SHADOW EFFECTS IN AN OFFSHORE WIND FARM – POTENTIAL OF VORTEX METHODS FOR WAKE MODELLING

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Summary

Offshore wind turbines in a wind farm are affected by wakes of upstream turbines and adjacent wind farms depending on the park layout and wind direction. As a result the power output may decrease, while structural loads are increasing. In this research a coupled numerical approach based on multi-body system and free vortex methods is used to simulate shadow effects on the Alpha Ventus wind farm. The AV5 is operating at 12 m/s wind speed at half wake conditions with enabled control system and flexible blades and tower. Results of power output, rotor speed, blade pitch and blade root moment over time and azimuth demonstrate the high impact of the half wake condition on the wind turbine performance and loads.

1. Introduction

630 MW of offshore wind capacity in the North and Baltic Sea was being connected to the German grid as at June 2014. According to the plans of the Federal Government a capacity of 15 GW is to be connected to the grid in 2030. The rising trend is based on the installation of larger wind farms with more turbines. Thus, park-to-park and turbine-to-turbine interaction are getting more important and result in non-free flow conditions depending on the park layout, wind direction and operational state. The wake shed by upstream turbines induces additional turbulence, influences structural loads and may reduce the power production.

In this research numerical simulations are carried out to investigate the impact of upstream wakes on a wind turbine model that uses flexible multi-body elements and is operated with a control system. The layout of the German offshore wind farm Alpha Ventus located 45 kilometres north of the island of Borkum (North Sea) is chosen and the turbines AV4 and AV5 are simulated (see Fig. 1).

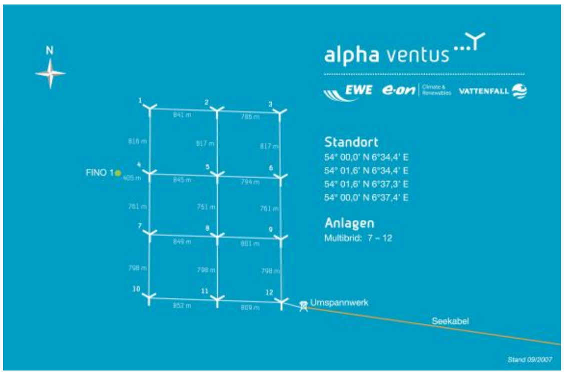

Fig. 1: Layout of wind farm Alpha Ventus [DOTI]

1.1 Relevance

High resolution measurement data of environmental conditions like wind speed and direction, turbulence intensity and wave period and length are publically available for the FINO 1 substation located 405 meters west of the AV4 (see Fig. 1). For 2012 the wind rose is demonstrated in Fig. 2 showing a main wind direction from south west at 9.6 m/s mean wind speed (all wind sectors). The AV5 is affected by wakes of adjacent turbines resulting only in undisturbed wind sectors. Thus, the influence of upstream wakes on the system behaviour and structural loads of the AV5 is of interest.

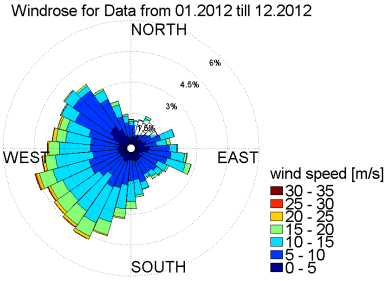

Fig. 2: Wind rose in 2012 at FINO 1

The applied coupled and integrated approach provides the opportunity to gain a detailed insight into the structural loads of wind turbines with inclusion of the control system and less computational resources needed than for standard fluid-structure interaction analyses based on FEM and CFD.

1.2 Literature Review

In the past several empirical models have been investigated for approximating the wake and the velocity deficit within the wake. They mainly differ in applicability and level of detail. A single wake can be described e.g. by one of the oldest wake models, the Park model, which is based on a balance of momentum, the Larsen model, based on the Prandtl turbulent boundary layer equations, or the Frandsen model, distinguishing between different wake zones. Models, like FLORIS, or the DWM model, have been developed to describe the wake in a more detailed manner and are developed to fulfil several purposes. Increasing the demanded complexity of

the wake model leads to simplifications of the Navier-Stokes equations, like the Anslie model.
Wake models are all somehow limited in physical representation and application but have more or less benefits in improving the computational effort. High fidelity models like CFD (Weihing, 2014) require large computational resources and their industrial application, thus, is difficult. An alternative approach based on free vortex methods is applied in this paper to consider both accuracy and computational efficiency.

2. Methodology

Numerical simulations in this research are conducted using a coupled approach. Aerodynamic loads on the rotor blades are calculated by means of the Free Vortex Methods (FVM) solver WInDS that has been originally developed at the University of Massachusetts Amherst by Sebastian (2011). The commercial MBS solver Simpack is applied for modelling of the structural properties and is coupled to FVM.

2.1 Structural Model

The AV4 and AV5 are represented by the NREL 5MW reference wind turbine (Jonkman, 2009). The structural model consists of bodies defined by mass, centre of gravity and moments of inertia that are connected by joints of various types (see Fig. 3). Modally reduced flexible Finite Element Method (FEM) bodies are implemented for representation of the rotor blades and tower. The rotor speed at given inflow conditions results from the blade pitch and generator torque that is controlled by means of the control system. External forces and disturbances are applied at markers allowing the computation of aerodynamic loads on the wind turbine. Here, aerodynamics are computed by an external fluid solver that is coupled to the MBS tool via a user force element. Hydrodynamic loads are neglected in this study and the rigid foundation is fixed to the seabed via a zero degree-of-freedom (DOF) joint. Additional, the low speed shaft torsional DOF is enabled. Thus, an integrated aero-servo-elastic multi-fidelity analysis is used in this research.

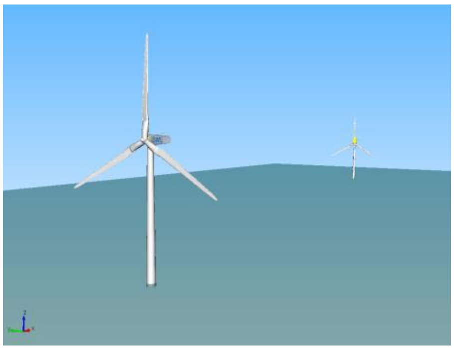

Fig. 3: Graphical representation of the structural model of the AV4 and AV5 in Simpack

2.2 Fluid Model

The fluid model is based on vortex methods, a potential flow approach with inviscid, incompressible and irrotational assumptions. Laplace's equation, a second-order, linear and partial differential equation, is the underlying mathematical statement. A vortex filament which is a curved line of concentrated vorticity satisfies the aforementioned assumptions. Similar to a magnetic field that is induced in the presence of an electric current, velocities are induced in the flow field in the presence of vortices. This effect is mathematically described by the Biot-Savart law. The induced velocity approaches infinity in the vicinity of the vortex filament. The resulting inconsistency to the physical reality is overcome by means of vortex core models. Vortex core models impact the stability and accuracy of the solver due to their numerical damping.
The evolving wake of the wind turbine is represented by a vortex lattice (see Fig. 4). It consists of vortex filaments that are allowed to convect and deform freely in the flow field. Shed vortex filaments account for flow unsteadiness and trailing vortex filaments are associated with the spanwise variation in lift on the blades. Additionally, the wake is coupled to a lifting-line model that relates the lift distribution of the rotor blades to the strengths of the vortex filaments.

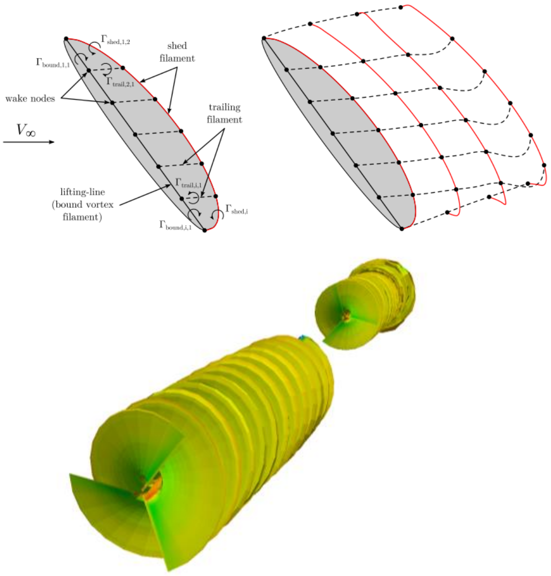

Fig. 4: Top: Vortex lattice representing the wake of a wing, Bottom: Illustration of the wake of the AV4 and AV5 wind turbines

The FVM solver, called WInDS (Wake Induced Dynamic Simulator), is written within Matlab and uses GPU acceleration (Beyer, 2014).

2.3 Coupling Scheme

The challenge of the proposed coupling methodology is the transfer of loads and motion information between the fluid and structural solvers. Essential tasks are coordinate transformation and interpolation, collection of loads and motion information and the transfer to a common storage. Also important are the distribution of loads and motion data and the synchronisation. A fully implicit and explicit iteration scheme is incorporated for transient simulations (see Fig. 5). Every time step is subdivided into multiple inner iterations and coupling data is exchanged. The structural solver is repeated after each coupling time step integration. Convergence and the number of coefficient loops of each time step are controlled by a moderator via user input.

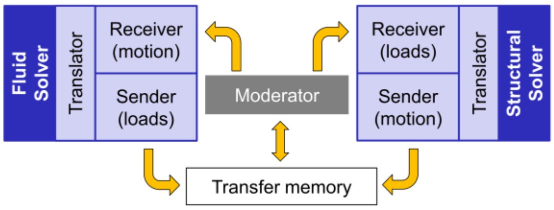

Fig. 5: Tasks within the coupling scheme

The original coupling has been developed by Arnold (2014) for the simulation of fluid-structure interaction on tidal current turbines using coupled MBS-CFD methods. A validation based on submerged free-decay experiments of spring, gravity and bending pendulums in an aquarium filled with water is demonstrated by Arnold (2015). An excellent correlation between numerical and experimental results demonstrates the validity of the methodology. An application of the MBS-CFD coupling for the analysis of hydrodynamic loads on floating offshore wind turbines is presented in Beyer (2015). The original coupling methodology has been modified by Lenz (2014) to account for aerodynamics loads on wind turbines based on FVM.

3. Results and Discussion

3.1 Load Case Description

The AV4 and AV5 wind turbines are operating at uniform inflow without shear at half wake conditions (50% shadowing). A wind speed of 12 m/s is chosen, which is closely above rated operational conditions of the NREL 5MW. 250 s are simulated at a coupling time step of *dt* = 0.2 s. Additional simulation properties are listed in Tab. 1. As the AV5 is of major interest in this study the AV4 is simplified by means of rigid blades and tower and deactivated controller meaning fixed pitch and rotor speed.

Property	**AV4**	**AV5**
Location (x/y)	0 m/0 m	845 m/63 m
Tower	Rigid	Flexible (10 modes)
Rotor blades	Rigid	Flexible (10 modes)
Controller	Fixed blade pitch (3.8°) and rotor speed (12.1 rpm)	Enabled (NREL 5MW baseline)

Tab. 1: Simulation properties

3.2 System Behaviour

The AV5 is highly affected by the wake of the AV4. The system behaviour is demonstrated in Fig. 6. Transients at the beginning of the simulation are neglected. A steady state at rated conditions of 12.1 rpm rotor speed, 3.8° blade pitch and 5 MW power output according to the specifications (Jonkman, 2009) is reached for 12 m/s at approximately 50 s. The blade pitch of the AV5 is approximately 0.6° higher indicating a good correlation of the applied fluid model compared to BEM. At around 70 s the wake of the AV4 hits the AV5 and the resulting half wake condition is influencing the system dynamically. The blades are pitched by the controller into the wind as the rotor speed decreases due to a reduction of the rotor effective wind speed. After transients the blade pitch is 0°, the rotor speed is fluctuating highly below rated at around 11.9 rpm and the electrical power drops and oscillates around 4.6 MW.

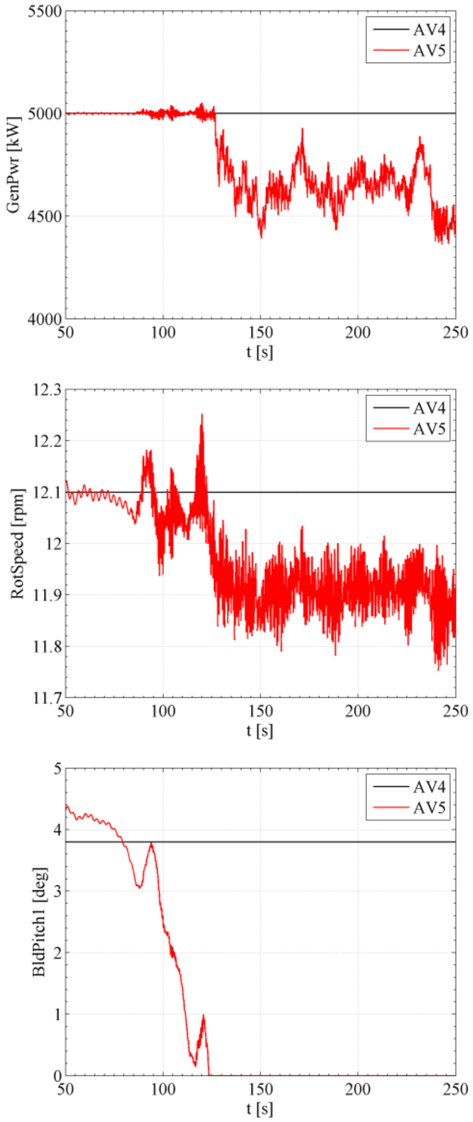

Fig. 6: System characteristics, Top: Electrical power, Middle: Rotor speed, Bottom: Blade pitch angle

3.3 Blade Loads and Aerodynamic Information

During a full revolution the blades of the AV5 are affected periodically by the half wake condition. The velocity fluctuations in the flow field over the azimuth, the flexibility of the rotor blade and the blade pitch that is set by the controller influence the effective angle of attack at each blade section. Thus, the aerodynamic lift changes over one revolution resulting in fluctuations of the blade loads. The half wake condition after 70 s simulation time results in a 1P excitation of the out-of-plane blade root moment (see Fig. 7).

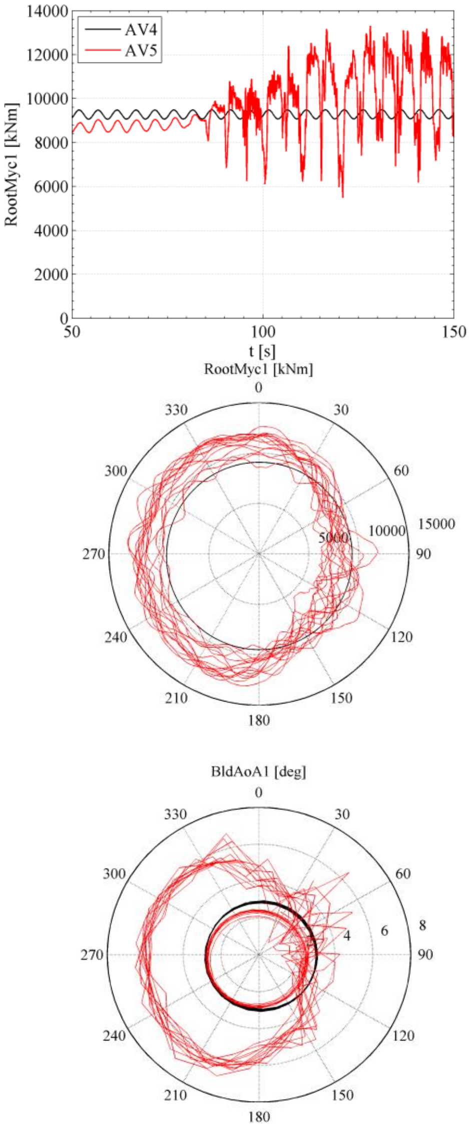

Fig. 7: Blade characteristics (AV4: black, AV5: red), Top: Out-of-plane blade root moment, Middle: Out-of-plane blade root moment over twelve revolutions, Bottom: Angle of attack of blade 1 at 80% rotor radius

The maxima, mean and standard deviation are increased leading to higher fatigue loads. A clear dependency on the azimuth angle is also demonstrated. The blade root moment decreases in the shed wake between approximately 0°-180° and increases between 180°-360° resulting in a cyclic excitation. The blade pitch angle is reduced as the controller “sees” less wind. Thus, the rotor thrust increases and the angle of attack is increased significantly if the blade azimuth is between 180°-360° (no shadowing). As a comparison the angle of attack at blade 1 at 80% rotor radius is plotted against results of the AV4 and the AV5 before shadowing.

3.3 Tower Loads

Due to the half wake condition fluctuations of the blade loads are acting on the flexible tower. The tower is twisted and the resulting tower base moment around the vertical axis is shown in Fig. 8.

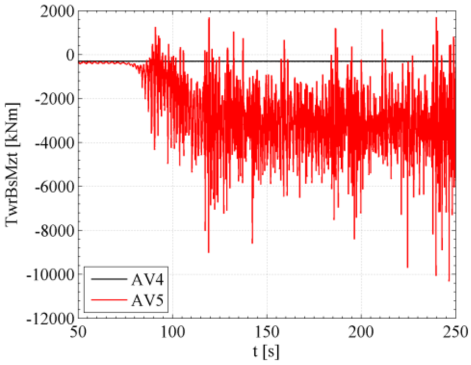

Fig. 8: Tower base moment around *z*-axis (vertical)

5. Acknowledgements

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6. References

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