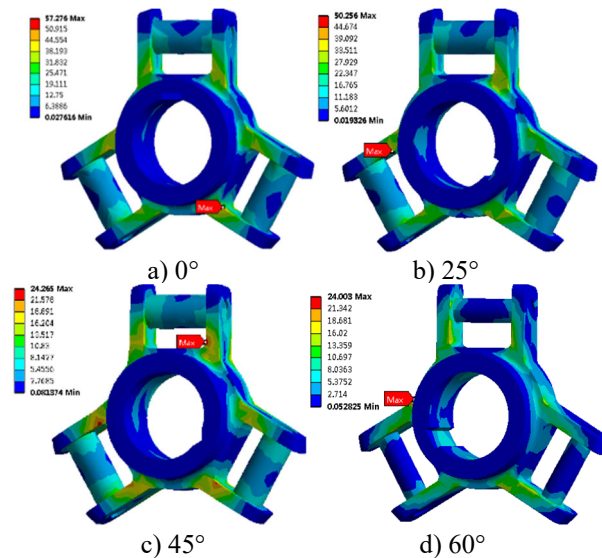


Figure 4. The stress cloud chart of large hub in different shrinkage angle.

3.4. Simulating Results in Different Speed

Because in actual situations, the change in a short period time of the wind speed cause the impeller to contract slowly, so the paper also selected 160RPM and 280RPM as

comparative study. Fig. 5a shows the change trend of the maximum stress value of the connecting rod in different speed, the maximum stress value first increasing and then decreasing when the shrinkage angle adds. Similarly, Fig. 5b shows the change trend of the maximum stress value of the small hub in

different speed. But the maximum stress value of the large hub at each speed condition decrease with the shrinkage angle

increase, its results are shown in Fig. 5c.

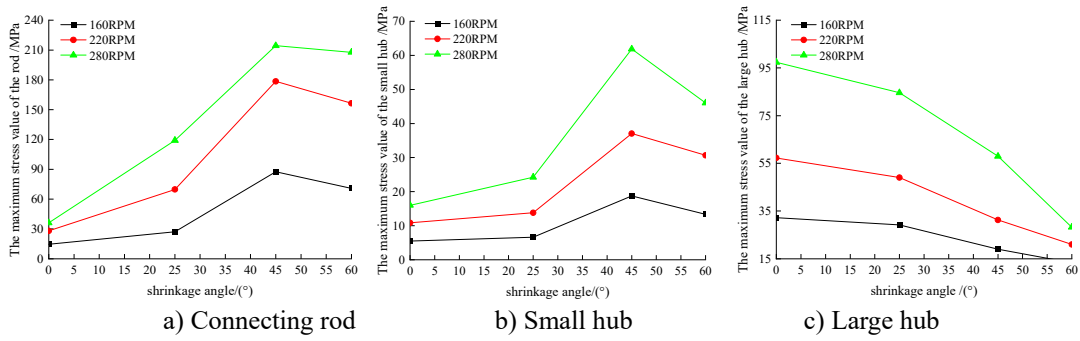


Figure 5. The stress value with the shrinkage angle in different rotational speed.

4. Load experiment

The umbrella wind turbine regulating mechanism parts coupling connection mode was complex, through the test can better grasp the stress of the parts under the actual operating condition, so on the basis of the numerical research of the

umbrella wind turbine regulator key parts load test, exploring the change with the shrinkage angle, verifying the safety and reliability of the umbrella wind turbine power regulating mechanism. The design parameters of umbrella wind turbine are shown in Table 1.

Table 1. Main design parameters of umbrella wind turbine

Design parameter	Value
Air density ρ /($\text{kg}\cdot\text{m}^3$)	1.225
Rated power P_n /(kW)	5
Rated wind speed V_n /($\text{m}\cdot\text{s}^{-1}$)	11
Design rotation rate n_{design} /(rpm)	220
Maximal rotation rate n_{max} /(rpm)	330
Radius of turn R/m	2.4

4.1. Strength Proof

In order to verify the correctness of the materials selected for all parts of the umbrella wind turbine in the design process, and to ensure the safe and stable operation of the umbrella wind turbine in the test environment, the maximum stress of each part under the condition of 280RMP was selected for strength verification. Strength proof conditions are by:

$$\sigma_{max} < \sigma_0 \tag{1}$$

$$\sigma_s = \sigma_0/n \tag{2}$$

where σ_{max} is the maximum stress value of the component calculated by simulation, MPa; σ_0 is the allowable stress value of the material, MPa; σ_s is the yield strength value of the material, MPa; n is the allowable safety factor, where the safety factor is 1.5.

The rod components used structural steel Q345, and the small hub and large hub use 45 # steel. The strength check results are shown in Table 2. The maximum stress value of each component is less than the allowable stress value of the material.

Table 2. Key Component Strength Proof calculation table

Parameter	Connecting rod	Small hub	Large hub
σ_{max} /MPa	214.42	61.86	84.62
σ_s /MPa	345	355	355
σ_0 /MPa	313.64	322.73	322.73

4.2. Experiment Process

Based on the numerical simulation results, the maximum stress concentration position of key components of the umbrella wind turbine, including connecting rod, small hub

and large hub are shown in Fig. 6. The BE350-4FB strain sheet produced by AVIC was selected for the load test, with the resistance value: $350.4 \pm 0.3 \Omega$, and the sensitivity coefficient: $2.07 \pm 1\%$.



a. Connecting rod b. Small hub c. Large hub
Figure 6. Load test measuring point layout.

Before conducting the experiment, adjusted the blade shrinkage angle to determine the travel distance of the top rod, and calibrated at different positions of different shrinkage angles corresponding to the top rod stroke. During the

experiment, the rotation of the servo motor could be manually controlled by controlling the servo motor driver to drive the top rod to the set position and adjust the shrinkage angle of the blade. Figure 7 shows the servo motor controller.

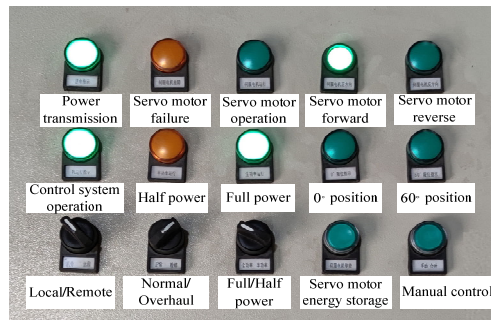


Figure7. Operation of umbrella wind turbine.

The wind speed within 3 ~ 20 m/s was used for the load test of key components of the umbrella wind turbine in different shrinkage angle conditions. After the wind speed in each section is stable, the data was collected and the stable measurement time is 1min. In order to ensure the safety of the

wind turbine during the test, the output voltage of the wind turbine was controlled that the speed does not exceed 350RPM and the output power does not exceed 7.5kW. The operation data of the umbrella wind turbine could be read through data monitoring. The operation is shown in Figure 8.

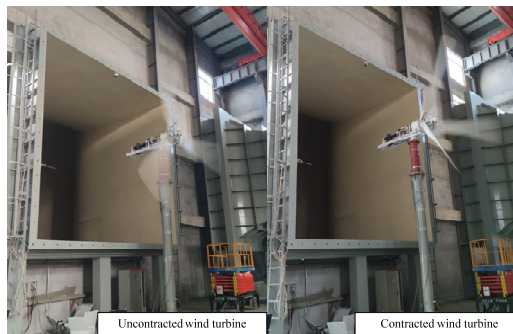


Figure 8. Operation of umbrella wind turbine

4.3. Result

The stress experiment results of the link in different shrinkage angle conditions are shown in Fig. 9a. With the shrinkage angle increasing, the link stress increases first and then decreases in different speed conditions, and reaches the maximum stress value at 45°shrinkage angle, which is consistent with the numerical simulation results. In 220RMP condition for analysis, the linkage stress value measured under 0°shrinkage angle condition is 78.07MPa, and the linkage stress increases to the maximum value of 178.55MPa by 128.70%; as the shrinkage angle continues to increase, the link stress begins to decrease. When the shrinkage angle increases to 60°, the link stress decreases to 148.02 MPa, or 82.90% of the 45°working condition.

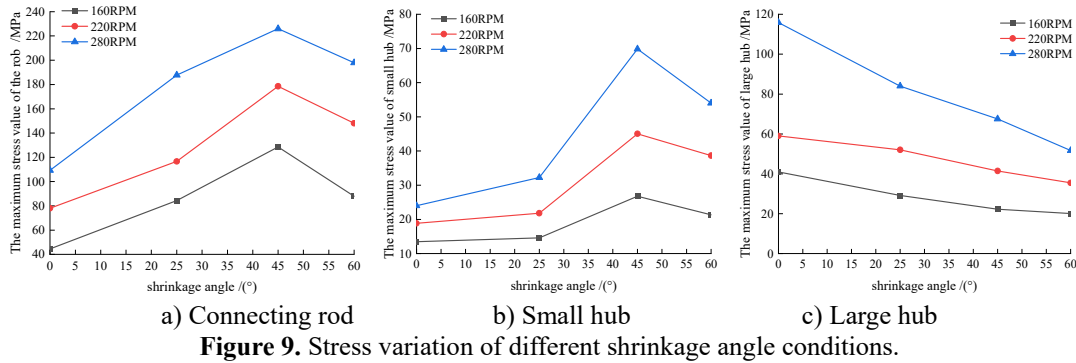
The stress experiment results of small hubs in different

shrinkage angle conditions are shown in Fig. 9b, which is the same as the numerical simulation results. As the shrinkage angle increases, the stress of small hubs is increasing first and then decreasing in different speed conditions, and then the maximum stress value is reached at the 45°shrinkage angle. Select 220RMP condition for analysis, the small hub stress value under 0°shrinkage angle is 18.87MPa, as the shrinkage angle increases to 45°, the small hub stress increases to 45.06MPa, the increase is 138.79%; As the shrinkage angle continues to increase, the small hub stress begins to decrease. When the shrinkage angle increases to 60°, the small hub stress decreases to 38.69 MPa, or 85.86% of the 45°working condition.

The stress experiment results of large hubs in different shrinkage angles are shown in Fig. 9c. The test measurement increases with the shrinkage angle, and the stress of large hubs

decreases, which is consistent with the numerical simulation results. The 220RMP condition was selected for analysis. If the large hub stress value measured in the 0°shrinkage angle

condition is 59.03MPa, the shrinkage angle increases to 60°, and the small hub stress is reduced to 35.47MPa, which is 60.09% of the 0°condition.

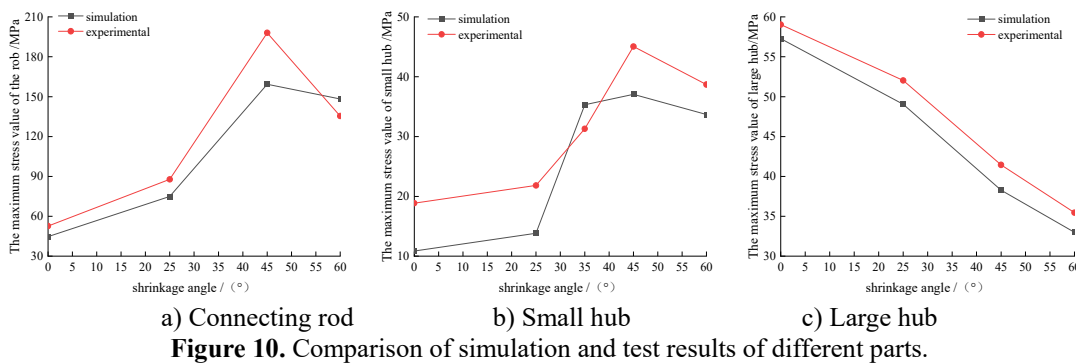


5. Comparison Between Experimental and Simulation Results

The numerical simulation results and the experimental results under the rated speed of 220RMP are selected for comparison. The results are shown in Fig. 10, and the numerical simulation results are basically consistent with the change trend of the test results. For linkage and small hubs, the stress results obtained by simulation and test increase first and then decrease with the increase of shrinkage angle, and all reach the maximum stress value at 45°; for large hubs, the stress results obtained by simulation and test decrease with

the increase of shrinkage angle. Although the test results are generally higher than the numerical simulation results, this is due to the factors such as extrusion between the components in the real environment.

To sum up, whether in the numerical simulation or test results in the 45° shrinkage angle condition of the key components connecting rod and small hub will reach the maximum stress value, so in the future application of umbrella wind turbine in the 45°, on the other hand should pay special attention to the operation of the connecting rod and small hub, to avoid the excessive deformation to the umbrella wind turbine safety risks.



6. Conclusions

In this paper, through numerical simulation and wind tunnel test, the stress conditions of key parts of the regulating mechanism of umbrella wind turbine under different shrinkage angles were investigated and analyzed, and the following conclusions were drawn.

Through experiment numerical simulation of the key components of the umbrella wind turbine regulating mechanism in different shrinkage angle conditions, the maximum stress value of the connecting rod is concentrated on the fixed arm near the fixed hole of the side pin shaft, and the strength of the above components meets the use requirements.

Through the test study of the key components of the umbrella wind turbine regulating mechanism in different shrinkage conditions, it is concluded that as the shrinkage angle increases, the stress on the connecting rod and the small hub increases first and then decreases, and reaches the maximum value under the 45° shrinkage angle; as the shrinkage angle increases, the stress on the large hub

decreases. The most special position of 45°shrinkage angle condition should be given key attention.

Acknowledgment

Inner Mongolia Natural Science Foundation, Study on fluid-structure interaction characteristics of umbrella wind turbine [grant no. 2020MS05032].

References

- [1] Pasupulati, S.V, J. Wallace J, and M. Dawson M. Variable length blades wind turbine, Proceedings of IEEE Power Engineering Society General Meeting, (2005).
- [2] Stoyanov, D. B.,Nixon, J. D. Alternative operational strategies for wind turbines in cold climates, Renewable energy, Vol.145(2020) No.1, p.2694-2706.
- [3] Franchina N, Persico G, Savini M. 2D-3D Computations of a Vertical Axis Wind Turbine Flow Field: Modeling Issues and Physical Interpretations, Renewable Energy, Vol.136(2019) No.6, p.1170-1189.

- [4] Dose B, Rahimi H, Stoevesand B, et al. Fluid-structure coupled investigations of the NREL 5 MW wind turbine for two downwind configurations, *Renewable Energy*, Vol.146(2019) No.2, p.1113-1123.
- [5] Xie, W., Pan Zeng, P., and Liping Lei. L. A novel folding blade of wind turbine rotor for effective power control, *Energy Conversion and Management*, Vol.101(2015), p.52-65.
- [6] Bao Daorina, Liu Xujiang, Wang Shuailong, et al. Study on stress strain characteristics of variable eccentric distance wind turbines, *Acta energiae solaris sinica*, Vol.43(2022), No.5, p296-304.
- [7] Bao Daorina, Liu Xujiang, Wang Xiaoxue, et al. Experimental verification of power regulation method for variable eccentricity wind turbine, *Acta energiae solaris sinica*, Vol.41(2020), No.10, p323-331.
- [8] Bao Daorina, Liu Xujiang, Wang Xiaoxue, et al. Analysis of Output Characteristics for Small Horizontal Axis Variable Eccentricity Wind Turbines, *China mechanical engineering*, Vol.31(2020), No.18, p2196-2205.
- [9] Liu Xiongfei, Wang Jianwen, Sun Feng, et al. Optimization analysis of the inclination angle of the gravity speed regulating mechanism of the wind turbine, *Acta energiae solaris sinica*, Vol.38(2017), No.7, p1929-1934.
- [10] Sun Feng. Liu Xiongfei, Wang Jianwen. Analysis on the mechanism of speed limit of gravity return type wind turbine, *Acta energiae solaris sinica*, Vol.(2017), No.1, p1-6.
- [11] Sun Feng. Wang Jianwen, Liu Xiongfei. Mechanism analysis and inclination optimization of wind turbine side speed limit mechanism, *Journal of Drainage and Irrigation Machinery Engineering*, Vol.35(2017), No.2, p152-157.