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A Two-Bladed Teetering Hub configuration for the DTU 10 MW RWT: loads considerations

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Abstract

As the size of wind turbine rotors continuously grows, the need for innovative solutions that would yield to lighter rotor configurations becomes more urgent. Traditional wind turbine designs have favored the classic three-bladed upwind rotor configuration. This work presents instead a concept study on an alternative downwind two-bladed rotor configuration.

The study is based on a model representative of next generation multi-MW wind turbines: the DTU 10-MW Reference Wind Turbine (RWT). As a first design iteration, the aerodynamic characteristics of the original rotor are maintained, and the rotor solidity is kept constant by increasing the blade chord by 50 %. The configuration allows saving 30 % of the rotor weight and material, corresponding to one blade, but implies several complications: lower power output due to increased tip losses effects, and increased load variations. The increase in load variations, and hence in fatigue damage, affects the turbine blades, shaft and tower, and originates from the aerodynamic unbalance on the rotor, as well as from aeroelastic interaction with the tower frequency.

To mitigate the load amplification caused by the interaction between the tower frequency and the rotational forcing, the tower mode frequency is lowered with a modified tower stiffness distributions. The loads caused by the aerodynamic unbalance are instead addressed by introducing a teetering hub configuration. The load alleviation potential of the teetering hub, and the required teeter angle range are evaluated for different stiffness values of the teeter bearing.

Objectives

- Propose a two bladed rotor design for the DTU 10 MW RWT
- The first design iteration is based on constant solidity scaling of the rotor geometry
- Quantify the power losses due to increased tip-loss effects
- Quantify the increase of the fatigue damage loads, and identify its sources
- Investigate aeroelastic interaction between tower frequency and the dominant 2P rotational forcing.
- Investigate the load alleviation potential of a teetering hub configuration.

1. Introduction

The continuous increase of wind turbine rotor size calls for innovative solutions that would yield to lighter rotor configurations. Traditional wind turbine designs have favored the classic three-bladed upwind rotor configuration. This work presents instead a concept study on an alternative configuration, where the weight of the rotor is reduced by decreasing the number of blades to two. Furthermore, the rotor is moved downwind from the tower, thus leading to increased tower clearance as the blades are deformed away from the tower by the wind loads.

The study is based on a wind turbine model representative of next generation multi-MW wind turbines: the DTU 10-MW Reference Wind Turbine (RWT) [1]. In its original configuration, the turbine has an up-wind rotor, three blades of 86.35 m span, and a rotor diameter of 178.3 m; the turbine is pitch regulated with variable speed rotor, table 1.

DTU 10 MW RWT		
Rated Power	*MW*	10
Num. Blades		3
Rotor Diam.	*m*	178.3
Blade length	*m*	86.35
Hub height	*m*	119.0
Rated Wind Speed	*m/s*	11.4
Rated Rot. Speed	*rpm*	9.6

Table 1. Main characteristics of the DTU 10-MW Reference Wind turbine [1].

As a first design iteration, the aerodynamic characteristics and operation points of the reference wind turbine are maintained. The two-bladed rotor configuration is hence derived assuming the same rotor solidity as in the reference wind turbine, and the blade chord length is increased by a factor of 1.5. The constant solidity scaling is described in the next section, and results in a rotor configuration 33 % lighter as the weight of one blade is saved.

On the other hand, the chosen two-bladed rotor configuration yields to a series of complications, detailed in the result section of the paper. Namely, the power output is reduced due to increased tip losses effects (section 3.1), and the fatigue Damage Equivalent Loads (DEL) of blades, shaft, and tower are increased (section 3.2). To reduce the increase of the fatigue damage, two mitigation solutions are investigated and presented in section 3.3: a redesign of the tower stiffness to reduce the interaction with the rotational forcing, and a teetering hub configuration to reduce the effects of the aerodynamic unbalance of the rotor.

2. Method

2.1. Two-bladed rotor design

The two-bladed configuration of the DTU 10-MW RWT is retrieved following a constant solidity scaling: the chord length and the blade thickness of the two-bladed rotor configuration are thus obtained by scaling the reference ones by a factor of 1.5.
The constant solidity approach allows maintaining similar aerodynamic characteristics. The turbine operates at the same rotational speed and tip speed ratio as the reference one, and the same blade relative thickness distribution and airfoil profile shapes are used. As a first approximation, the airfoil steady aerodynamic profile coefficients are assumed to be equal to the original DTU 10-MW RWT ones, thus neglecting the effects from the increased Reynolds number.

The structure of the blade is approximated to a main spar with a rectangular cross section, and the same section modulus as in the reference blade is assumed. The scaling of the blade chord and thickness by a factor of 1.5 thus implies that the thickness of the spar section walls is reduced by a factor of 1/1.5 [2]. The resulting spar section maintains the same area as the original one, and its second moments of area are increased by the square of the scaling factor. Therefore, each of the blades in the two-bladed configuration is assumed to have the same weight as the original blade, and the stiffness increased by a factor of 2.25 (1.5^2) in both bending directions. Please note that the simplified blade scaling neglects any structural requirements that might arise from buckling restrictions, and also neglects the increase in weight given by the larger blade shell.

By assuming that the original weight of the shaft and hub components is maintained, the two-bladed rotor configuration is lighter than the three bladed by the weight of one blade, hence reducing the total rotor weight by about 33 %, table 2.

		3 Bladed	2 Bladed
Blade Mass	*[ton]*	41.70	41.70
Rotor Mass	*[ton]*	125.10	83.40

Table 2. With a constant solidity scaling the weight of the blade is assumed to be the same, and therefore the rotor weight is reduced by 33% in the two-bladed configuration.

2.2. Simulation setup

The performance of the two-bladed configuration is evaluated by performing aeroelastic simulations of the turbine response. The simulations are carried out with the state-of-the-art code HAWC2 [3], which combines a multi-body structural model, with BEM based unsteady aerodynamic models.

The simulations are performed in the wind field conditions prescribed by the IEC standard [4] for a wind turbine in normal operation. The fatigue damage equivalent loads (DEL) are evaluated using standard rainflow counting and Palmgren-Miner linear damage assumption [5]. The simulations are performed with a mean wind speed at hub height of 10 m/s, and a 3D turbulent wind field as described by Mann's model [6], for a turbulence intensity of 0.1834, corresponding to a class B turbine in the IEC standard [4].

3. Results

The proposed rotor configuration reduces the weight of the rotor by one third, but has significant drawbacks: reduction of the power output due to increased tip losses effects, and increase of loads on the turbine structural components.

3.1. Power reduction due to higher tip losses effects

Aerodynamic simulations of the stiff rotor reports that due to the increased tip losses effects, the power coefficient below rated conditions is reduced. BEM simulations returns a reduction close to 4.2 %, whereas EllipSys 3D CFD computations return slightly lower reductions (3.5 %), figure 1.

The increased tip losses yield thus to a 2 % reduction of AEP, figure 2. A further 1 % of AEP is lost due to increased tower shadow effects in the downwind configuration, in spite of the increase in the effective rotor area as no cone and tilt are assumed in the downwind rotor configuration.

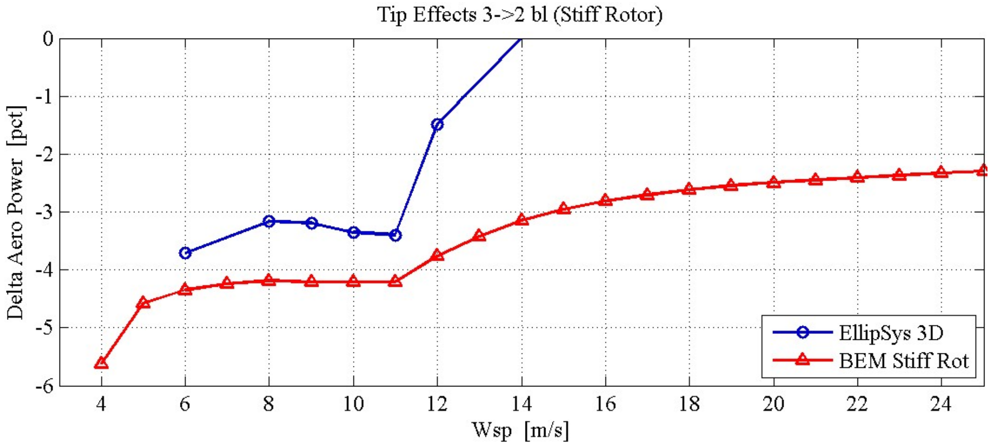

Figure 1: Aerodynamic analysis of the stiff rotor. Power reduction on the two bladed rotor due to tip losses.

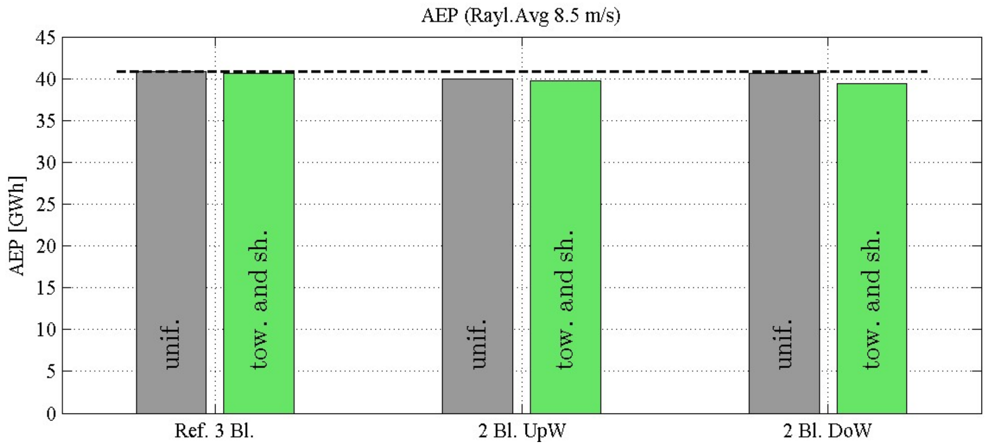

Figure 2: Annual energy production for the investigated rotor configurations in a class II IEC site. The proposed two-bladed rotor configuration leads to an overall AEP output that is approximately 3 % lower than the corresponding power output from the reference wind turbine (an efficiency factor of 0.935 is assumed in all cases).

3.2. Increase of Fatigue Damage Equivalent Loads

In the two-bladed rotor configuration a significant increase of the fatigue damage equivalent loads (DEL) is reported at several locations on the structure, figure 3. The increases in DEL on the blade flapwise moment (+50 %) and on the shaft (more than doubled) are mainly caused by the increase of the blade chord length and by the aerodynamic unbalance over the rotor area.

The increase on the tower DEL is instead partly due to the higher energy content in the turbulent wind field sampled by the two rotating blades, which gives a dominant frequency of 2P (two times the rotational frequency), which is closer to the higher energy content of the turbulent wind spectrum. The effects of the turbulence sampling on the increase of the tower loads can be better observed on the stiff tower analysis, red bars in figure 3. Clearly visible in the flexible tower analysis especially in the fore-aft direction, an important contribution to the increase of the tower loads originates instead from the aeroelastic interaction of the dominant 2P forcing frequency with the tower mode frequency, which could be mitigated by modifying the tower frequency, as presented in the next section.

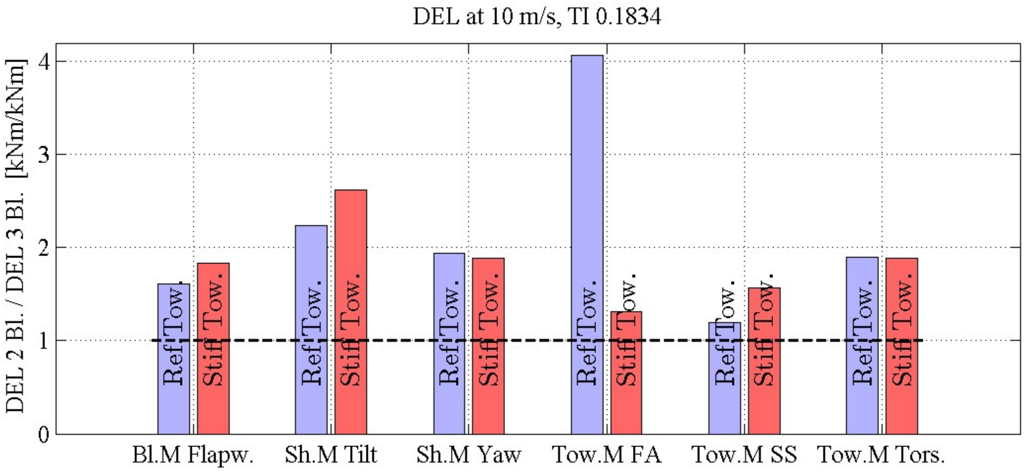

Figure 3: Increase in the fatigue DEL for the two-bladed rotor configuration with respect to the reference three-bladed configuration.

3.3. Load mitigation solutions

Compliant tower structure

The interaction between the tower and the prevailing forcing frequencies is investigated by monitoring the tower DEL for different tower stiffness distributions, figure 4. The aerodynamic forcing on non-rotating structures has a prevailing frequency equal to the number of blades times the rotational frequency (1P). A clear amplification of the tower loads is observed as the frequency of the tower approaches the prevailing forcing frequency: 3P in the reference configuration, and lower (2P) in the two-bladed configuration.
Reducing the interaction and hence the DEL without modifying the turbine rotational speed would require a redesign of the tower toward a more complaint structure, with a frequency equal to 1-1.5 times the rotational one. On the other hand, lower tower frequencies would require a re-tuning of the controller toward a slower response, and might interact negatively with the wave loads.
The following simulations are performed with a tower stiffness reduced to return a tower frequency equal to 1.36 times the rotational one (which returns a tower fore-aft DEL equal to the one obtained with a completely stiff tower structure).

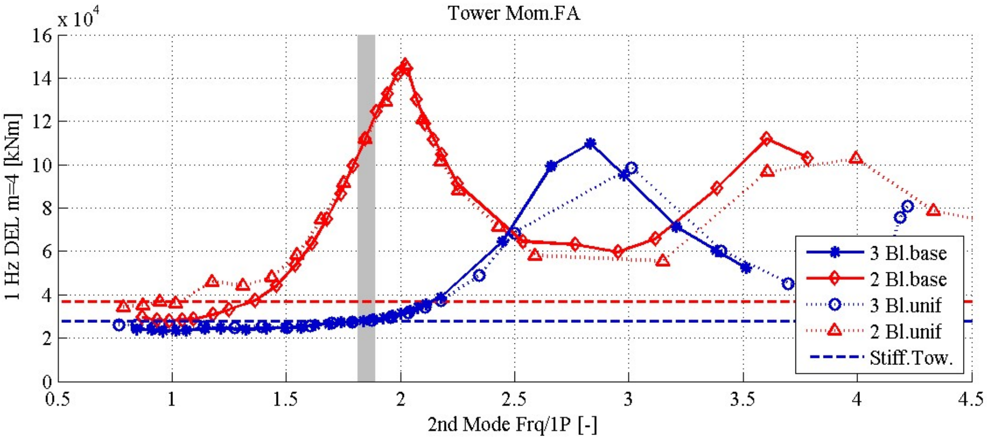

Figure 4: Response on the DEL at the tower bottom from different tower stiffness configurations. The grey shaded area indicates the tower mode frequencies for the reference wind turbine. Simulations at 10 m/s, 1P = 0.14 Hz.

Teetering hub configuration

The load variation caused by the unbalance of the aerodynamic loads over the rotor area can be partly alleviated by decoupling the blade plane from the rotor plane, i.e. by adopting a teetering hub configuration [2]. Different configurations are investigated by varying the “stiffness” of the teetering joint: a teetering hub with low or none stiffness opposes no resistance to the teeter angle variation, hence the restoring moment is small or null, and the teeter angle range is at its maximum. On the contrary, by increasing the teeter stiffness, e.g. by a spring system, the configuration resemble more a rigid hub one, where the teeter excursion is small, and the restoring moment is large, and so is the moment transferred to the rest of the structure, figure 5.

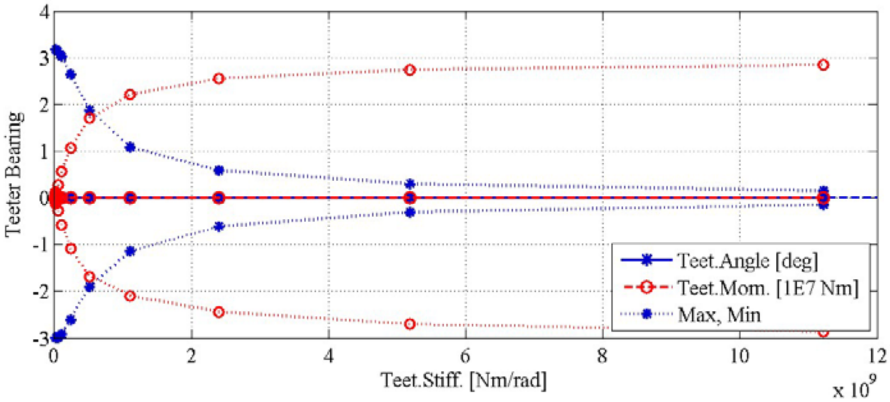

Figure 5: Variation of teetering angle, and teetering restoring moment for increasing stiffness of the teetering hub joint.

The teetering hub effectively reduces the fatigue loads. The DEL on the shaft titling moment is 80 % lower than with a rigid hub, figure 6 left. Also the DEL on the blade flapwise bending moment is reduced by approximately 35 %, figure 6 right. The tower presents an increase of the Side-To-Side DEL close to 20 %, and a decrease of the Fore-Aft DEL also close to 20 %; the DEL of the tower torsion moment is instead significantly reduced (80 %) with the free teetering hub.

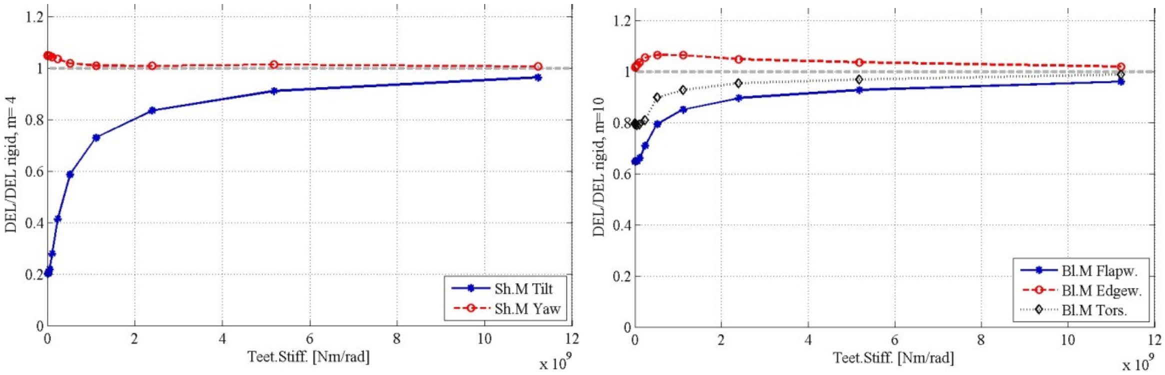

Figure 6: Variation of the fatigue DEL on the shaft moment (left) and on the blade root bending moment (right) for different stiffness configuration of the teetering joint. Please note that the fatigue DEL are normalized by the loads obtained with a rigid hub configuration (the curves tend to units).

The lower the stiffness of the teeter joint, the higher the load alleviation, but also the higher the excursion required to the teeter angle, and hence the displacement of the blade out of the rotor plane. In the considered simulation conditions, the wind shear causes a tilting moment on the blade plane, to which the teeter mechanism responds by yawing the blade plane (gyroscopic precession [7]). Therefore, the maximum teeter angles are reached with the blades in horizontal position, and the tower clearance is nearly the same as in the rigid hub case, figure 7. In the same figure, also note the beneficial effects of the downwind rotor configuration in terms of increased tower clearance as the blades deflect under the action of the wind loads.

Nevertheless, in conditions of low rotational speed (as startup or shutdown), or in presence of marked horizontal shears (large turbulence structures or half wake operation) the teetering hub may cause a critical reduction of the blade tip-tower clearance. The teeter joint stiffness should be hence result from a compromise between load alleviation and tower clearance problem at different operating conditions. Or, in alternative, Larsen et al. [2] propose a teetering hub configuration where the teeter angle, and hence the blade tip displacement, are reduced by using individual pitch control with pitch variations proportional to the teeter angle.

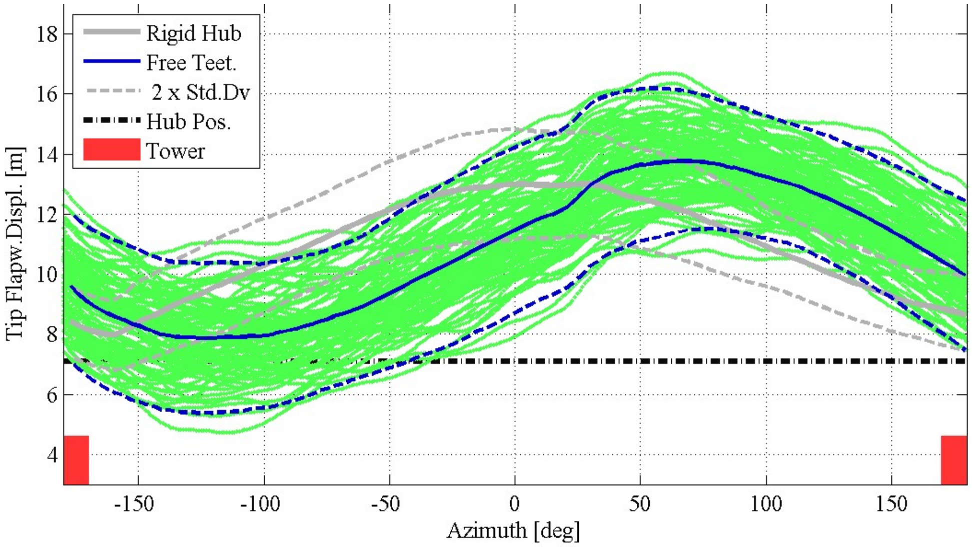

Figure 7: Flapwise positions of the blade tip for different azimuthal angles (0° blade points upwards). Comparison of the free teetering hub configuration versus the rigid hub one. Due to gyroscopic recession, the maximum teeter angles, and hence blade tip displacement occur when the blade is horizontal.

4. Conclusion and future work

The paper proposes a two-bladed downwind rotor configuration for the DTU 10 MW RWT, which is derived following a constant solidity scaling that increases the chord length by 50 %, and maintains the same aerodynamic characteristics.

In the two-bladed configuration, the rotor weight is reduced by approximately 30 %; on the other hand, several drawbacks are reported:

- The expected energy output is reduced by approximately 3 % due to increased tip losses effects, and increased tower shadow losses in the downwind configuration.
- The fatigue DEL increase on the blade root, on the shaft and on the tower.

The increase in DEL is explained by the larger chord and hence larger aerodynamic forcing along each blade, but also by the sampling of the turbulent wind field that now occurs with a lower frequency (2P) and therefore intercepts higher energy from the turbulence spectrum. Also, the two bladed configuration causes a larger unbalance of the aerodynamic loads over the rotor, and an interaction of the prevailing forcing frequency 2P with the tower frequency.

The load increase from the interaction with the tower mode can be reduced by increasing the separation between tower frequency and the 2P frequency. A more compliant tower structure would reduce the load increase due to the frequencies interaction, but might have a negative influence on the controller behavior, and eventually on wave loading.

A teetering hub configuration proved very effective in reducing the loads due to the aerodynamic unbalance, but the excursion of the teetering angle might result in a critical reduction of the blade-tower clearance in particular operating conditions.

To conclude, the proposed constant solidity design has a number of drawbacks that are unlikely to be compensated by the weight reduction. Future work should hence consider alternative design approaches: for instance by reducing the rotor solidity and increasing the rotational speed of the rotor. The aerodynamic characteristics will need to be modified accordingly. A lower solidity design would lead to lower weight savings, but also reduce the drawbacks observed with the current design.

Acknowledgment

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