Proceedings of the 7th GACM Colloquium on Computational Mechanics for Young Scientists from Academia and Industry October 11-13, 2017 in Stuttgart, Germany

Aeroelasticity of Large Horizontal Axis Wind Turbines: Simulation Approaches and Modeling Challenges

Mohamed Sayed[1]*, Thorsten Lutz[1], Shahrokh Shayegan[2] Roland Wüchner[2]

Micro Abstract
Currently, the wind turbine design trend is up-scaling which results in larger slender and flexible wind turbine blades. Therefore, as wind turbine blades become lighter and more flexible, aeroelastic instabilities must be of great concern. Most of the current aeroelasticity tools are based on simplified models of the aerodynamics and the structural dynamics. Therefore, the accuracy level of the engineering models compared to the high-fidelity models were investigated.

[1]Institute of Aerodynamics and Gas Dynamics, University of Stuttgart, Stuttgart, Germany

[2]Chair of Structural Analysis, Technical University of Munich, München, Germany

***Corresponding author**: sayed@iag.uni-stuttgart.de

Introduction

Currently, most of the wind turbine aero-elastic models are based on simplified aerodynamic models such as the Blade-Element Momentum theory (BEM) [2, 8]. In addition, the wind turbine flexible components (such as the blades) are modelled structurally by means of beam elements [7, 8]. The BEM-based method is computationally efficient and provides reasonable estimations of the aero-elastic behaviour of flexible blades, but some aerodynamic phenomena are not captured accurately. Mainly, BEM theory is based on the one-dimensional momentum equilibrium. In fact, it neglects any three-dimensional effects. Therefore several corrections are needed in order to account for all complex unsteady and 3D aerodynamic effects [4]. As the wind turbine rotor diameter increases, including more complex geometries such as pre-cone, rotor tilt and pre-bended blades, symmetric inflow conditions can not be assumed any more. Therefore, it becomes inaccurate simulating it with the dynamic inflow model of the BEM based simulations [7]. Also modelling the blades by beam elements could not be able to capture the profile deformations that might happen at high loading conditions. Any profile deformations will result in a change in the aerodynamic characteristics of it and then the total performance of the wind turbine might be changed. Therefore, aero-elastic investigations were performed based on two different structural models in order to find their impact on the aero-elasticity of large scale wind turbines. In the present study, the CFD solver, CSD solver, the wind turbine configuration, the computational setups and the coupling interface used in this study are described in section 1. Then the aeroelastic response and effects on the blade performance are evaluated in section 2. The results are compared with the CFD results by modelling the blade as a rigid model to investigate the effects of blade deformations on the rotor blade aerodynamic performance.

1 Numerical Setup

1.1 Wind Turbine Configuration

The wind turbine examined in the present study is the generic reference turbine of the ongoing European InnWind project. It is a large HAWT with 178.3 m rotor diameter, a hub height of 119 m and FFA-W3 airfoil series. The complete blade structural properties, the material properties and the elastic properties of the beam and the shell models are defined in [1]. Due to the rotational periodicity of the 3-bladed rotor, a 120 degree sector of the rotor is considered in the present study. Therefore, only a single blade and one-third of nacelle/hub are modelled where the aerodynamics of the full rotor are taken into account through periodic constraints. Figure 1 shows an adequate geometrical CAD surface model of one blade and nacelle/hub established using CATIA which is a multi-platform CAD/CAM/CAE commercial software developed by the French company Dassault Systemes. Pre-bended blades are used with about 3.73%R at the blade tip.

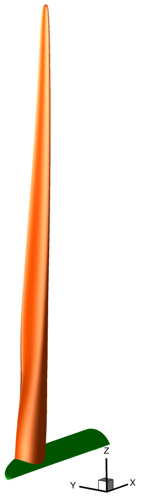


Figure 1. Blade and nacelle/hub surfaces

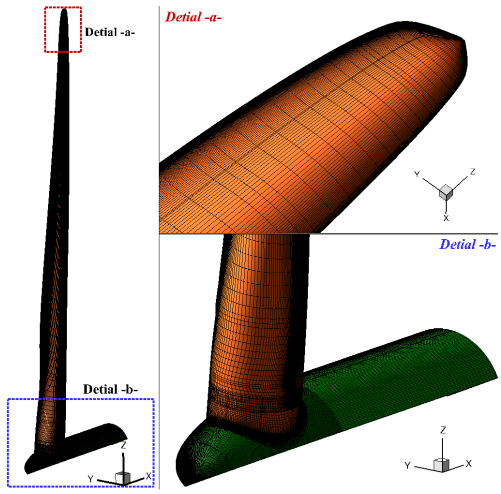


Figure 2. Blade and nacelle/hub surface meshes

1.2 CFD Setup

FLOWer is the CFD solver utilized in the present study which it is provided by the German Aerospace Center DLR [3] with specific extensions implemented at the IAG to obtain the aerodynamic loads by solving the Reynolds-averaged Navier-Stokes equations (RANS). The Wilcox k-ω turbulence model with fully turbulent flow state is used. Implicit dual time-stepping scheme is utilized for the time integration of the RANS equations according to Jameson. An Arbitrary Lagrangian Eulerian (ALE) approach is employed for the grid motions of the rotating parts. The grid over-set method is applied by means of the CHIMERA technique which enables better meshing control of complex geometries. In recent years, a process chain for wind turbine CFD simulations was developed at the IAG to accelerate the pre-processing stage of simulations. This process chain includes a high quality blade grid generation script and one must carefully set the different parameters to control and insure the quality of the generated mesh. Several CFD simulations of different offshore and onshore wind turbines have been conducted using that process chain at IAG [6, 11].

Gridgen® is used in this research to generate the volume meshes for all sub-domains. For each sub-domain, an independent grid is created with adopted refinement. The final generated CFD volume meshes are based on a structured overset mesh technique (the surface meshes are presented in Figure 2). This overset feature allows more mesh control over all the wind turbine parts, as every component is meshed separately. Finally the volume domains are placed together and overlapped using CHIMERA overlapping mesh technique. The blade mesh is generated and refined by a special scripts developed at IAG. A background mesh is created to extend the computational domain to the far field [6]. The far field dimensions are defined in terms of the blade radius (R) as follows: 6R in the upstream direction, 9R in the downstream direction and 6R in the far field direction. These values are chosen based on studies done by Sayed et. al. [6]. The final grid statistics of the different volume domains used in the CFD and the coupled simulations are shown in Table 1.

Table 1. CFD Grid statistics

Domain	Blade	Hub and Nacelle	Background	Blade-Hub-Connector	Total number of cells
Number of cells [millions]	5.2	2.4	5	0.5	13.1

1.3 CSD Setup

The CSD solver used to solve the structure dynamics is Carat++. It is a general finite element solver developed over the last years at the Chair of Structural Analysis TUM. Different elements can be used such as spring, damper, mass, truss, beam, membrane, shell and solid elements including geometrical and material non-linearity as well as some composite material description for membranes and shells. It is used to perform different linear/nonlinear static and dynamic structural analyses. The blade was firstly modelled using 51 3D non-linear co-rotational beam elements which allow large rotations (see Figure 3a). The beam formulation is based on the Timoshenko Beam theory which takes into account the shear deformation. Each beam element has 6 Degree of Freedom (DoF) per node (3 translational and 3 rotational DoFs). It was also modelled by a 4-node shell element with 6-DoFs per node. The shell element formulation was based on the degeneration principle. A non-linear shell formulation was used with linear displacement variation across the thickness and with Reissner-Mindlin kinematics. The Carat++ shell model was created with total number of 34849 Quadrilateral elements connecting 33271 nodes (see Figure 3b). The implicit generalized-α method was used for the time integration of the transient simulations.

(a) The beam model **(b)** The shell Model

Figure 3. The CSD computational models for the beam and shell representations

1.4 CFD-CSD Coupling Interface

The coupling frame work used in this study is the Enhanced Multi-Physics Interface Research Engine (EMPIRE) developed at Technical University of Munich (TUM) [9]. It can be used for co-simulation with multiple-codes which suits the multi-physics problems. EMPIRE can be used to set up co-simulation flexibly with different coupling algorithms, for data communication among multiple-codes and to do mapping between non-matching grids as described in Figure 4.

2 Impacts of the Structural Models

Linear and nonlinear structural dynamic analyses were employed in the beam coupled simulations while only linear shell model was included. Five coupled revolutions were conducted and the azimuthal variations of the flapwise and edgewise deformations at the blade tip were presented in Figure 5. As shown, higher deformations in all directions were predicted with almost $2.2m$ higher flapwise deformation approximately $0.7m$ higher edgewise deformation predicted by the linear beam model. But compared to the nonlinear beam model results, $\approx 4.2m$ higher

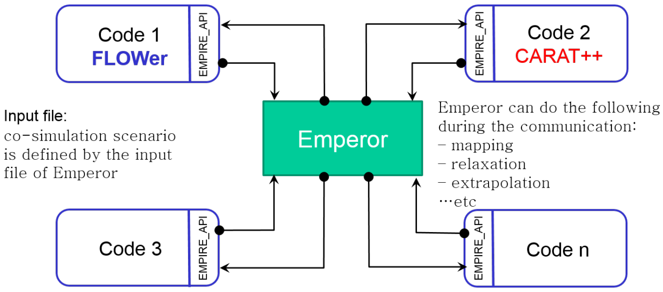
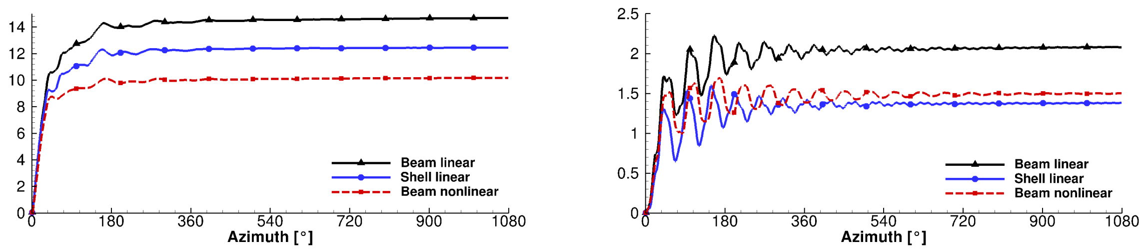


Figure 4. Schematic description of EMPIRE flow work

flapwise deformation result from by excluding the nonlinearity which corresponds to $\approx 44\%$ more deformation in the flapwise direction compared to the nonlinear beam model. A major cause of this huge increase in the deformations was the radial deformation that approaches $\approx 1.3m$ at the blade tip from the shell linear model and $\approx 1.6m$ from the beam linear model. This radial deformations increase the blade radius and in turn increase the blade surface area (as shown in Figure 6) results in more forces and more deformations in the flapwise and edgewise directions. Also the linear models overestimate the tip deflections when large deflections occur because it fails to capture the geometric nonlinearities [10].

In general, the differences in the results from the shell and beam elements conducted by the same analysis type (linear/nonlinear) are due to the different characteristics inherent by the different element formulations. It was reported that the overestimation in the flapwise blade deflection was a main indicator of the nonlinear effects in the blade dynamic response [5]. Moreover, the geometric nonlinearities must be included in the aeroelastic simulations for such large wind turbines not only in the fatigue or buckling analyses but also in the performance analyses. Also, including the geometric nonlinearities, the blade tip flapwise deflection was significantly reduced compared to the linear model. This large difference in the deflections could be vital for the blade designers.



(a) Flapwise [m] **(b)** Edgewise [m]

Figure 5. Azimuthal variations of the blade deformations at the leading edge of different spanwise locations

The effect of these changes in the structural models on the wind turbine performance was also discussed. The power was determined and normalized by the value of the rigid turbine blade. The azimuthal variations of the power over the last coupled revolution (after five coupled revolutions) was presented in Figure 7. It was found that the generated power from the flexible blades are higher than the one from the rigid blade. The normalized power was increased by $\approx 1\%$, $\approx 3.4\%$ and $\approx 4.3\%$ from the nonlinear beam model, the linear shell model and the linear beam model respectively. The large increase predicted from the linear model was due to the increase in the rotor area since the blade was stretched in the radial direction as shown in Figure 6. In addition, The total torque calculated from the blade forces are affected by the edgewise and radial forces in $y-$direction and $z-$direction respectively and by the locations these forces. The blade sectional loads in the $y-$ and $z-$direction were presented as shown in Figure 8. As shown in Figure 8a, very small change of the force distributions due to the change in the angle of attack as a consequence of the torsion deformation. This small change does not affect the power results that much since the decrease predicted in the outer region was overcome by the increase in the radial distance and the total difference would be very tiny. In contrast, a complete change in the radial force was predicted as shown in Figure 8b. For the rigid blade, vertical upward radial force was predicted (positive) since the blade was pre-bended towards the flow. In case of flexible blade, the blade was bended (due to deformations) to the other direction (negative) with the flow direction and its value increases with increasing the flapwise deformations. Therefore, the maximum radial force results from the linear beam model since it was the most bended one as shown in Figure 6. Changing the direction of the radial force might not contribute to the torque if the edgewise deformations are small. Since the edgewise deformations are $\approx 1.5m$, or more in case of linear beam model, the contribution of the radial force increases such that more torque was predicted.

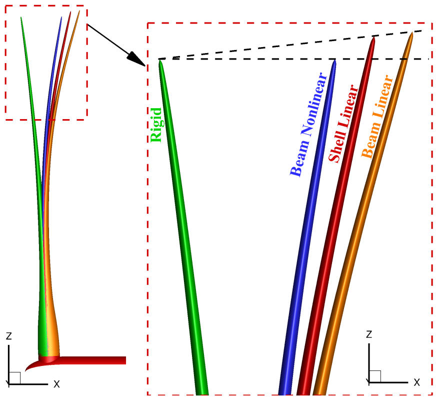


Figure 6. Surface deformation after five coupled revolutions from different structural models

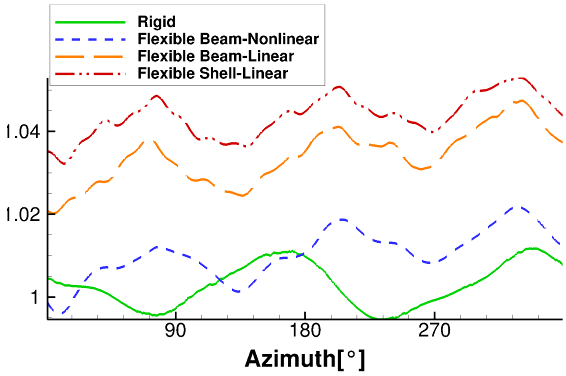
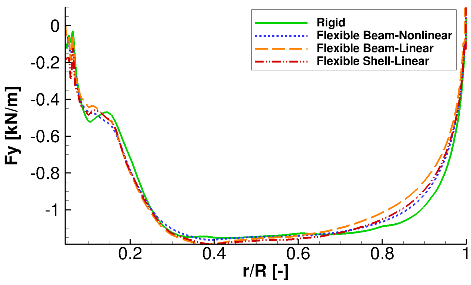
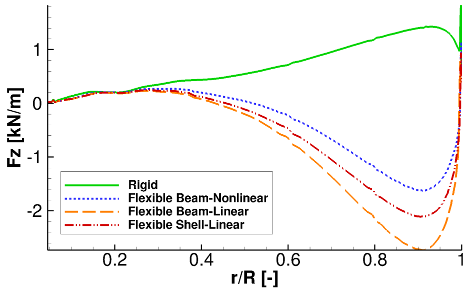


Figure 7. Normalized power result from CFD-CSD simulations by different structural models compared to the rigid result



(a) Edgewise Force



(b) Radial Force

Figure 8. The sectional load distributions in $y-$direction and $z-$direction over the blade radius at the position of 0° azimuth angle after five coupled revolutions

Conclusions

Two different structural models were used to examine the effect of the structural models on the aeroelstic response of the wind turbine. It was concluded that, the aeroelastic results based on the beam model are in good agreement with the results from the full FE shell model. The shell model predicted thickness increase but it was not clear weather it was due to the use of linear model or it was a correct de-cambering captured. Less torsional deformations was predicted from the beam model since the properties and the centers were generated from the shell model and that might cause some error. The time used to conduct coupled simulations modelling the blade by beam elements was almost 50% of the one needed by modelling the blade with shell elements.

Acknowledgements

The DAAD (Deutscher Akademischer Austauschdienst)is acknowledged for financial support.

References

[1] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. C. Henriksen, A. Natarajan, and M. Hansen. Description of the dtu 10 mw reference wind turbine. *DTU Wind Energy Report-I-0092*, 5, 2013.

[2] M. Jeong, S. Yoo, and I. Lee. *Aeroelastic analysis for large wind turbine rotor blades*, pages 9–14. AIAA, 2011.

[3] N. Kroll, C.-C. Rossow, K. Becker, and F. Thiele. The megaflow project. *Aerospace Science and Technology*, 4(4):223–237, 2000.

[4] H. A. Madsen, V. Riziotis, F. Zahle, M. Hansen, H. Snel, F. Grasso, T. Larsen, E. Politis, and F. Rasmussen. Blade element momentum modeling of inflow with shear in comparison with advanced model results. *Wind Energy*, 15(1):63–81, 2012.

[5] D. Manolas, V. Riziotis, and S. Voutsinas. Assessing the importance of geometric nonlinear effects in the prediction of wind turbine blade loads. *Journal of Computational and Nonlinear Dynamics*, 10(4):041008, 2015.

[6] M. Sayed, T. Lutz, and E. Krämer. *Aerodynamic investigation of flow over a multi-megawatt slender bladed horizontal-axis wind turbine*, pages 773–780. CRC Press, 2015.

[7] M. Sayed, T. Lutz, E. Krämer, S. Shayegan, A. Ghantasala, R. Wüchner, and K.-U. Bletzinger. High fidelity cfd-csd aeroelastic analysis of slender bladed horizontal-axis wind turbine. In *Journal of Physics: Conference Series*, volume 753, page 042009. IOP Publishing, 2016.

[8] M. A. Sayed, T. Lutz, E. Krämer, and F. Borisade. Aero-elastic analysis and classical flutter of a multi-megawatt slender bladed horizontal-axis wind turbine. pages 617–626, 2016.

[9] S. Sicklinger, V. Belsky, B. Engelmann, H. Elmqvist, H. Olsson, R. Wüchner, and K.-U. Bletzinger. Interface jacobian-based co-simulation. *International Journal of Numerical Methods in Engineering*, 98(6):418–444, 2014.

[10] L. Wang, X. Liu, N. Renevier, M. Stables, and G. M. Hall. Nonlinear aeroelastic modelling for wind turbine blades based on blade element momentum theory and geometrically exact beam theory. *Energy*, 76:487–501, 2014.

[11] P. Weihing, K. Meister, C. Schulz, T. Lutz, and E. Krämer. Cfd simulations on interference effects between offshore wind turbines. In *Journal of Physics: Conference Series*, volume 524, page 012143. IOP Publishing, 2014.