Aeroelastic Wind Turbine Simulation in SIMPACK Coupled with the ECNAero-Module



Due to the rapidly increasing rotor diameters, an accurate load prediction of wind turbines continues to gain importance. Such loads are mainly caused by the rotor aerodynamics, and therefore, are related to the effective wind speed on a blade section. The effective wind speed is influenced by the wind speed in the rotor plane, the actual shape of the rotor blades as well as their spatial location and movement in the wind field. For this reason, adequate aerodynamic models have to be coupled to solvers of the structural dynamics for aeroelastic simulations (Fig. 1). Advanced aeroelastic simulations that are based on the presented approach play a key role in capturing the correct loading conditions on a specific turbine. This article presents simulation results performed on a large scale wind turbine using SIMPACK coupled with the new ECNAero-Module as examined in the diploma thesis of Morten Bülk [1].

BLADE ELEMENT MOMENTUM THEORY (BEM) FOR HORIZONTAL AXIS WIND **TURBINE AERODYNAMICS**

The BEM method is the current standard for calculating wind loads within aeroelastic simulation tools. Assuming an inviscid, incompressible and axisymmetric flow, BEM assumes control volume integrals for conservation of mass, axial and angular momentum balances, and energy conservation. Therefore, the rotor plane is split into multiple annuli which are independently considered. This, and the lack of wake modeling, which is known to have a retroaction with the rotor, are well known restrictions. Furthermore, some important three-dimensional aerodynamic effects such as the change of induction due to a finite number of blades (tip loss), oblique inflow, and dynamic inflow, are considered in BEM using empiric correction models. Nevertheless, BEM has the significant advantage of very small computational effort compared

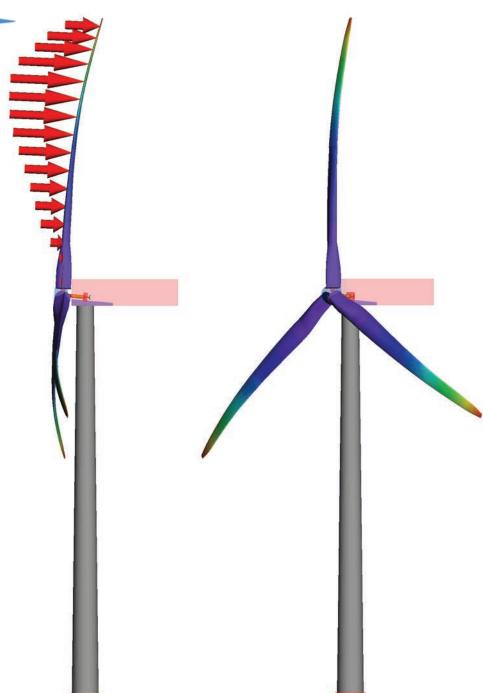


Fig. 1: Aeroelastic coupling SIMPACK - ECNAero-Module

with more physical and sophisticated simulation tools like Computational Fluid Dynamics (CFD).

The Energy Research Centre of the Netherlands (ECN) has developed a new BEM code with advanced implementation of state-ofthe-art correction models integrated into the "ECNAero-Module". This model is based on the BEM implementation in PHATAS [2], which has been refined through many years of usage in wind energy research and industry. Amongst the programmed extensions

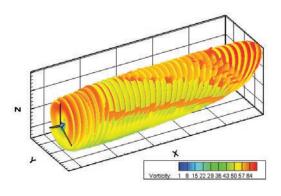


Fig. 2: AWSM wake with sheared inflow conditions

are the ECN dynamic inflow and the oblique inflow model [2]. The modeling is subject to continuous improvement by means of validation with experiments and other codes such as AWSM.

AERODYNAMIC WIND TURBINE SIMULATION MODULE (AWSM)

To overcome the limitations of BEM, especially concerning wake and time dependent wake-related phenomena (Fig. 2), as well as to fill the gap between simple BEM calculations and the very complex — hence time-consuming — CFD simulation, ECN developed the "Aerodynamic Wind Turbine Simulation Module" (AWSM) [3]. AWSM is based on a generalized lifting line theory in combination with a free vortex wake method. One main assumption is that the extension of the geometry in span-wise direction is predominant compared to the ones in chord-wise and thickness direction. The lift generated around an airfoil depends only on the circulation Γ , which defines the strength of a vortex. Therefore, the real geometry in AWSM is represented by discrete vortices located at the quarter chord points of the cross sections, forming the so called lifting line. Hence, the total flow field in chord-wise direction is concentrated in this point (Fig. 3). Along the lifting line, the generated elementary force can be determined by using the three dimensional form of the Kutta-Jukowsky theorem. The strength of every vortex is calculated by equalizing the lift according to the Kutta-Joukowski equation and the lift generated by the specific lift coefficient of each cross section of the blade. As in the continuous flow-field representation, the vorticity is shed from the trailing edge (TE) of the configuration surface and convected downstream in the AWSM flow model as time advances. The advantage of AWSM is that the magnitude and direction of the velocities, and thus, the lift coefficient C, depend on all modeled vortices in space, i.e., the vortices at the surface and in the wake. The blade geometry consists of one or more strips that carry a vortex ring whose bound vortices are located at the quarter chord position and at the trailing edge (Fig. 3). Therefore, this approach enables AWSM to model advanced blade shapes including winglets, pre-bent and pre-swept blades.

ECN AERO-MODULE AND SIMPACK INTERFACE

ECN has assembled both aerodynamic models in the so called "ECNAero-Module" [4]. Several dynamic stall models, 3D correction models, wind modeling options and a module for calculating the tower effect are also included. In contrast to CFD calculation, which allows solving the flow in the boundary layer of a blade, BEM and AWSM rely on airfoil tables. Therefore,

the aerodynamic coefficients have to be supplied by the user. This approach allows the user

to perform the complex airfoil design, using, e.g., wind tunnel measurements independently from the load simulations. The package is coupled to SIMPACK which solves the structural dynamics of the wind turbine (Fig. 4). In SIMPACK 9.0, a standard interface to the ECNAero-Module has been developed as a force element which allows easy coupling for co-simulation.

SIMULATION OF AN NREL 5MW TURBINE

Simulations using the new ECNAero-Module coupled with SIMPACK have been performed on the "UpWind Reference Wind Turbine" originally formulated by the National Renewable Energy Laboratory (NREL) in the USA. This turbine model consists of a typical three-bladed horizontal axis rotor with a diameter of 126 meters, a hub height of 90 meters and a rated power of 5 MW (Fig. 1).

LOAD CASES

"To overcome the limitations of BEM,

ECN developed the "Aerodynamic Wind

Turbine Simulation Module" (AWSM)."

Because of the generally different approach used in BEM and AWSM, diverging results are already expected in simplified load cases using rigid turbine models with uni-

> form, homogeneous wind fields. Starting with an axial inflow on a non-coned and non-tilted rotor — a

load case that best matches the design of the BEM approach — the difference in BEM and AWSM results at optimum conditions can be depicted and used as a reference for further comparison of advanced load case conditions. Later, in order to analyze

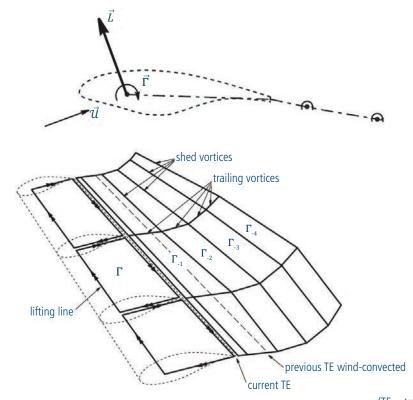
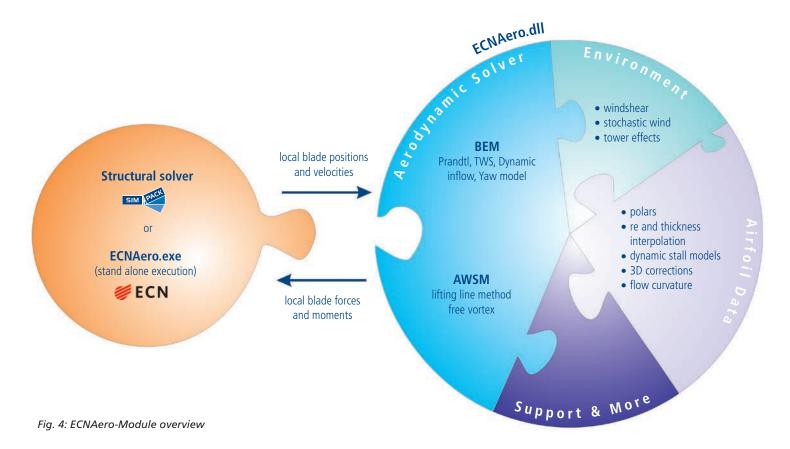


Fig. 3: AWSM modeling approach

(TE = trailing edge)



the isolated effects which match the known shortcomings of BEM, the turbine setup or inflow conditions are adjusted. The results of three representative load cases are shown below:

- 1) reference load case
- 2) coned rotor
- 3) individual pitch step

All load cases are performed on a rigid turbine setup without considering the tower dam effect. Furthermore, an axial, homogeneous inflow of 8 m/s and a fixed rotor speed of 9.155 rpm cause the turbine to operate at an optimal tip speed ratio of 7.55. The three rotor blades are each represented by 17 aerodynamic cross sections. To reach a steady state, 12 rotor revolutions are simulated for each load case before taking the results or performing a pitch movement.

1) The reference load case uses a turbine without cone and tilt. Fig. 5 shows the angle of attack over the radial length of the upward pointing blade. For this load case, one can see a very good correlation between BEM and AWSM results. The tip region shows some deviation which gives evidence to the different methods of tip modeling. For BEM, the so called "Prandtl tip loss factor" takes a finite number of blades into account by modeling tip vortices. The lifting line formalism already accounts for the trailing tip vortices so AWSM does not need a correction model for that effect.

2) The second load case uses a rigid, 2.5° coned rotor and is compared to the reference load case. Similar to the first load case, Fig. 6 shows the angle of attack over radial length of the upward pointing blade. One can see that BEM and AWSM show not only different angles of attack but, in addition, the effect of coning is predicted differently for the AWSM case. BEM shows a more or

less constant angle of attack, whereas AWSM predicts the angle of attack to become higher

for a coned rotor. This is because AWSM also considers induction in the radial direction which results in the expansion of the stream tube while passing the rotor. For outboard sections of the coned rotor, this results in a better orientation of the blade towards the resultant inflow direction. It must be noted here that corrections due to flow curvature for a coned rotor ("virtual camber" of a section) have been switched off for both BEM and AWSM.

3) The turbine of the third load case is set up like the reference load case, i.e., a nonconed and non-tilt rotor. After reaching steady state, blade 1 is pitched individually with a pitch rate of about 6.3 deg/s from 0° to 3° in the stall direction. After 20 seconds, blade 1 is pitched back to 0° at the same pitch rate. Figures 7 and 8 show the angles of attack over time for blades 1, 2 and 3 for this individual pitch movement. The first obvious statement that can be made for both codes and for all blades is that a change in angle of attack occurs during the maneuver. However, the effects covered by the different codes result in dramatically diverging predictions. After the occurrence of the higher (respectively lower) angle of attack, one can see an inconsistent course in BEM

> results (Fig. 7) which is caused by the empirical "dynamic inflow" model. Furthermore,

for blade 2 and blade 3, BEM predicts the same change in angle of attack caused by changed axial annulus averaged induction, and thereby, the independence of all three blades. AWSM, on the other hand, takes the dependency of all three blades into account by modeling the wake, and predicts different loads for blade 2 and 3, depending on the orientation, and thereby, the blade 1 sequence (Fig. 8).

CONCLUSION AND PROSPECT

"AWSM also considers induction

in the radial direction"

Some effects which are covered by empirical correction models in the BEM code are directly included in the AWSM approach. Furthermore, the AWSM code covers some effects like radial and blade dependency,

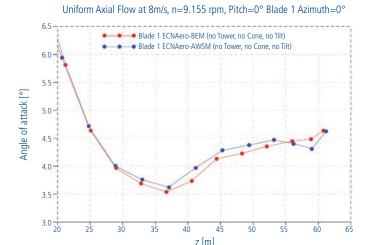


Fig. 5: Angle of attack for blade 1 in reference load case

Uniform Axial Flow at 8m/s, n=9.155 rpm, Pitch=0°, Blade 1 Azimuth=0°

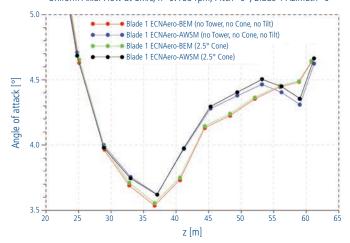


Fig. 6: Angle of attack for blade 1 in coned rotor load case

as well as other wake and time dependent wake-related phenomena which cannot be modeled in BEM. These skills will become essential for modern aerodynamic code when considering individual blade pitch control and advanced blade shapes including winglets, pre-bent and pre-swept blades.

The present work shows the first results of this modeling. Further study should include more complex load cases (e.g., wind gusts, grid loss)

and blade geometry to discover the full potential of this approach. The computational effort using AWSM is dependant upon on the wake modeling, and therefore accuracy is needed. The user is able to control the accuracy of wake modeling. Despite this, the calculation time compared with BEM in this project is, with a factor of around 350, much higher for AWSM. For BEM, this results in a computation period of around 17 seconds for an 80 second load case, while AWSM needs 98 minutes for the same load case. Although the calculation time is already significantly shorter than any other CFD based software, ECN is developing AWSM to reduce the calculation time even further. In the future, the ECNAero-Module can be

> used for comparing aerodynamic other tools like the free BEM-Code "AeroDyn" from NREL as well as other CFD tools. Another

planned extension is to expand the capability of AWSM to include the predictions of park effects, by considering the wake from multiple turbines in one total flow field.

INFORMATION AND CONTACT

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"AWSM takes the dependency of

all three blades into account by

modeling the wake, and predicts

different loads for the blades."

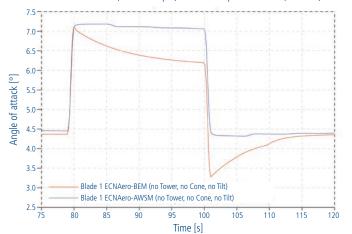


Fig. 7: Angle of attack for blade 1 in individual pitch load case

Uniform Axial Flow at 8m/s, n=9.155 rpm, B 1 Pitch step $0^{\circ} \rightarrow -3^{\circ} \rightarrow 0^{\circ}$, B2 & B3, z/Z=0.85

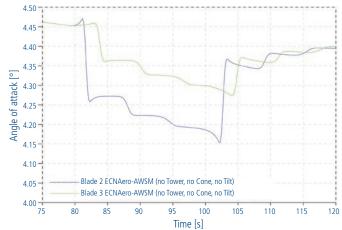


Fig. 8: Angle of attack for blade 2 and 3 in individual pitch load case