Aeroelastic simulation of multi-MW wind turbines using a free vortex model coupled to a geometrically exact beam model

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Abstract. The current paper investigates the aeroelastic modelling of large, flexible multi-MW wind turbine blades. Most current performance prediction tools make use of the Blade Element Momentum (BEM) model, based upon a number of simplifying assumptions that hold only under steady conditions. This is why a lifting line free vortex wake (LLFVW) algorithm is used here to accurately resolve unsteady wind turbine aerodynamics. A coupling to the structural analysis tool BeamDyn, based on geometrically exact beam theory, allows for time-resolved aeroelastic simulations with highly deflected blades including bend-twist coupling. Predictions of blade loading and deformation for rigid and flexible blades are analysed with reference to different aerodynamic and structural approaches. The emergency shutdown procedure is chosen as an exemplary design load case causing large deflections to place emphasis on the influence of structural coupling and demonstrate the necessity of high fidelity structural models.

Nomenclature

AOA Angle of Attack
BD BeamDyn
BEM Blade Element Momentum Method
ED ElastoDyn
IP in-plane
LLFVW Lifting Line Free Vortex Wake
OOP out-of-plane

1. Introduction

BEM theory [1] is still the standard approach for wind turbine load case calculations. In the past, the method's advantages of robustness and low computational effort outweighed drawbacks such as simplifying assumptions. With increasing computational power however, these benefits diminish and higher order representations of the unsteady aerodynamics have moved into focus, among them lagrangian wake models.
Recent publications [2, 3, 4] have proven essential advantages of vortex wake methods with wake treatment over BEM theory, among others with regard to yawed flow and dynamic inflow. These provide better predictive capabilities for off-design conditions which cause severely unsteady blade loads.

Local blade element aerodynamics change when structural blade deflections are considered. Thus, the predicted angles of attack (AOA) and blade loads differ from simulations with rigid blades. The progression towards larger, more flexible blades not only causes unsteady aerodynamic loads but also makes the consideration of the substantial blade deflections, which are on the order of meters, an absolute necessity.

2. Modelling

Vortex methods are based on the assumption of inviscid, potential flow. The blade is discretized into a finite number of panels which are replaced by ring vortices consisting of bound and trailing vortex filaments. The bound vortex at the quarter chord represents the lifting line of the blade section. Panel circulation can be calculated from the Kutta-Joukowsky theorem and the lift coefficient, known from tabulated 2D polar data. The circulation of the shed and trailing vortices of the wake panels results from application of the Kutta condition. The velocity induced by all vortex elements is calculated with the Biot-Savart law.

The advanced blade design and simulation code QBlade has a lifting line free vortex wake (LLFVW) module [5, 6] which is loosely based on the formulation developed by van Garrel for ECN’s AAWSM code [7]. A large range of control and modelling parameters are available to define time and blade discretization, boundary conditions, wake structure and additional models such as tower influence or unsteady aerodynamics [8]. The implementation was optimized for computational efficiency by including, among others, multi-threading, GPU computing capability, the concentration of wake vorticity and wake truncation [3, 9]. It thus uses only a fraction of the resources of Computational Fluid Dynamics (CFD) simulations with fluid structure interaction.

To perform aeroelastic simulations, the code has now been coupled [4] to two different structural solvers of NREL’s FAST v8 [10, 11] while aerodynamic forcing is still provided by the LLFVW algorithm. Sections of the FAST source code have been rewritten to output the necessary instantaneous data at chosen stages of the simulation, which are then passed to QBlade which performs the aerodynamic calculations and passes the new loading back to FAST, see Figure 1. This is referred to as a loose coupling and is sufficient for the majority of simulations provided structural and aerodynamic time steps are resolved sufficiently. As the structural natural frequencies of the turbine are usually much higher than any aerodynamic excitations, the integration time step of the structural dynamics module $dT_s$ must generally be much smaller than the aerodynamic time step $dT_a$. The structural loop hence usually requires many more iterations than the aerodynamic loop which contains it.

The structural dynamics module ElastoDyn v1.03.00 [12] consists of a combined multi-body and modal-dynamics formulation representing the whole wind turbine system including blades and tower (modal) as well as platform, nacelle, generator, drive shaft and hub (multi-body). The modal-based solver provides a simplified, non-linear Euler-Bernoulli beam model [13] to calculate small to moderate blade deflections of isotropic materials ignoring shear deformation, axial and torsional DOFs. The dominant mode shapes are found externally (e.g. from modal tests or BModes [14]) and represented as 6th-order polynomials.
In the second approach, the structural solver BeamDyn v1.00.00 [15] is used. Instead of a modal representation of the blades, the solver is based upon the geometrically exact beam theory and has been implemented by spatially discretizing the beam with Legendre spectral finite elements and integrated temporally with a generalized-α scheme, which is an unconditionally stable (for linear systems), second-order accurate algorithm. By providing the sectional mass and stiffness matrices, the model allows for an accurate representation of composite beam layups which exhibit nonlinear behavior as a result of anisotropic materials, structural coupling or large deflections [16]. These matrices were taken by making use of the definition provided with the BECAS software [17], and transformed accordingly to comply with the IEC blade coordinate system.\(^1\) A short summary of the structural models has been provided in Table 1.

| Model       | Beam  | Number of Discretisation Elements | Structural Timestep [s] |
|-------------|-------|-----------------------------------|------------------------|
| ElastoDyn   | Linear| 51                                | 0.0125                 |
| BeamDyn     | Linear| 6                                 | 0.0010                 |

For the comparative BEM calculations AeroDyn [18], the BEM module of NREL’s FAST, has been used. The implemented library made use of AeroDyn v15.00.00 [19] to enable simulations with both BeamDyn and ElastoDyn; this version however lacked an unsteady aerodynamic model and an unsteady wake model. This has since been remedied in newer versions [18].

\(^1\) These values can be provided upon request.
3. Results
As a state of the art reference rotor, the DTU 10 MW turbine [20] is chosen as the example geometry. The turbine properties are summarized in Table 2.

Table 2. DTU 10 MW Turbine Properties

| Parameter                          | Value                  |
|------------------------------------|------------------------|
| Rated power                        | 10 MW                  |
| Orientation, Configuration         | Upwind, 3 Blades       |
| Control                            | Variable Speed, Collective Pitch |
| Rotor, Hub diameter                | 178.3 m, 5.6 m         |
| Hub height                         | 119 m                  |
| Rated wind speed                   | 11.4 ms⁻¹              |
| Cut-in, Cut-out wind speed         | 4 ms⁻¹, 25 ms⁻¹        |
| Cut-in, Rated rotor speed          | 6 RPM, 9.6 RPM         |
| Overhang, Shaft tilt, Precone      | 7.1 m, 5°, -2.5°       |

3.1. Natural Frequencies
Unlike the aeroelastic code HAWC2 [21], the structural solver of FAST currently does not have the capability to solve for the natural frequencies of the entire turbine system. To check the modes of the model, the approach of free decay simulations [22] has been adopted. The spectral response of the parked system was determined by impulsively loading the rotor, followed by the removal of all aerodynamic loads. The total simulation duration was 300 s.

The power spectral density (PSD) plots of the blade tip out-of-plane deflections and tower top fore-aft displacement are presented in Figure 2. The natural frequencies obtained with BeamDyn show a good agreement with ElastoDyn and HAWC2 results [20, 22]. Some predominant modes can be identified in both graphs, namely the 1st tower fore-aft mode as well as the 1st and 2nd blade collective flap modes. The 1st blade asymmetric flap mode and 1st and 2nd blade asymmetric edge modes are, for example, more pronounced in the PSD of the in-plane blade tip deflections.

3.2. Rigid simulations
Figure 3 presents the predicted normal and tangential blade loading for a range of wind speeds computed with the CFD code EllipSys3D [23] together with the converged curves from rigid rotor BEM (AeroDyn) and LLFVW (QBlade) simulations. In QBlade, the blade section 2D polar data and blade pitch values for the different cases were set according to the DTU 10 MW reference turbine [24]. The CFD simulations make use of a \( \gamma - Re_\theta \) correlation based free transition model with the turbulence intensity at the rotor set to 0.1% [20]. The surface mesh had 256 and 128 cells in the chordwise and spanwise directions, respectively. The volume mesh extended 128 cells in the direction normal to the blade surface with an initial cell height of \( 2 \cdot 10^{-6} \) m, resulting in a total cell count of approximately 14 million with a \( y^+ \) value below 2.

With respect to the CFD, the LLFVW model performs slightly better than the BEM method. Deviations in the root region stem from differing large AOA predictions of the models as well as from a Gurney flap in the CFD simulations. The excellent agreement for the rest of the blade shows that the implemented vortex method provides an accurate, high fidelity representation of the aerodynamic loading at only a fraction of the computational expense of the CFD.
3.3. Elastic simulations

A wind ramp simulation shown in Figure 4 has been considered to assess the two structural solvers’ performance during steady operation in comparison to BEM+ElastoDyn results from FAST [22]. In the ramp simulation, wind speed step changes of $0.5 \text{ms}^{-1}$ were applied every $50 \text{s}$ from the cut-in wind speed of $4 \text{ms}^{-1}$ up to the cut-out wind speed of $25 \text{ms}^{-1}$. For the regulation of blade pitch and rotational speed, the controller implementation of [25] is used in QBlade.

With the LLFVW method and both structural solvers, reasonable agreement with the steady state BEM calculations is reached for most of the operating range. The exact same results cannot be expected due to the different aerodynamic and structural simulation approaches. Using the LLFVW+ElastoDyn, deviations from BEM+ElastoDyn results occur due to the aerodynamic modelling. A comparison of LLFVW with ElastoDyn and BeamDyn reveals the influence of the different beam models.
During the LLFVW ramp simulations, reasonable values of the power output are reached with realistic time lags introduced by the development of the wake. The rotational speed starts at its minimum of 6 RPM and is adjusted by the controller with increasing wind speed. Above rated power, it is held constant at the rated value of 9.6 RPM. It can be concluded that the conventional control system works well for the combination of the LLFVW algorithm with both ElastoDyn and BeamDyn.

At low wind speeds, the rotor torque is regulated to optimise the power production. In this region, the BEM pitch angles are well matched by the LLFVW simulations. Deviations result from the different aerodynamics representations, including unsteady inflow and dynamic stall modelling and the convergence time of the wake which influences the controller. When the rated power of 10 MW is reached, the blades are pitched to limit the power output to this value. With BeamDyn, much higher pitch values are needed than with ElastoDyn. This is due to the consideration of additional blade twist from bend-twist coupling and shows the necessity of higher order beam models when large deflections are expected.

Figure 5 (left) illustrates the moving window time averaged in-plane (IP) and out-of-plane (OOP) blade tip deflections for the wind ramp scenario. With both structural solvers, the deflections reach their maximum value around rated power. Reasonable agreement can be observed but larger overall deflections are produced with BeamDyn’s structural model.

Highly unsteady operation leads to strong gradients in the flow field and large blade
deflections. Furthermore, structural coupling gives rise to other effects such as blade twisting. To emphasise the difference between the applied beam models, the moving window time averaged blade twist angle and AOA are shown in Figure 5 (right). The geometrically exact beam model of BeamDyn produces additional twist of approximately 7 degrees due to bending of the blades and the associated AOA increases by almost 2 degrees. With the modal solver of ElastoDyn, no such bend-twist coupling is modelled. It generates a constant blade twist angle and thus different AOA results than BeamDyn. The predictions with regard to unsteady aerodynamic effects such as deep and dynamic stall (which strongly depend on the predicted AOA) correspondingly differ as well. Hence, stall that occurs in fact on the blades might not be detected because of the aeroelastic modelling. This has considerable influence not only on the turbine performance but also on the fatigue loads and lifespan of the blades.

3.4. Emergency shutdown simulation
Figure 6 shows the blade tip deflections during an emergency stop (DLC 5.1) which represents an exemplary off-design load case which causes large deflections under unsteady conditions. Again, the calculations have been carried out with AeroDyn in combination with ElastoDyn as well as with QBlade’s LLFVW method with both ElastoDyn and BeamDyn.

The predictions are comparable with respect to the deflection magnitudes and duration of the shutdown procedure. Small differences of the blade tip deflections occur as a result of the different aerodynamics modelling when comparing BEM+ElastoDyn and LLFVW+ElastoDyn. However, the predicted rate of change of both IP and OOP blade tip deflections is greater in BeamDyn simulations. This has important consequences on fatigue life estimation as structural gradients also play a significant role in fatigue loading.
As previously described, structural coupling is only captured by the combination of the LLFVW algorithm with BeamDyn. Thus, additional blade twisting (e.g. as a result of bending of the blades) can be reproduced. The blade tip AOA and twist angle for all three simulation cases are presented in Figure 7. Again, the results from BEM and LLFVW theory with ElastoDyn agree very well, along with the magnitude of AOA predicted by all three models. There is however a difference in the AOA predicted from ElastoDyn and BeamDyn which is most pronounced in the regions of maximum blade tip deflection where structural coupling has the largest influence.

It can be seen that the ElastoDyn twist angle remains roughly constant during the whole shutdown procedure with both aerodynamics models. This is not realistic behaviour as the sudden deceleration will induce enormous loads, large deflections and thus significant bend-twist coupling. The BeamDyn twist angle on the other hand considers the additional twist from aeroelastic coupling and is thus more appropriate to model extremely unsteady loads such as those which occur during an emergency shutdown. In Figure 7, this is demonstrated by the
pronounced change in blade tip twist during the shutdown procedure. With LLFVW+BeamDyn, the twist rapidly increases from -3 to +3 degrees of blade twist and then slowly goes down to zero. This can be explained with reference to Figure 6, where the IP deflection is shown to persist long after the shutdown procedure is initialised. Again, the structural coupling influences the local aerodynamics and stall behaviour and thus the fatigue life of the blade.

4. Conclusions

With the modal-based solver ElastoDyn, bend-twist coupling is not considered, an assumption which has generally not shown to heavily impact results for small to medium-sized turbines, particularly with comparatively more rigid blades. However with regard to future rotor designs with much larger, flexible blades, its neglect results in less reliable predictions when analysing unsteady operating conditions where large deflections can cause considerable aeroelastic coupling. To capture the coupling between bend-twist and unsteady aerodynamic effects, the LLFVW aerodynamic model of QBlade is combined with the geometrically exact beam model of BeamDyn. The approach acknowledges additional blade twist due to the bending of the blades. This has been demonstrated for steady simulation cases as well as for an emergency stop scenario.

Further work is necessary to quantify the impact that the improved aerodynamic and structural modelling has on the predicted fatigue loads on the blades. A large influence on the fatigue limit estimations of the turbine is to be expected. This results not only from the aeroelastic interactions during extreme operating situations, but also, and perhaps more importantly, from the impact that the convergence time of the wake has on the controller reaction.

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