Wind Turbine Simulation Using a Coupled Free Wake and Multibody System Code

Stefan Hauptmann, Daniel Kaufer, Martin Kühn
Endowed Chair of Wind Energy, Universität Stuttgart, Germany,
+49 (0) 711 685 60339, hauptmannn@ifb.uni-stuttgart.de

Summary

This paper contributes to the development of an aeroelastic simulation tool for wind turbines based on a coupled non-linear multibody simulation and a non-linear lifting line vortex wake theory code. The structural blade modelling in the multibody simulation tool SIMPACK and the theory of the aerodynamic module AWSM is described as well as the coupling strategy of the multibody and the aerodynamic module. The evaluation of the potential of the described simulation approach is performed in detail by comparing some exemplary and simplified load cases. The paper concludes with an outlook on the further development, which should overcome shortcomings in the present industrial simulation approach.

1 Introduction

In the current design process, aeroelastic simulation of wind turbine dynamics is generally performed with special software codes, developed solely for this application. These codes often use only a few modal degrees of freedom for the consideration of structural dynamics, whereas the simulation of rotor aerodynamics is based on the blade element momentum theory (BEM). More detailed analysis of the structural dynamics can be performed with multibody system (MBS) codes. More sophisticated aerodynamic models are available for simulation of the specific aerodynamic behaviour of wind turbines. This paper attempts to contribute to the development of the next generation of aeroelastic design tools by demonstrating the generation of structural rotor blade models in a MBS code like SIMPACK, the coupling of multibody simulation codes with lifting line theories, for example the free vortex wake model AWSM [1] and the validation using a coupling of SIMPACK and a BEM module [2].

2 Structural Rotor Blade Model

For structural modelling of rotor blades in the MBS code SIMPACK, a pre-processor has been developed to generate rotor blade models using a modal reduced beam element approach [3]. The user can choose between different modelling approaches to optimise the level of detail depending on its application. The so called “Simple” model is created using only a few input parameters and enables bending in only the flapwise or edgewise directions. A “Sophisticated” model also takes into account many additional terms such as cross term inertia, torsional rigidity, pre-bend, and pre-sweep. Bend-twist coupling and non-homogeneous material can also be represented. Furthermore, non-linear bending and also shear effects can be ignored or included. Therefore, either Euler-Bernoulli or Timoshenko beam elements are provided for both modelling approaches mentioned.

3 The Aerodynamic Module AWSM

3.1 Theoretical Background

The used aerodynamic module AWSM (Aerodynamic Wind turbine Simulation Module) has been developed by the Energy Research Centre of the Netherlands (ECN) [1] to overcome the limitations of the state-of-the-art blade element momentum theory (BEM), in particularly with respect to wake calculations. Many empirical corrections are included in BEM codes with respect to 3-dimensional effects of the entire rotor aerodynamics, e.g. corrections for tip losses due to boundary circulation and induction effects of the off-flowing wake. AWSM tries to fill the gap between simple BEM calculations and the very complex and hence time-consuming computational fluid dynamics (CFD). AWSM applies the potential flow theory. This theory is based on assumptions like irrotational flow field and inviscid consideration of the flow. This enables the introduction of a so-called potential gradient field, which describes the three velocity components in space by only one single variable, namely the potential of velocity. The law of conservation of mass and the principle of linear momentum describe the flow field, but they can be transformed into the Laplace equation under compliance with the assumptions described above. The advantage of the Laplace equation is its linearity and therefore the ability of superimposing the total solution from elementary solutions which can be determined analytically. The important ones in aerodynamics view are called parallel streaming, sources, sinks and vortices. The names have been given due to the drawing of the stream lines of each elementary solution. Finally, we can subsume that any inviscid flow can be approximated by suitable superimposing of the solutions of the Laplace equation, e.g. the flow around an airfoil. A further large step was found by Kutta-Joukowski. The lift generated around an airfoil depends only on the circulation Γ, which defines the strength of a vortex. Sources and sinks have only displacement effects. It must be noted that drag cannot be determined reasonably because of inviscid assumption.

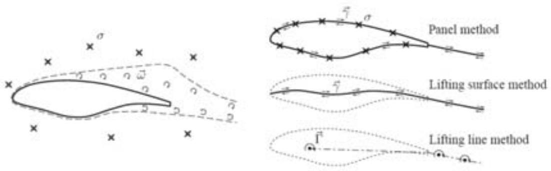

Figure 1: Flow field approximations, Garrel [1]

Figure 1 shows typical potential theory methods and it also illustrates how the flow field can be approximated. The panel method still considers thickness effects. The lifting surface method reduces the airfoil to a continuous vortex distribution along the skeletal line and the lifting line method concentrates the vortex distribution to a single vortex, which is often located at the quarter chord line of a lifting surface.

The latter method is used by AWSM. Leading edge and trailing edge points of a lifting surface define the geometry and deformations of the structure and can be specified by 3-dimensional displacements of these edge points during the calculation. AWSM allows multiple and constant vortex rings in the lifting surface. Each vortex induces velocities according to the law of Biot-Savart. The lifting line method determines the actual strength of the vortex rings placed on the surface in each time step. Vortex rings of previous times are transported downwind and hence they create the wake behind the lifting surface. The strength of every vortex is calculated by equalising the lift according to the Kutta-Joukowski equation and the lift generated by the specific lift coefficient of each cross section of the blade. The challenge is that the magnitude and direction of the velocities $\vec{v}$ and thus the lift coefficient C_l depend on all modelled vortices in space (see Eq. 1), i.e. the vortices at the surface and in the wake. Therefore, an iterative process is applied until sufficient accuracy is reached.

$$\Gamma = f\left(t, c_l(\alpha), \vec{v}(\Gamma)\right) \quad (1)$$

Finally, the new calculated vortex strength along the lifting surface can be used to evaluate the velocities and local angles of attack once more and thus the lift and drag can be evaluated using a lift and drag coefficient look-up table. Important are accurate coefficient tables for lift and drag of the used airfoils.

3.2 Coupling of AWSM and SIMPACK

The non-linear lifting line vortex wake theory code AWSM is coupled to the non-linear multibody simulation code SIMPACK. Until now, a serial coupling between SIMPACK and AWSM is implemented to enable aeroelastic simulations of wind turbines [4]. The algorithm is sketched in Figure 2.

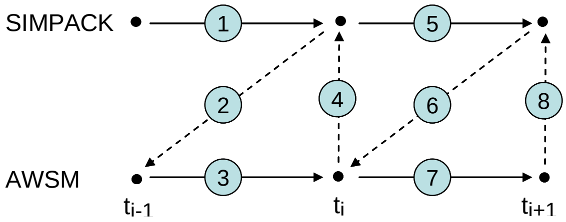

Figure 2: Coupling algorithm

The coupling is limited to the wind turbine rotor. Hence the motion of the tower is not implemented yet, but could be treated analogously. The interface environment of SIMPACK is given by the User Routines, which are free programmable units within SIMPACK. AWSM has been compiled as part of SIMPACK, because parallel calculations of both codes are not feasible. AWSM has to wait for solutions of SIMPACK and the other way around. In this manner the communication speed is fast, due to direct operations in the same memory area. All local blade deformations and the actual status of the wind turbine, i.e. rotation angle, pitch angle, are passed from SIMPACK to AWSM. AWSM hands over the corresponding loads regarding all elastic motions to SIMPACK.

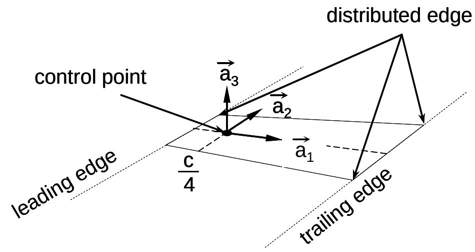

Figure 3: Geometry of blade sections

The aerodynamic loads are calculated at defined control points as shown in Figure 3. The location is situated at the quarter chord line c/4 in the middle of each blade element, whereas the displacements influence the edge points of each section. A corresponding modelling in both codes is important. Therefore it is suggested to use a number of blade markers in SIMPACK which is equal to twice the number of AWSM edge points minus one. Finally the implemented coupling allows fully coupled aeroelastic simulations of wind turbine rotors and in the future it will be extended to consider nacelle, tower and foundation motions to cover the entire turbine structure.

4 Simulations

4.1 Simulation Model

Simulations with the coupled vortex wake and multibody simulation codes are performed to validate the coupling and to evaluate and demonstrate the capabilities of the aeroelastic tool. The simulations are based on the rotor of the generic NREL 1,5MW reference turbine with 70m rotor diameter. The structural model consists of a rigid rotor hub and three flexible rotor blades. The blades are modelled with the pre-processor described above using the sophisticated approach considering the bending and torsional modes and the appropriate coupling effects. The rotor speed can either be kept constant or a simple generator model can be used.

The aerodynamic model is built-up in the free vortex wake code AWSM, and for validation purposes the corresponding model is used in the BEM code AeroDyn. For all simulations no turbulence model is used and the deterministic wind is kept constant over the whole rotor disc but can change in time.

4.2 Coupled Simulations
The aeroelastic coupling of the two codes is checked with an artificial dynamic loading situation.

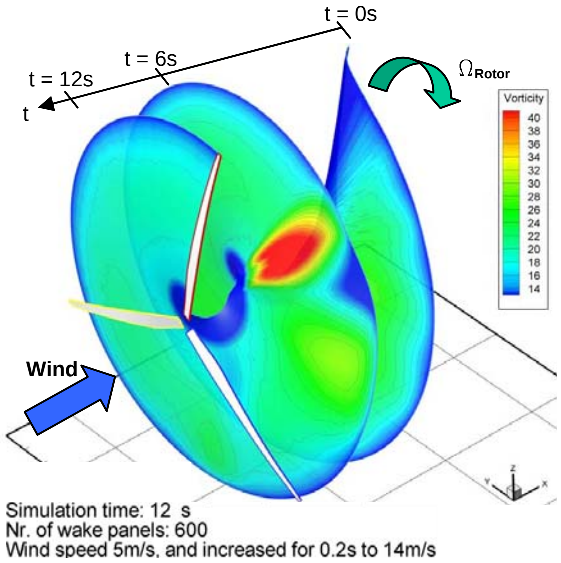

Figure 4: Influence of a wind gust on the vorticity.

Figure 4 represents the vorticity of a single rotor blade during rotor run-up and occurrence of a deterministic wind gust modelled with the coupled SIMPACK and AWSM codes. The picture shows the dissemination of the wake in space. The given time line indicates the development of the wake's history. The strength of the vorticity is given by colours. Blue represents a low vorticity, whereas red indicates a high vorticity. According to Kutta-Joukowski, the vorticity is proportional to the local lift of the blade section and is therefore an indicator for blade loading.

Starting at t=0s, one can see the increase in vorticity during run-up of the rotor. After that, at about t=6s, the rotor speed becomes stationary and the vorticity remains constant. At about t=8s a wind gust occurs and the wind speed is increased from 5m/s to 14m/s and returns to 5m/s only 0.2s later. Due to the increase in wind speed the vorticity rises dramatically. When the wind speed returns to the constant velocity of 5m/s the vorticity does not become constant instantly. Instead the vorticity needs some time to decay. This effect is due to the fact that the rotor blade is modelled as a flexible body and is excited by the gust. The structural movements cause changes in the local wind speed, the angle of attack and the corresponding vorticity. This well-known effect is used for validation of the coupled codes.

4.3 Simulation of Simplified Load Cases.
In this Section the model mentioned in section 4.1 is used to simulate some simplified load cases and to compare the results with the coupling to the BEM code AeroDyn. In this paper only the two most interesting load cases are mentioned.

<u>Steady Operation</u>
The steady operation load case is used only for validation of the results of the free vortex wake and the BEM codes coupled to SIMPACK. In this load case the rotor speed as well as the wind speed is kept constant.

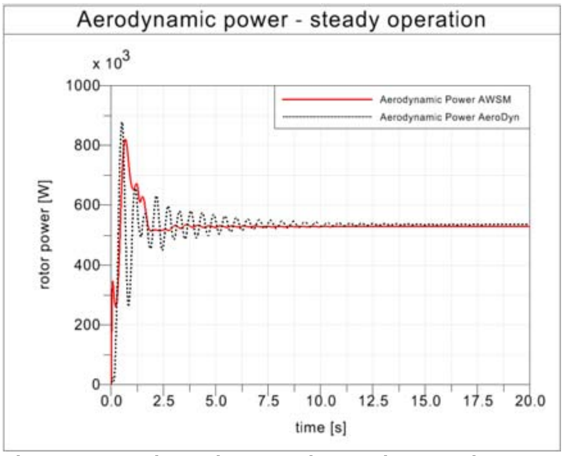

Figure 5: Aerodynamic power in steady operation

Figure 5 plots the aerodynamic power of the rotor during steady operation at 8m/s wind speed simulated with AWSM/SIMPACK and AeroDyn/SIMPACK. The red line represents the power output when using AWSM, whereas the blue line relates to AeroDyn. It is shown that the BEM solution takes more time to converge, but in steady state condition both codes show a good correlation.

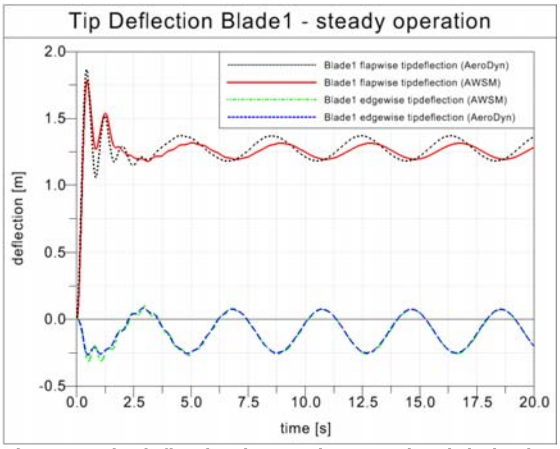

Figure 6: Tip deflection in steady operation (Blade 1)

Figure 6 explains the blade tip deflection of rotor blade 1 in edgewise and in flapwise direction, simulated with both considered aerodynamic codes.

One can see a good correlation of the deflection in edgewise direction and only a minor phase shift in flapwise direction.

Pitch Misalignment

In the second load case, the pitch angle of rotor blade 1 is changed independently of the other blades. The pitch angle of rotor blade 1 is increased about +7.3deg between 20s and 30s of the simulated time.

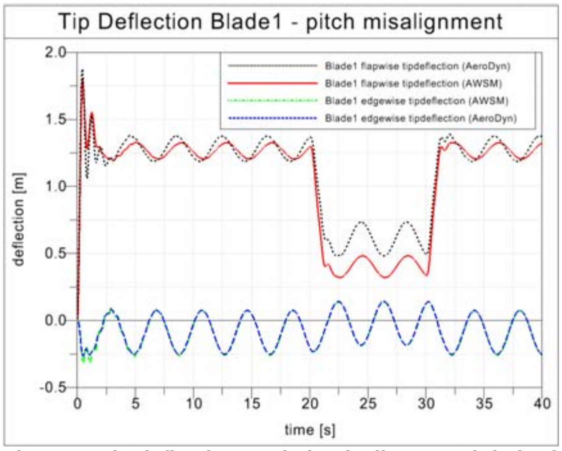

Figure 7: Tip deflection at pitch misalignment (Blade 1)

Figure 7 presents the tip deflection of rotor blade 1 during an individual pitch manoeuvre of this rotor blade. The asymmetric pitch action leads to different solutions in the considered codes. The BEM theory predicts a smaller reduction in deflection than the free-wake code. This effect was expected because the BEM theory does not take any variation of the rotor induction between different blades into account Therefore, it can be assumed that the AWSM solution in this case is more reliable than the BEM solution.

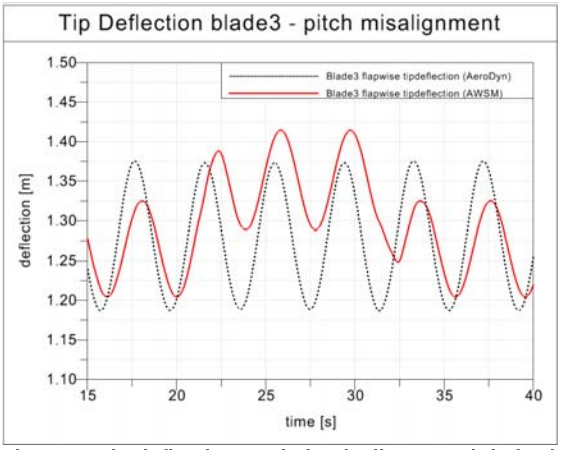

Figure 8: Tip deflection at pitch misalignment (Blade 3)

Another interesting effect of asymmetric pitch action is highlighted in Figure 8. It plots the tip deflection of rotor blade 3 that follows blade 1, which is pitched individually. One can see that there is a difference between the predicted tip deflections of the two codes. The BEM code predicts the motion of rotor blade 3 to be unaffected by the pitching of blade 1. The AWSM code predicts an increase in deflection for blade 3. This effect is due to the fact that the BEM code does not have a correction module to consider such individual pitch effects and therefore does not consider the influence of rotor blade 1 to blade 3. In the AWSM code the wake, calculated for each individual rotor blade influences all of the rotor blades and it seems that this approach is more precise than the BEM code.

5 Conclusions

The rapid development of wind turbine technology results in a need for a next generation of aeroelastic simulation codes. Therefore, a newly developed pre-processor for rotor blade structural models is introduced and a coupling between the lifting line vortex wake theory code AWSM and the non-linear multibody simulation code SIMPACK is implemented. The tests of the coupled codes are successful and the results are plausible. The load case “individual pitch action” demonstrates the advantages of the use of free-wake models for aeroelastic simulations.

6 Future Works

In the next steps, the load cases that are not covered in sufficient detail with a BEM code will be identified and the optimal modeling strategy for each load case will be shown. This includes the analyses of the optimal level of detail for the structural model and also for the aerodynamic model. Also the evaluation of even more advanced aerodynamic models like CFD (RANS) will be performed and it will be analysed whether the use of such models is an advantage for aeroelastic design calculations and whether the additional computational effort is cost effective.

Acknowledgement

The use of the AWSM code developed by ECN is kindly acknowledged. We would further like to thank ECN for facilitating the research internship of D. Kaufer.

References

[1] Garrel, A. v.: “Development of a Wind Turbine Aerodynamics Simulation Module”, Report ECN-C--03-079, ECN 2003

[2] Hauptmann, S.: “Aeroelastic Simulation of a Wind Turbine and Drive Train Resonance Analysis Using the Multibody Simulation Code SIMPACK”, DEWEK 2006, Bremen

[3] Mulski, S.: „Rotor Blade Generator”, SIMPACK News, Wessling, 2007

[4] Kaufer, D.: “Coupling a Free Vortex Wake Model and a Multibody Simulation Code for Aeroelastic Simulation of Wind Turbines”, SWE, Universität Stuttgart, 2007, Student Thesis