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Aerodynamic modelling of wind turbine blade loads during extreme deflection events

Matthew Harrison¹, Menno Kloosterman², and Ricard Buils Urbano¹

¹DNV GL, One Linear Park, Avon St, Bristol, BS2 0PS, UK
²DNV GL, Energieweg 17, 9743 AN Groningen, Netherlands

matthew.harrison@dnvg.com

Abstract. Long, flexible wind turbine blades experience significant deflections during operation. Historically, the blade element momentum model in Bladed assumed that the blade is split into a set of radial aerodynamic sections which are aligned perpendicular to the pitch axis, and that any rotation of the sections due to deflection, pre-bend or pre-sweep in the blade can be ignored. For modern-day flexible rotor blades, under extreme loading conditions, this assumption no longer holds. Including this rotation when calculating inflow velocities and angle of attack, and when resolving the resultant forces at the element, causes a significant change in axial force ($F_z$) along the pitch axis, and therefore the blade out of plane bending moment ($M_y$). This in turn drives a change in overturning moments on the hub (which is driven by differences in bending moments between blades). An example 160m rotor shows an increase of 68% in hub overturning moment during an extreme gust event when aerofoil rotation due to deflection is included. This is verified through comparison to the alternative free vortex wake rotor model in Bladed. DNV GL Bladed includes the rotation of aerofoils by default at version 4.8.

1. Introduction
DNV GL Bladed is a coupled aero-hydro-servo-elastic code for modelling wind turbines with fixed and floating foundations. Two models of rotor aerodynamics are implemented in version 4.8 of the code: blade element momentum (BEM) theory, and a lifting-line free vortex wake method (FVW). While BEM theory relies on empirical models to represent tip loss (finite blade number), oblique inflow (skewed wake), turbulent wake states, and dynamic inflow, FVW represents these characteristics physically in the model.

In BEM the blade is split (radially) into aerofoil sections, and forces are calculated normal and tangential to the rotor plane. For an un-loaded blade, with no pre-bend, the sections are perpendicular to the blade pitch axis. As the blade deflects, the neutral axis deviates from the pitch axis, and the sections rotate. The historical implementation of the Bladed BEM code ignored this rotation which is reasonable for small blade deflections. However, as blade lengths and deflections increase, rotations also increase. Out of plane rotations of greater than 25° may be expected for a flexible 70-80m blade. This rotation causes significant deviations in inflow velocity, angle of attack, and resolved loads for each element, and can drive asymmetric hub loading. The implementation of BEM theory in Bladed 4.8 models all blade rotations (i.e. in edgewise, flapwise and torsional directions) by default, but with an option for simplification for smaller rotors.
This paper compares loading results between BEM including aerofoil rotation, and BEM not including rotation, to understand the significance of aerofoil rotation on loads. The FVW model is also compared to provide a verification of the BEM results. Two different wind turbine models are used: a 77m blade used on a 7MW 160m rotor that was developed in-house by DNV GL to represent a typical offshore wind turbine design; and a 54m blade developed by We4Ce-TRES4 which is applied on a generic 2MW wind turbine and is suitable for low-wind onshore sites. Results are analysed from load cases involving an extreme coherent gust with direction change (ECD, as defined in [1]) which have been found to drive large blade deflections and rotations.

2. Model and load case definition

2.1. Summary of model theory

2.1.1. Bladed implementation of blade element momentum theory. The historical BEM code used in Bladed has been developed over several decades. The model follows text-book BEM-theory with the following engineering models and corrections:

- Drag included in induction calculations
- Prandtl tip loss model
- Glauert correction for highly loaded rotors
- Dynamic wake based on Pitt&Peters [2]
- Dynamic stall with in-house modifications based on Beddoes-Leishman work [3]
- No skew wake correction
- Only takes into account blade section deformations due to torsion, not due to bending.

Details of this model which was the default model up to Bladed version 4.7 can be found in the Bladed theory manual [4].

In Bladed 4.8 a completely rewritten BEM module is introduced. The following key differences can be noted compared to the legacy implementation:

- Additional dynamic wake model based on Øye [5]
- Dynamic stall model based on recent work by DTU [6]
- Glauert momentum model and skew wake correction [7]
- All blade orientations and deformations are taken into account by default.

Details of the new model can be found in the theory manual of Bladed version 4.8 [8]. Rotational augmentation can be considered in Bladed by pre-processing the aerofoil data using the method defined in [9].

2.1.2. Free vortex wake (FVW) theory. The free vortex wake theory follows the theory as described in [10] and [11]. A Beddoes-Leishman type dynamic stall model can be added where the terms due to shed vorticity are switched off as these are included inherently in the vortex wake [6]. As with BEM, 3D turbulent wind fields can be defined as the input environmental conditions. The FVW model included in Bladed 4.8 models aerofoil rotation by default.

Options are available to use a Free Wake and Fixed Wake solution. In case of the Fixed Wake solution the wake transport velocity is based on the induced velocity calculated at 70% of the rotor radius. For the Free Wake solution the induction between all vortex elements is taken into consideration up to a certain user-defined distance downstream where the wake is “frozen” and convected with the local wind velocity.

One of the main advantages of FVW is that it intrinsically models root and tip losses, the effects of yawed flow, turbulent wake states and dynamic wake effects. Corrections only need to be made for stall delay/dynamic stall. This means that the model should have a wider validity, since it is not limited by the assumptions of empirical corrections.
2.1.3. The treatment of aerofoil orientation in rotor models. Figure 1 shows the inflow wind velocity at un-deformed and deflected blade elements. In this case the out of plane deflection of the blade is sufficient to cause an element at the tip to rotate by 20° relative to the blade pitch axis. This has the effect of reducing the velocity component due to the axial wind by a factor of $\cos(20°) = 0.94$. The force components on the element are resolved into directions normal and tangential to the rotor plane, and the aerofoil rotation increases the in plane forces (e.g. $F_z$ along the blade axis) due to both the change in angle of attack, and the resolved direction of the force. This can increase overall blade root bending moment, and implicitly further increase the blade deflection.

![Diagram](image.png)

**Figure 1.** Wind velocity at a deformed blade element.

2.2. Turbine models

The properties of the turbines simulated in this paper are shown in Table 1. The effects of rotational augmentation at the blade root [9] were not included in this analysis.

| Property                                      | 7MW reference turbine | We4ce 2MW |
|-----------------------------------------------|-----------------------|-----------|
| Rated power (MW)                              | 7MW                   | 2MW       |
| Nominal diameter (m)                          | 159.9                 | 111       |
| Rated wind speed (m/s)                        | 7.8                   | 10        |
| Blade length (m)                              | 77.8                  | 54.2      |
| Blade mass (kg)                               | 36400                 | 10258     |
| Maximum chord length (m)                      | 4.8                   | 3.5       |
| 1st flapwise frequency (Hz)                    | 0.44                  | 0.50      |
| 1st edgewise frequency (Hz)                    | 0.73                  | 0.86      |
| Static tip deflection at rated steady wind (m)| 12.7                  | 7.7       |
| Minimum rotor speed (rpm)                      | 9.1                   | 1         |
| Maximum rotor speed (rpm)                      | 11.9                  | 12.9      |
| Optimum tip speed ratio (-)                    | 10                    | 10.9      |

2.3. Load cases

During internal studies, it has been found that the extreme coherent gust with direction change (ECD) cases drive significant blade deflections. For this study, all cases (e.g. at rated wind speed, and 2m/s above and below) were simulated. The maximum hub overturning moment was compared between the
two BEM models to find the largest discrepancies, and results are presented for cases that result in the highest difference. The load case setup is summarized in Table 2.

**Table 2. Load cases generating large differences in hub overturning moment**

| Turbine                | V0 (m/s) | ΔV (m/s) | Vend (m/s) | Direction change (deg) | Δt (sec) | Initial azimuth (deg) | Wind direction (deg) |
|------------------------|----------|----------|------------|------------------------|----------|------------------------|----------------------|
| 7MW reference turbine  | 9        | 15       | 24         | -80                    | 10       | 22.5                   | 8                    |
| We4ce 2MW turbine      | 8        | 15       | 23         | 90                     | 10       | 90                     | 0                    |

Steady wind with speed and direction transient (rise time = 10s). 140 second simulations. Half-type transient occurs 10s into simulation. Wind gradient exponent (exponential model), α = 0.2.

3. Results and discussion

3.1. Parked rotor

Before the comparison of the ECD cases, a simple case is considered to illustrate the blade loading differences between the two BEM models under steady conditions. This is achieved through a parked rotor simulation under steady wind where no dynamic effects are seen. The rotor is locked at 0° azimuth and gravity loads are switched off so that the effect on the aerodynamic loads can be isolated. Figure 2 shows forces on a parked blade, which has no prebend, and is subject to 100m/s wind in the x direction (i.e. into the page), no wind shear is included, the rotor is locked. The blade is at a parked pitch position with the chord approximately parallel to the wind (depending on twist angle). Under 100m/s wind the blade tip section rotates by 31.3° when using the resolved BEM model. The simplified internal blade force vectors are calculated in the y direction only, whilst resolving for the aerofoil rotation introduces an Fz component, and slightly reduces the Fy component (Figure 2b). The moment Mx about the blade root (which is calculated from the Fy and Fz forces, and is in the stationary hub axes system) increases from 275kNm to 321kNm when the rotation is included. Note that the internal blade loads are accumulated along the blade: the Fz component seen at the root is not a result of aerofoil rotation, but due to the Fz forces acting on that section from outboard sections.

![Figure 2. Internal forces on a parked blade with 100m/s onset wind speed in the x direction.](image-url)
3.2. 7MW turbine – ECD case
For the 7MW turbine a large difference in overturning moment was found in a case where the wind speed increases from 9 m/s to 24 m/s and the wind direction changes from 8° to -72°. The peak overturning moment on the hub centre (Myz) differs by 68% between the resolved model and the model assuming simplified aerofoil orientation. For the resolved model the peak overturning moment occurs at 31.55s, and the internal force vectors on the three blades at this point are shown in Figure 3. The positive overturning moment is centered above the hub with blades 1 and 3 applying an imbalance compared to blade 2. The time history of wind speed and direction, rotor speed, and hub overturning moment are shown in Figure 4; and for blade forces, deflections, angle of attack and pitch angle in Figure 5.

The difference between the two BEM models could be a result of a difference in controller behavior, driving different rotor speeds and blade pitch angles between the simulations, rather than the way the forces are resolved. This difference is inevitable since tip deflections are 20° even during steady wind conditions (see 5d and 5e at time 15-20s), meaning that blade loads will be different between the models, driving a different controller response. The rotor speed and pitch angles for the three models are shown in Table 3 (at the time of peak Myz in the resolved model, or equivalent azimuth). Between the two BEM models pitch angles differ by around 1° for blades 1 and 2, and 2° for blade 3. Angle of attack is more similar between the blades, differing by up to 0.2°, indicating that the controller is stabilizing this parameter. Contrary to the differences in pitch angle, blade 1 and 2 show the largest difference in loading, and blade 3 the smallest. These results suggest that the difference in load cannot be directly correlated to controller behavior.

Two aspects appear to drive the increase in overturning moment: firstly, the change in the Fx and Fz load components resulting directly from resolving the forces with the aerofoil rotation; and secondly the effect these resolved forces have in increasing or reducing blade deflections, thereby further increasing the angular difference between the simplified and resolved forces. This combined effect increases blade 1 deflection (seen in Figure 3a) and reduces blade 2 deflection (seen in Figure 3a and Figure 3b), and increases the My moment about the hub centre.

Comparing Figure 5a and Figure 5b shows the same result as seen in the vector plot: in the resolved model blade moment Mxy is higher for blade 1 and smaller for blade 2 increasing the overturning moment. Comparing Figure 5d and Figure 5e shows the out of plane rotation at the tip of blade 1 increasing from around 27.5° (simplified) to 32.5° (resolved). Resolving the forces causes angle of attack to increased slightly at Blade 2, and reduce at Blade 1, seen in Figure 5g, and Figure 5h.

Figures 5c, f, i and l show the time history for the FVW model with resolved forces. The comparison verifies the changes seen in the resolved BEM model. Figure 4c shows a similar peak in the hub overturning moment in the resolved BEM and FVW models. There is a time/azimuth lag in the vortex line model compared to BEM, so the blade numbering is different at the peak overturning moment, but the same combination of high and low values of blade bending moments is seen at the time of peak load (Figure 5c), and similar magnitudes of out of plane deflections (f) and angles of attack (i) are also observed.

| Table 3. 7MW turbine blade pitch and angles of attack |
|--------------------------------------------------------|
| Rotor speed (rpm) | Pitch angle (deg) | Angle of attack at 66m radius (deg) |
|                | Blade 1 | Blade 2 | Blade 3 | Blade 1 | Blade 2 | Blade 3 |
| Simplified (31.8s) BEM | 10.5 | 0.20 | -2.99 | 2.78 | 6.12 | 5.39 | 5.32 |
| Resolved (31.55s) BEM | 10.6 | 1.33 | -1.71 | 0.37 | 6.20 | 4.84 | 5.01 |
| FVW (31.8s) | 10.7 | -1.29 | -0.32 | 1.60 | 6.10 | 4.29 | 6.08 |
Figure 3. Forces on 7MW turbine blades at the time of maximum hub overturning moment: 31.55s (Resolved), 31.8s (Simplified). Equal azimuth shown for clarity.

Figure 4. Time history of rotor parameters; 7MW reference turbine (black dashed line is the time of peak Myz in the resolved BEM model)
3.3. We4ce 2MW – ECD case

For this turbine a maximum difference of 47.6% in extreme hub overturning moment is found between simplified and resolved models, for a case where the wind speed starts at 8 m/s and increases to 23 m/s, and the wind direction turns from 0° to 90°. The force vectors on the blades for this case are shown in Figure 6, the time history for rotor parameters is shown in Figure 7, and blade parameters in Figure 8. In these simulations the controller is simpler than for the 7MW turbine, and at 28.45s rotor speeds are very similar and all blades are at 0° pitch. It can be assumed that the controller is not driving the difference seen in loads.

The overturning moment is centered below the hub, with blades 1 and 3 applying an imbalance force compared to blade 1. The main difference is seen in the loads on blade 1. In the resolved case the Blade 1 Fx load components are increased along the blade, causing an increased deflection, and combining to increase the Blade Mxy moment.

Comparing Figure 8a and 8b shows an increase in Blade 1 Mxy moment (from simplified to resolved BEM) at 28.45s, and shows that at this point Blade 2 Mxy is lower in the resolved case (which is not easy to detect in the vector plot). The range of blade deflections is greater for the
resolved case (Figure 8d compared to Figure 8e). The effect on angle of attack is shown in Figure 8g and Figure 8h, with higher values in for the resolved case.

The comparison to the vortex line model is shown in Figure 8c, f, i, and l. There is less of a time/azimuth lag between the models than in the 7MW turbine case and the vortex line model verifies the behavior of the resolved BEM model.

Figure 6. Force vectors on 2MW turbine blades at 28.45m/s. Equal azimuth.

Figure 7. Time history of rotor parameters; 2MW we4ce turbine (black dashed line is the time of peak Myz in the resolved BEM model)
Figure 8. Time history of blade parameters; 2MW we4ce turbine (black dashed line is the time of peak Myz in the resolved BEM model)

4. Conclusions
This paper compares wind turbine aerodynamic models, considering the effect of aerofoil rotation due to blade deflection on blade bending moments and hub overturning moment. Two different turbines are simulated during an extreme coherent gust with direction change. The following observations are made when comparing the BEM model with aerofoil rotation neglected (simplified), and airfoil rotation resolved:

- For both a 77m and 54m blade, large deflections cause rotations in the tip aerofoil of up to 25°.
- The effect of resolving inflow velocities and forces at each section, to include this rotation, is that force components normal and parallel to the pitch axis (Fx, Fz) change, driving a further change in blade deflection.
- The change in force distribution drives a change in the blade bending moment My.
- In specific wind scenarios this change can result in a significant increase in bending moment at one blade, and simultaneous reduction at another, driving an overall increase in hub overturning moment.
• For the turbines simulated, controller behavior does not appear to drive differences in loads between simulations, but a different controller/turbine combination could show a different result, and potentially smaller differences in loading.

This result has been verified by comparing blade element momentum theory and a free vortex wake aerodynamics model, which demonstrates the same change in loading and increase in hub overturning moment. Bladed has been the subject of numerous previous verification and validation studies, e.g. [12] [13], and future work will focus on verifying the results in this paper against alternative wind turbine load calculation software.

The BEM model with resolved aerofoil orientations and forces is the default model in Bladed 4.8. It predicts large increases in hub overturning moment (potentially around 70% increase) compared to the simplified model, for turbines with long/flexible blades. The FVW aerodynamics model is also available in Bladed 4.8.

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