

An Innovative Umbrella-Type Rotor of Horizontal Axis Wind Turbine to Regulate Power and Reduce Wind Thrust

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Abstract

The concept of innovative umbrella-type rotor of horizontal axis wind turbine is proposed in current study. This rotor type is designed to realize both active power regulation and wind thrust reduction. The rotor is folding at hub and is pitching and coning coupled due to the inclined folding axis, which resembles the umbrella configuration. The folding mechanism that aims at refining the loads at hub has also been designed. Wind tunnel experiments for small rotor models have been conducted to offer data. The rotor performance is estimated in terms of power coefficient (C_p) and thrust coefficient (C_t). Wind tunnel test result shows that the innovative rotor effectively regulates C_p and C_t . The highest C_p and C_t are 0.048 and 0.28 respectively, while by regulation the lowest value are simply 0.009 and 0.16 respectively in current study. It is also found that the regulation sensitivities are larger in case of larger folding axis incline angle. A constant power output of 0.521 watt in increasing wind speed is achieved and the fold angle variation relative to wind speed is obtained. In addition, the innovative rotor is found to bear less thrust than the traditional pitch regulated type, with the maximum reduction about 7.4% in current study. A detailed load analysis on the proposed folding mechanism has also been conducted. It is found that moments acting on the hub are converted to the tension mode. The folding mechanism well refines the loads distribution on hub.

Key words: blade pitch; rotor coning; power coefficient; wind thrust;

1. Introduction

The development of wind turbine is consistently associated with two topics: the power regulation and wind loads reduction. Power regulation is typically achieved by blade stall and pitch control. New approaches have been proposed, for example the retractable rotor [1] and blade partial span pitch control [2]. For wind loads reduction, the DOWEC project proposed a pre-coned upwind rotor with flexible blades [3]. Actually, late in the last century, aiming at controlling both power and loads, downwind configured, active stall and coning controlled rotor concept has been raised [4]. The two blades were hinged on the teetering hub through a "three-point support structure". Through the rotor coning deflection, the blade span direction aligns with the load direction and thus the cantilever-based loads are reduced considerably. It is reported that the blade and rotor loads are reduced between 25% to 50% during operation as well as during stand still in extreme winds.

In current study, an innovative umbrella-type rotor is proposed. This rotor aims to offer a new approach to regulate power and reduce wind thrust. It is upwind configured and blades are capable to fold upstream at hub according to wind conditions, which resembles the umbrella configuration. The folding axis, however, is not perpendicular to the blade span direction, and instead, inclines to it, tilting down to the rotor revolution direction. Consequently, the rotor is pitching and coning coupled by the folding hinge structurally. The folding axis incline angle (γ) determines pitching and coning sensitivities theoretically. The proposed rotor is illustrated in Fig. 1.

Rotor pitching plays a key role in regulating power and wind thrust, and besides, rotor coning results in swept area reduction which offers extra wind thrust reduction.

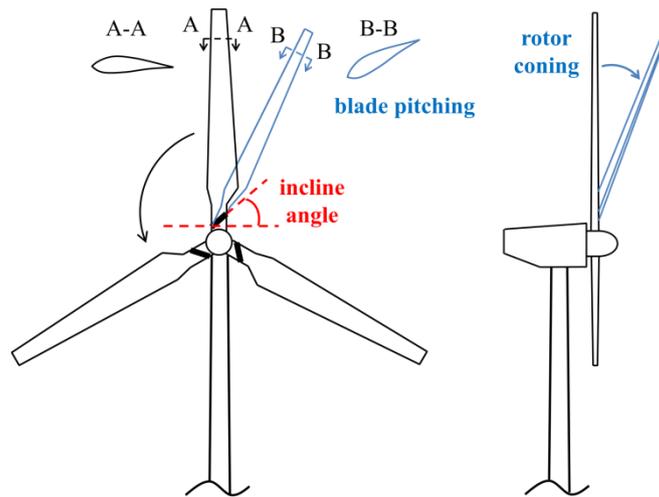


Figure 1: Concept of innovative umbrella-type rotor

A folding mechanism for umbrella-type rotor has been designed elaborately. The mechanism consists of a hub, an inclined hinge assembling and an actuating structure shown in Fig. 2. The blade is connected to the hub by the inclined hinge assembling. A screw rod is fixed on the center line of the hub and is driven by the motor. Once the screw rod rotates, a slider moves linearly along it. This movement is transferred to the blade folding motion through a link rod as the link rod connects blade root and slider with spherical joints. From the loading point of view, since the hinge assembling is incapable in offering torque along the folding axis direction, the huge bending moment on hub is considerably converted to the tension of the link rod and the compression of the screw rod. Compared to the blade span dimension, the hub dimension (l) is much smaller. Hence, bending acting on the hub is sufficiently reduced. In practice, the hub dimension (l), the distance between link support position and hinge (J) and the screw rod length (K) are determined and optimized according to rotor operation conditions. Since screw rod is usually designed as short as possible, and tension mode is a favorable load pattern for link structure, the loads on the hub is believed to be well refined. All the components are covered in a cowling, avoiding damages from the natural environment.

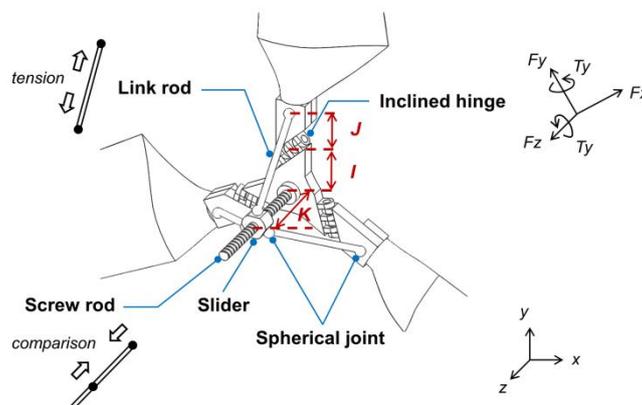


Figure 2: Schematic diagram of folding mechanism for umbrella-type rotor

The patent authorization of this rotor concept and corresponding folding mechanism design is in process [5]. By conducting wind tunnel experiment, supporting data is obtained to validate the rotor effectiveness in power and wind thrust regulation. In engineering practice, the detailed rotor aerodynamic analysis is required. In

current study, loads on key components of folding mechanism are also analyzed based on a specific condition. This analysis aims at demonstrating the folding mechanism load-relief property. Further studies are required to promote this rotor design and development.

2. Experiment setup

The experiments were conducted in a low speed wind tunnel in Tsinghua University. A rotor test system with a magnetic brake and sensors to measure revolution rate, torque and wind thrust was set up. A photograph of the test system is shown in Fig. 3. The tested blade has a length of 0.3 m and is scaled down from the “NREL PHASE VI” blade with a scaling ratio of 15:1. All the tested rotors were configured with three blades and possessed a diameter of 0.65 m with a wind tunnel blockage ratio of 14.7%. The original “NREL PHASE VI” rotor test conditions were not available in current experiment due to facility capacity limits including load and revolution rate measurement limits. Besides, in the trial test, during pitching process, the power of rotor with scaled down original blades was found to increase initially and then drop down. As the innovative rotor is designed to reduce power output consistently during the overall pitching process, the tested blade is pre-pitched at 18.18° . The modified blade then possesses a much lower C_p (power coefficient) and TSR (tip speed ratio), meeting the measurement requirements. Since the experiment is to prove the innovative rotor validity in power and wind thrust regulation, the blade modification including profile scaling down and pre-pitching is believed to be reasonable. Three hubs with incline angle of 30° , 45° and 60° , a pitch regulated hub and blades were 3D printed with synthetic resin. The fold angle and pitch angle were adjusted manually and blades were fixed at desired fold or pitch angle during experiments. A tested rotor in wind tunnel is shown in Fig. 4. The wind thrust data was collected for the whole turbine including rotor and nacelle, and then the turbine C_t (thrust coefficient) was calculated. Rotor swept area diminishment due to rotor coning was not taken into account in calculating C_p and C_t . The blockage correction was considered based on Ref. [6].

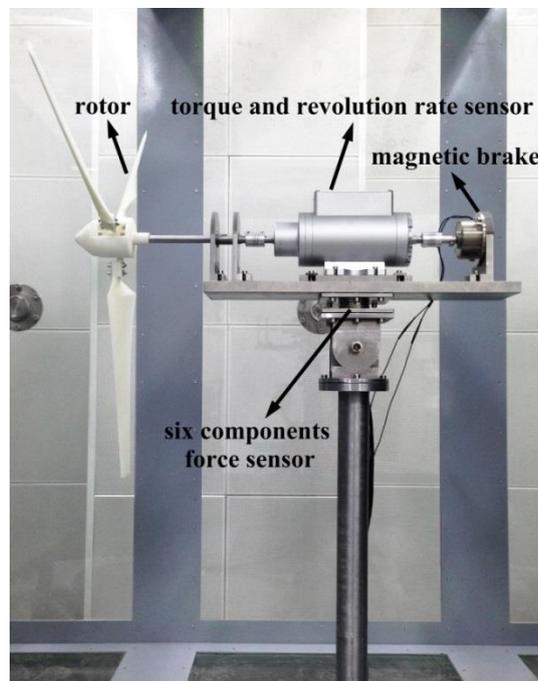
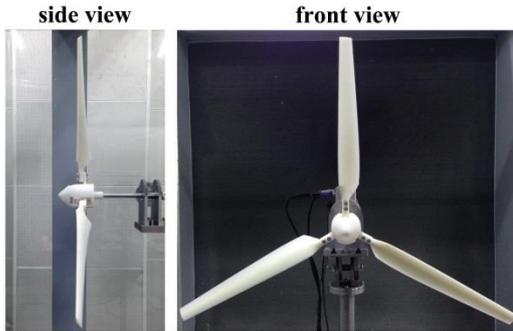


Figure 3: Photograph of rotor test system

unfolded blade



folded blade

incline angle: 60°; fold angle: 40°

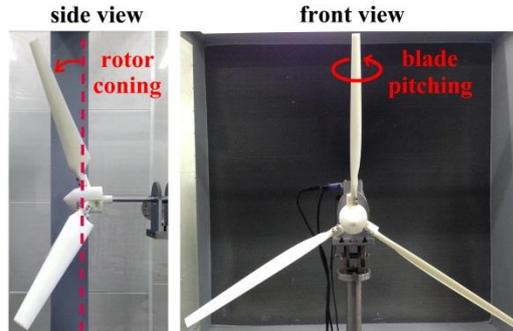


Figure 4: Photograph of tested umbrella-type rotor

The following steps are taken to study the innovative rotor performance. Firstly, turbine C_p and C_t are measured in wind speed of 4 m/s for rotor with γ of 45°. This experiment is to study the innovative rotor model aerodynamic performance. Next, in increasing wind speed, the rotors are folded or pitched to regulate power. This experiment is conducted for rotors with γ of 30°, 45° and 60° and pitch regulated rotor. Then, based on power regulation experiment data, C_p regulation sensitivity is analyzed for three umbrella-type rotors. Wind thrust is compared between turbines with umbrella-type and pitch regulated rotors. Turbine C_t regulation sensitivity is also analyzed. Finally, an umbrella-type rotor with three original “NREL PHASE VI” blades is modeled and the multi-body dynamic analysis is conducted. The loads distribution on the folding mechanism is analyzed and the results are also compared to that of an ordinary fixed hub.

3. Results, analysis and discussion

3.1 Power regulation performance of umbrella-type rotor

The turbine C_p and C_t for rotor ($\gamma=45^\circ$) in wind speed of 4 m/s are shown in Fig. 5. A drastic drop of both C_p and C_t , and a shift of TSR to lower range are found as the blade is folded. The turbine highest C_p and C_t are 0.048 and 0.28 respectively for normal rotor, while they drop to 0.009 and 0.16 for rotor with fold angle of 40°. This rotor behavior is favorable in high wind speed. The decline of C_p and C_t could lead to limitation on power and wind thrust growth, and low TSR avoids the over speed of rotor. The result shows that the innovative rotor has potential to achieve both power and wind thrust regulation.

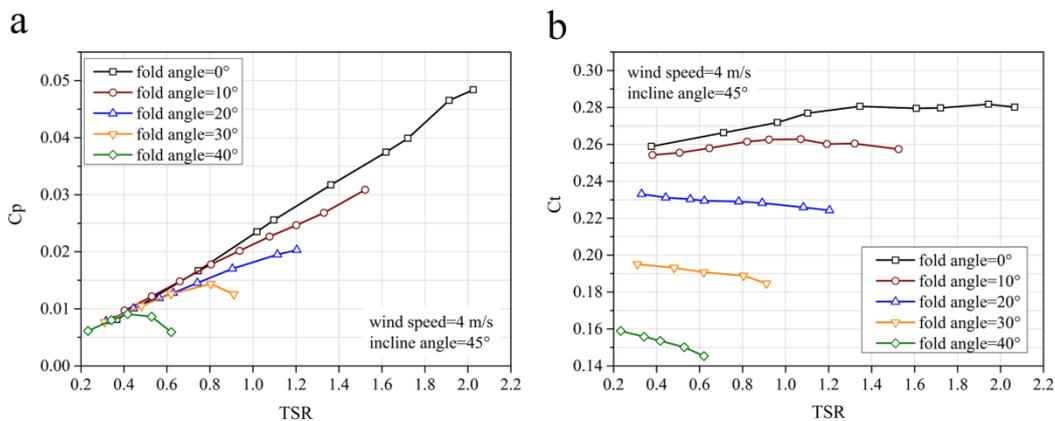


Figure 5: Umbrella-type turbine performance: (a) C_p variation along TSR and (b) C_t variation along TSR

Fig. 6 shows the rotor fold angle variation along wind speed to maintain constant power of 0.521 watt. In the experiment, the brake torque was fixed and the rotor revolved at 200 RPM constantly. The wind speed was

adjusted so that the rotor maintained the constant speed and power output. Results reveal that fold angle increases with the wind speed. The fold angle adjustment is less in case of larger incline angle. This result sufficiently demonstrates that the rotor is capable in regulating power and limiting speed growth in high wind speed.

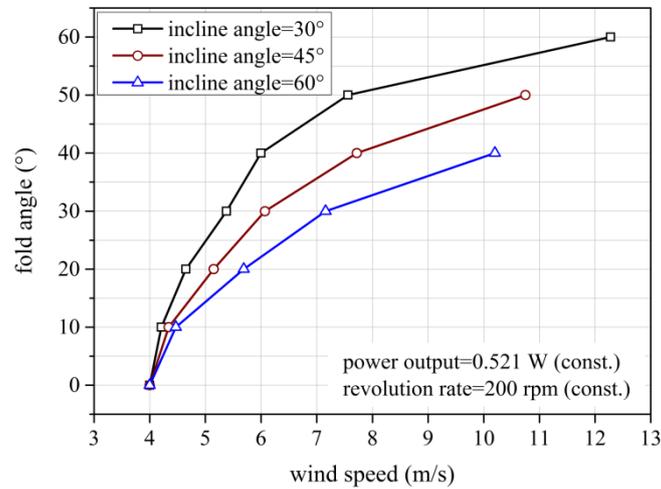


Figure 6: Fold angle variation along wind speed to maintain constant power

Based on power regulation experiment data, rotor C_p variation along fold angle is analyzed shown in Fig. 7. For all innovative rotors, C_p decreases with the increase of fold angle. It should be noticed that larger incline angle leads to more sensitive C_p regulation. At fold angle of 40°, C_p is 0.0024 for rotor with γ of 60°, which is simply 20.39% to that with γ of 30°. This is due to the fact that larger incline angle leads to higher pitching rate. The experiment result indicates that incline angle magnitude is the key to C_p regulation sensitivity.

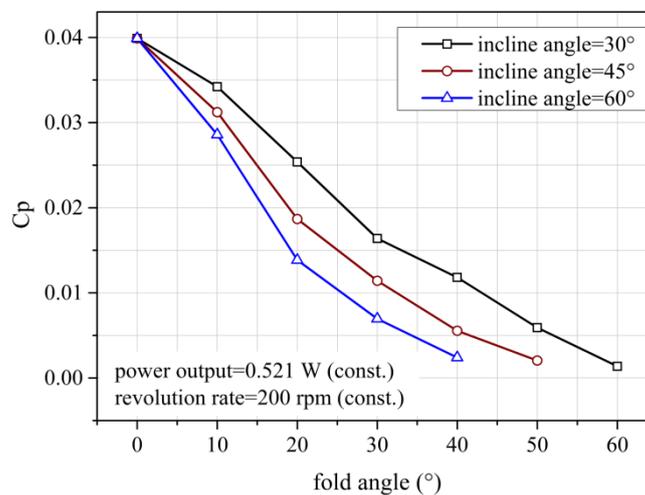


Figure 7: Umbrella-type rotor C_p variation along fold angle

3.2 Investigation on wind thrust acting on umbrella-type rotor

An identical power regulation experiment was conducted for the pitch regulated rotor. Wind thrust data for turbines with three umbrella-type and pitch regulated rotors are presented in Fig. 8. Under identical operation conditions, less wind thrust is observed for umbrella-type turbines as compared to pitch regulated type. This phenomenon corresponds to the distinct rotor coning configuration which is not available for pitch regulated type. A detailed analysis on the thrust comparison is shown in Fig. 9. As can be seen, the smaller incline angle is, the less wind thrust the turbine bears. For turbine with γ of 60°, the highest thrust is 98.2% to that of pitch regulated

type, yet it is 92.6% for turbine with γ of 30° . This is reasonable as smaller incline angle provides a higher coning rate. The umbrella-type turbine C_t variation along fold angle is presented in Fig. 10. Similar to C_p , C_t declines considerably for all tested rotors and the variation is more sensitive in case of larger incline angle. Considering Fig. 7, Fig. 9 and Fig. 10, for umbrella-type rotor, blade pitching is the key to C_p and C_t regulation sensitivity. However, under identical C_p conditions, rotor coning provides an extra C_t reduction.

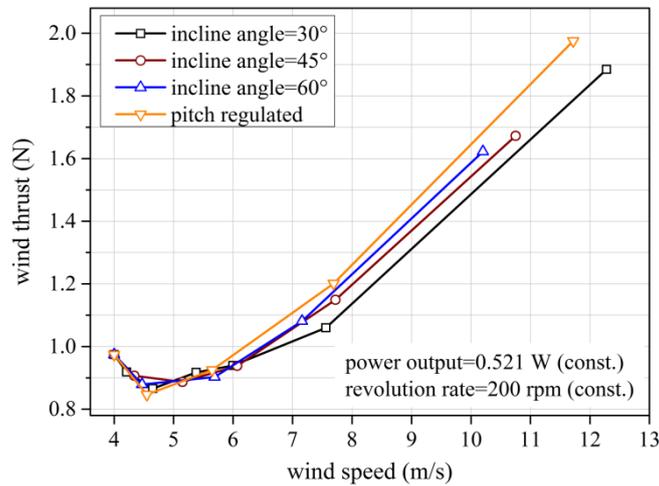


Figure 8: Wind thrust variation along wind speed for tested turbines

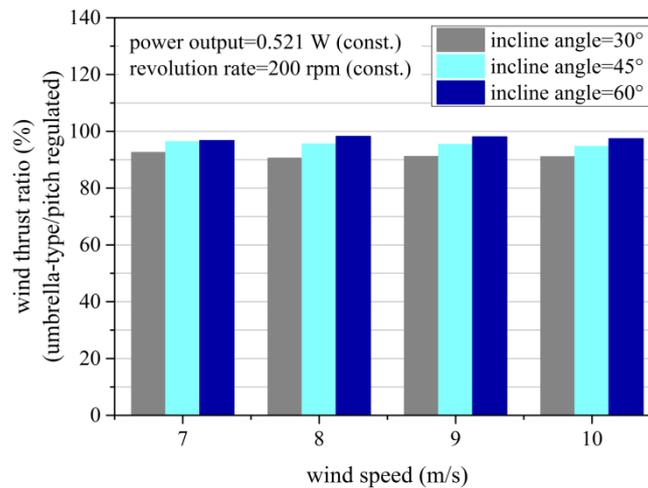


Figure 9: Wind thrust ratio of umbrella-type to pitch regulated turbine

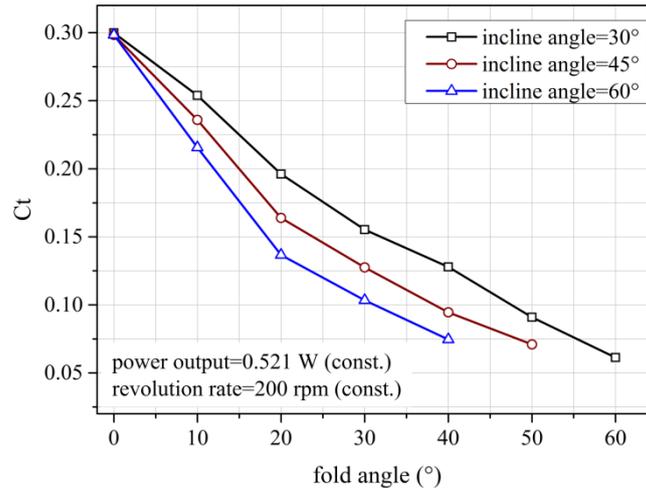


Figure 10: Umbrella-type turbine C_t variation along fold angle

3.3 Analysis on loads acting on folding mechanism

In order to have an insight on the folding mechanism behavior, an analysis on loads acting on key components of folding mechanism was conducted. In this analysis, the blade scale and profile is identical to the “NREL PHASE VI” blade with a length of 5.029 m and a mass of 60.25 Kg. As a modification, the rotor consists of three blades and the blade pitch angle is fixed at 3° . The hinge incline angle is 45° and each blade is folded at 20° . For folding mechanism geometry, referring to Fig. 2, the rotor hub dimension (I) is determined as 0.33 m and distance between link support position and hinge (J) is 0.515 m. The screw rod length (K) is 0.54 m. According to Ref. [7], each blade is divided into 11 segments and the mass and aerodynamic properties are applied to each blade element. The rotor revolves at 71.63 RPM and the wind speed is fixed at 10 m/s. An algorithm based on modified BEM (blade element momentum theory) has already been developed by the authors to calculate the umbrella-type rotor aerodynamic loads. Based on this code and the operation condition, the rotor aerodynamic loads are obtained. Furthermore, blade gravities and centrifugal forces are obtained and all these loads are applied to blade elements. By solving the equilibrium equation of the rotor system, the forces on the hinge axis and the link rod are gained. It is to be noticed that the blade to which the hinge is connected is straight up originally with blade phase of zero. As a comparison, the blade is also connected to the hub simply through a fixed connector which possesses an identical orientation as the inclined hinge assembling. The loads on the inclined hinge and the fixed connector are compared.

The six force components acting on the hinge and the fixed connector are shown in Fig. 11. The force direction definition is based on folding axis local coordinate shown in Fig. 2. As can be seen, folding hinge and fixed connector bear comparable force components of both f_x and f_y , while a considerable decline of torque t_x is observed in case of folding hinge. This is reasonable since the hinge is incapable of offering torque along its rotation axis. Similar behavior is observed for torque t_y . The highest torque t_y acting on folding hinge is -610 Nm and yet the highest acting on fixed connector reaches 3322 Nm. In addition, folding hinge shows advantages in alleviating torque along wind speed direction t_z . Due to the distinct folding mechanism design, the moment t_x and t_y are converted to the tension of link rod. The link rod bears a tension between 14966 N to 17344 N. To be balanced, the folding hinge consequently bears an additional considerable force f_z as shown in Fig. 11. As mentioned in section 1, the previously proposed downwind coning rotor also utilizes rotor coning and pitching to regulate power and wind thrust. By coning rotor downwind, this kind of rotor tries to align wind loads along blade span direction to reduce cantilever loads. However the proposed folding mechanism effectively utilizes the principle of truss-frame structure to convert torques and moments to tension mode.

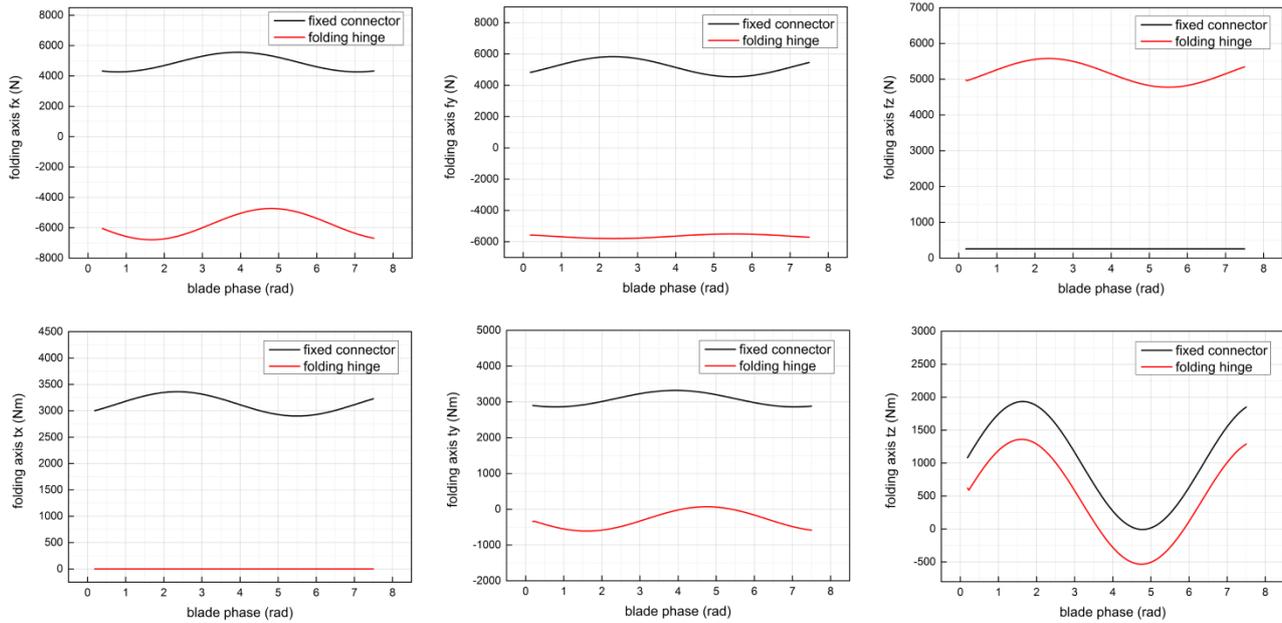


Figure 11: Loads acting on folding hinge and fixed connector

Conclusion

An innovative umbrella-type rotor concept for power regulation and wind thrust reduction is proposed. Umbrella-type rotor models were made and wind tunnel experiments were conducted. The turbine C_p and C_t declined considerably when the blades were folded. The highest C_p and C_t were 0.048 and 0.28 respectively, while by regulation the highest values were simply 0.009 and 0.16 respectively in current study. Constant speed of 200 RPM and power of 0.521 watt were achieved with the umbrella-type rotor models in increasing wind speed. Innovative rotor is more desirable in reducing wind thrust than pitch regulated type. Compared to pitch regulated rotor, the maximum thrust reduction about 7.4% was found for umbrella-type rotor in current study. In addition, for innovative rotor, larger incline angle leads to both more sensitive C_p and C_t regulations. A folding mechanism for umbrella-type rotor is also proposed. Compared to fixed connector between blade and hub, the moments acting on folding hinge are much less and are converted to the link rod tension mode. The load pattern for the folding mechanism is favorable.

Acknowledgement

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