Structure Design and Analysis of a Novel Forward-folding Rotor used in a Downwind Horizontal-axis Turbine

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Abstract. To alleviate the stiffness constraints of the conventional blade and thus reduce the rotor mass, a novel forward-folding rotor (Downwind Forward-folding Rotor, DFFR) used in a downwind horizontal-axis turbine is presented. This novel rotor is designed to align the combination of gravitational, centrifugal, and thrust forces along the blade path, resulting in primarily tensile loads instead of cantilever loads on the blades. The DFFR blades fold forward at a power-limited condition, which induces the change of the blade pitch angle and cone angle and thus maintains a constant power output. To quantify the mass savings, a 5-MW DFFR was designed based on the NREL 5-MW reference rotor. According to the results calculated by an improved BEM method, the rotor power and torque of the 5-MW DFFR have a slight increase compared with those of the NREL-5MW reference rotor, while the rotor thrust of the 5-MW DFFR is smaller than that of the NREL-5MW reference rotor. Furthermore, based on the finite element analysis, the blade of the 5-MW DFFR had an 18.9% mass saving and an 8.4% peak stress reduction compared with the blade of the NREL-5MW reference rotor, over a range of operating wind speeds and azimuthal angles.

1. Introduction

Wind energy, a kind of renewable energy, has been widely utilized over the past decades in the world. The average wind turbine rated power has increased 60-fold over the past 40 years and is expected to reach 10-20 MW in the future [1, 2]. One of the most significant design issues associated with the large-scale wind turbines is limiting the blade mass. It is difficult to reduce the blade mass for conventional large-scale wind turbines since the blade mass is fundamentally related to the stiffness required to prevent the blade-tower strike and resist the peak loads. In this regard, downwind configuration was considered to be used in the large-scale wind turbines since the blade-tower collisions are avoided in operation, thus the blade can be designed lighter and more flexible to reduce the manufacture and installation cost [3-5].

Some innovative downwind rotor concepts, such as a downwind coned rotor (present by P M Jamieson et al. [6]) and a two-bladed 15 kW flexible downwind turbine (presented by F Rasmussen et al. [7]), were proposed to relax stiffness constraints of the conventional blade. However, these rotor concepts were mainly used in the small or medium scale turbine. Therefore, a morphing downwind-aligned rotor (MoDaR) [8] and a downwind pre-aligned rotor (DPAR) [9] applied in extreme-scale wind turbines (≥10 MW) were proposed by B Ichter et al. and E Loth et al., respectively, to achieve blade mass saving and peak structural stress reduction. Nevertheless, the additional morphing
mechanism in the MoDaR may negate these mass savings [8], while the rotor cone angle cannot be adjusted in the DPAR [9].

Based on the previous work, a novel rotor concept with blade forward-folding along the oblique axis used in the large-scale downwind turbine was previously introduced by H Meng et al. [10] and defined as a downwind forward-folding rotor (DFFR). In the DFFR, the rotor cone angle and the blade pitch angle can be adjusted coupledly by only one mechanism (an oblique folding axis), to achieve peak structural stress reduction and power output control simultaneously. In this paper, the structural design and mass saving analysis of a 5-MW DFFR were presented. The structural analysis results of the 5-MW DFFR was also compared with that of the NREL 5-MW reference rotor to validate the peak stress reduction by blade forward-folding method.

2. Concept of the downwind forward-folding rotor

As shown in Figure 1, the blade of the DFFR can fold along a near-hub oblique axis instead of rotating around the pitch axis, to maintain a constant power output under the power-limited condition. The incline angle of the folding axis ($\gamma$), is defined as the angle between the folding axis and the axis that is perpendicular to the blade length direction, and is in the range from -90º to 90º. The blade fold angle ($\delta$) is defined as the blade rotation angle along the folding axis, as shown in Figure 1. When the blade folds along the folding axis, both the blade coning (control the load alignment) and the pitching (control the power output) is generated.

![Figure 1. Schematic diagram of the DFFR.](image)

Inspired by the load alignment concept [8], the DFFR folds at a certain angle (defined as initial fold angle ($\delta_0$)) at the sub-rated and rated wind speeds ($V_{cut-in} \leq V \leq V_{rated}$) to align the combination of the gravitational, centrifugal, and thrust forces along the blade path (in Figure 1), resulting in primarily tensile loads. When the wind speed increases above the rated wind speed, the blades fold forward, leading to the increase of the blade pitch angle ($\beta$) to maintain constant power output, as well as the decrease of the induced rotor cone angle ($\theta$) to achieve the load alignment (because of the reduced downwind thrust). As shown in Figure 1, the fold angle ($\delta$) can be decomposed into three components: induced rotor cone angle ($\theta$), induced slant angle on conical surface ($\phi$), and induced blade self-rotation angle ($\psi$). These three angles can be shown as follows:

$$\theta = \arctan \frac{\cos \gamma \sin \delta}{\sin^2 \gamma + \cos^2 \gamma \cos \delta}$$
\[
\varphi = \arcsin \left( \sin \gamma \cos \gamma \left(1 - \cos \delta \right) \right)
\]

\[
\psi = \arctan \left( \frac{\sin \gamma \sin \delta}{\cos^2 \gamma + \sin^2 \gamma \cos \delta} \right)
\]

Figure 2 shows the relationship of the fold angle (\(\delta\)), the blade angle of attack (\(\alpha\)), and the rotor power output (\(P\)) with respect to the wind speed. It can be seen that under (a) sub-rated and (b) rated conditions, the DFFR operates with an initial fold angle (\(\delta_0\)). The blades fold forward when the wind speed increases above the rated wind speed, and the blade angle of attack (\(\alpha\)) of the DFFR decreases, which can degrade the blade aerodynamic performance and thus maintain a constant power output.

3. Blade design for a 5-MW DFFR

To quantify the mass saving benefits of the DFFR, the blade model of a 5-MW DFFR was established based on the NREL 5-MW reference wind turbine rotor [11] (defined as 5-MW ConvR). The incline angle of the folding axis (\(\gamma\)) and the initial fold angle (\(\delta_0\)) are designed as 60º and 35º, respectively, and the location of the folding axis was defined as 11.3% blade span. The 5-MW DFFR has the same airfoil, blade size, and chord length distribution as the 5-MW ConvR, while the blade twist angle distribution of the DFFR need to be re-designed based on the ConvR to eliminate the change of blade pitch angle induced by the initial fold angle (\(\delta_0\)). Based on the improved blade element momentum (BEM) method proposed by W Xie et al. [12], the blade angles of attack of the DFFR were ensured to be the same as those of the ConvR, by adding different offset angles to the twist angle of each blade element all along the blade span of the ConvR. The twist angle and the angle of attack distributions of the ConvR and the DFFR along blade span were shown in Figure 3.

The blade internal structure and material of the ConvR and the DFFR were referred from the technical report presented by B R Resor [13]. Different parts (leading edge, spar cap, trailing edge, reinforcement, and shear web) of the entire blade are composed by several layers of different materials. Material properties used in the blade model are summarized in Table 1.
To provide a comparison to the DFFR concept, a conventional 5-MW turbine blade was first created according to the literature [13], the internal structure of the conventional blade can be seen in Figure 4(a). For the 5-MW DFFR blade, compared with the 5-MW ConvR, the numbers of material layers of the spar cap (UD Carbon), leading edge (FOAM) and the trailing edge (FOAM) were reduced, while the number of material layers of the blade root (Triax) was slightly increased, as shown in Figure 5. Furthermore, the shear webs thickness of the DFFR blade were reduced from 50 mm to 30 mm, and a third shear web was added to the trailing edge. The internal structure of the DFFR blade can be seen in Figure 4(b). The blade mass of the DFFR was calculated as 10,302 kg after mass reduction design, compared to the counterpart of the ConvR blade with a mass of 12,703 kg, having an 18.9% mass reduction.

Table 1. Summary of material properties [13].

| Layer Thickness (mm) | Ex (MPa) | Ey (MPa) | Gxy (MPa) | prxy | Dens. (kg/m$^3$) | Main material for which part |
|----------------------|----------|----------|-----------|------|-----------------|-----------------------------|
| Gelcoat              | 0.05     | 3440     | 1380      | 0.3  | 1235            | Blade surface               |
| E-LT-5500 (UD)      | 0.47     | 41,800   | 14,000    | 2630 | 0.28            | 1920                        |
| (Triax)             | 0.94     | 27,700   | 13,650    | 7200 | 0.39            | Blade root                  |
| Saeretex (DB)       | 1        | 13,600   | 13,300    | 11,800 | 0.49            | Shear web                   |
| FOAM                | 1        | 256      | 256       | 22   | 0.3             | 200                         |
| Carbon (UD)         | 0.47     | 114,500  | 8390      | 5990 | 0.27            | 1220                        |

Figure 3. Twist angle and angle of attack (AoA) distributions of the ConvR and the DFFR along blade span station.

Figure 4. Cross section of internal structure for the (a) ConvR blade and (b) DFFR blade.
4. Aerodynamic and structural analysis for the conventional and DFFR blades
Before conducting the structural analysis of the two blades, the aerodynamic forces of the two rotors should be determined first. Blade Element Momentum (BEM) method, a basic theory in the field of rotor aerodynamics, was applied to calculate the rotor torque, thrust and power of the 5-MW ConvR under various operating wind speeds. The results of calculation were quite coincident with the values in the NREL 5-MW reference turbine report [11]. For the 5-MW DFFR, an improved BEM method [12] was used to calculate the aerodynamic forces. The calculated results of the two rotors were shown in Figure 6, it can be seen that the rotor power and torque of the 5-MW DFFR have a slight increase compared with those of the 5-MW ConvR, while the rotor thrust of the 5-MW DFFR is smaller than that of the 5-MW ConvR.
Figure 6. Comparison of the (a) rotor torque, (b) rotor power, and (c) rotor thrust between the ConvR and the DFFR

To compare the peak stress of the two blades, a ConvR blade model and a DFFR blade model were analysed using Finite Element Analysis (FEA) with ANSYS. The SHELL181, which is suitable for thin applications, was used in ANSYS, and the element size is 0.08 m for the entire blade model. The ConvR blade was simulated using an 103,992 element mesh, and the DFFR blade was simulated using an 102,553 element mesh. The aerodynamic forces calculated by improved BEM method were assigned to each node averagely by ANSYS commands, while the gravitational and centrifugal forces were applied via the ANSYS built-in inertial loading function. In addition, a fixed constraint was applied at the end of blade root for the ConvR, and the location where the folding axis is attached to blade for the DFFR, respectively.

(a) (b)

Figure 7. (a) Peak Von Mises Stresses and (b) blade tip displacements of the ConvR and the DFFR blade as a function of operating wind speeds

Both the ConvR blade and the DFFR blade were simulated over a full range of operating wind speeds and azimuthal angles. Under a certain wind speed, the peak stress was selecting from the maximum Von Mises stresses over various azimuthal angles. The variation in peak Von Mises stresses of the ConvR blade and the DFFR blade is shown in Figure 7(a). It can be seen that both the ConvR blade and the DFFR blade has a peak stress at rated conditions; and the DFFR blade peaks with a stress of 65.7 MPa, having an 8.4% reduction compared with the ConvR blade (peaks with a stress of 71.8 MPa). As shown in Figure 7(b), the blade tip displacement of the DFFR blade is also smaller than that of the ConvR blade. Some results of the two rotors were listed in Table 2.

Table 2. Comparisons between the DFFR and the ConvR.

|                      | DFFR  | ConvR | Reduction ratio |
|----------------------|-------|-------|-----------------|
| Blade peak stress (MPa) | 65.7  | 71.8  | 8.4%            |
| Shear web peak stress (MPa) | 48.1  | 57.0  | 15.6%           |
| Blade tip displacement (m) | 3.50  | 4.23  | 17.2%           |
| Blade mass (kg)        | 10,302| 12,703| 18.9%           |

5. Conclusion
The DFFR concept may be able to alleviate the blade stiffness constraints and thus reduce the rotor mass, since it is designed to align the combination of gravitational, centrifugal, and thrust forces along the blade path, resulting in primarily tensile loads instead of cantilever loads on the blades. To
quantify the mass savings of the DFFR concept, a Finite Element Analysis was conducted for a 5-MW DFFR, which is designed based on the NREL 5-MW wind turbine rotor. The blade mass of the DFFR (10,302 kg) has an 18.9% reduction compared with that of the ConvR (12,703 kg), by reducing the numbers of material layers of the blade. The aerodynamic performances of the DFFR and the ConvR were investigated based on the improved BEM method. The results show that the rotor power and torque of the DFFR have a slight increase compared with those of the ConvR, while the rotor thrust of the DFFR is smaller than that of the ConvR. At last, according to the FEA results, the peak stress of the DFFR (65.7 MPa) is lower than that of the ConvR (71.8 MPa) by 8.4%, which means the blade mass saving and the peak stress reduction can be achieved by DFFR concept. However, the rotor concept feasibility requires the more elaborate aerodynamic analysis and structure design, including the design of the folding mechanism and associated control strategy.

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