Investigation of the validity of BEM for the simulation of wind turbines in complex load cases and a comparison with experiments and CFD

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1. Introduction

One of the most common approaches to simulate the aerodynamics of wind turbines is the Blade Element Momentum (BEM) theory. Low cost in simulations, which is a result of this two dimensional theory, makes the simulation of more than thousand load cases within a short amount of time affordable. Nevertheless, complex three dimensional flows which occur in the wind turbines cannot be captured by the BEM model.

Several experimental and numerical studies showed that codes based on BEM are often not sufficiently accurate and reliable for predicting complex aerodynamic behavior acting on the wind turbine blades [1, 2]. Some of the common difficult cases which can arise are: Aerodynamic behaviour of rotor blades under yawed conditions, rotor tower interaction, and standstill cases.

This work investigates the validity of Blade Element Momentum (BEM) codes for some important designed conditions. These include the yawed flow, rotor tower interaction for downwind type turbine and the standstill case. Computational Fluid Dynamics (CFD) and experimental data (when available) will be used for the propose of validation. The key aerodynamic quantities such as power, thrust, Flap and edgewise deflection and sectional forces are investigated for different turbine class and by using wind tunnel measurements and numerical simulations. Therefore, the capability of BEM on investigation the key aerodynamic parameters for different conditions are presented and discussed.

2. Approach

In this work the open-source software OpenFOAM [3] is used for CFD simulations. For the BEM calculations, the FAST code [4] is used. When available data from the NREl Phase VI experiments were included in the investigations. In the following three different scenarios are presented and the results are discussed.

3. Yawed flow

One of the common difficulties can arise during the modelling the aerodynamic behaviour of rotor blades under yawed conditions. These cases can result in different problematic situations such as: flow separation, azimuthal variation of the loads, advancing and retreating and unbalance in the flow induced by the skewed wake [1, 5]. Thus, currently a major concern regarding

BEM methods is the applicability of yawed models in the design process of the wind turbines. However, these models are usually suffering from some uncertainties such as the general validity of the model at extreme yaw and non-uniform tunnel flow and dynamic yaw [5, 2]. Therefore, it is essential to conduct more complex and realistic simulations in order to capture all the important details, which play a role in the correct modelling of the wind turbines.

In this part NREL VI wind turbine [6] is simulated using CFD and FAST. In CFD the simulations are conducted using the Spalart-Allmaras-DDES model [7] for 30 degree of yaw and a wind tunnel speed of $5m/s$. The computational grid has a spherical shape and is fully structured based on hexahedral cells. The total grid size is 22 million cells. It has 300 cells around the airfoils, 250 cells in the span-wise direction for each blade, and 300 cells in the wall normal direction. The y^+ values at the surface are kept below 1 everywhere on the blade surface. The effect of tower and nacelle is neglect for these simulations. The physical time step is $\Delta t = 2 \times 10^{-4}$. The converged numerical result is achieved after 5 rotation.

For the FAST code three different yaw correction models, namely Pitt and Peters [8], the model from Schepers [5] and Generalized Dynamic Wake (GDW) [8] are used. In Fig 1 the CFD results show a reasonable agreement with the experimental data for both normal and tangential force coefficients. Hence, CFD can be used as a reference to compare the BEM results for larger rotors where experimental data is not available.

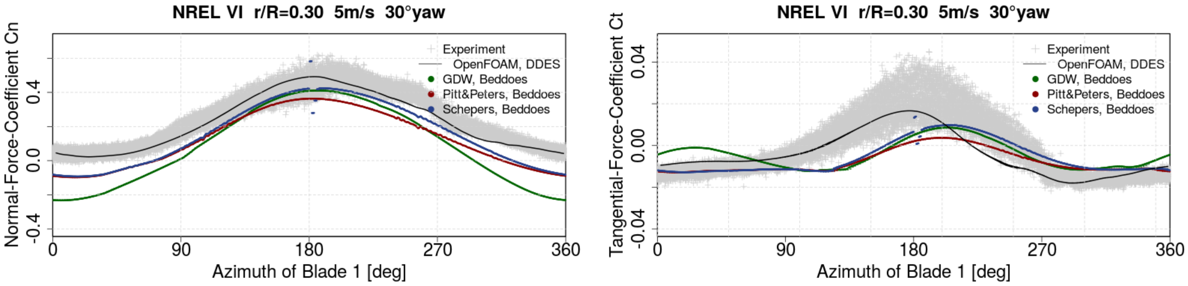

Figure 1. Normal and tangential force coefficients for 30% of span for wind speed of 5 m/s and 30 degree of yaw .

In terms of the normal force coefficient at 30% span, all three correction models are predicting the maximum forces at the same azimuthal position. However the Pitt and Peters model shows a smaller amplitude and the GDW model is underestimating the forces at the upper half of the rotor blade significantly. The model from Schepers has a closer agreement to the experimental results in terms of amplitude and phase. The results for the tangential force coefficient using these three correction models show more deviation from the experimental results. All the correction model results are shifted towards the upwind side of the blade. This can be due to the fact that Pitt & Peters model and GDW are not taking to the account the root free vorticity effect. The model from Schepers has the closer agreement to the experiments since this model is considering the root free vorticity effect as a function of blade radius. In the full paper a MW class turbine will be investigated terms for local forces (e.g. Cn and CT), flapwise bending moments and integrated quantities such as power and thrust. CFD simulation will be used for the purpose of validation. The drawbacks of each individual yaw model will be addressed.

4. Rotor tower interaction

Due to new materials, control strategies and the fact, that noise is offshore not a driving factor, downwind turbines seem go into a revival. So far Ming Yang, Hitachi and the Dutch developer 2-B Energy have been developing on downwind concepts lately [9].

The effect of the tower shadow is here a crucial question in the aerodynamics. In BEM based calculations mostly either a wind deficit, from potential theory, or empirical models are used [9, 10]. Here, we investigate, how much this assumption holds using CFD simulations.

We use the NREL Phase VI turbine for this investigation. For the mesh generation the bladeBlockMesher, developed by ForWind and Fraunhofer IWES was used [11]. It creates a structured blockMesh around wind turbines blades. The rotor was meshed separately in a cylindrical mesh from the surrounding mesh. The latter has been meshed in a half-cylindrical way with the hub distance of 5D to the inlet and crossflow cylinder walls and 10D distance to the outflow. Overall ca. 10 Million cells have been used. The k- SST model has been used for unsteady RANS turbulence modeling [12]. The simulations have been done for different inflow velocities U_0: Mainly $U_0 = 7$m/s and $U_0 = 10$m/s. At the latter case the blade was already stalling, which lead to strongly unsteady conditions on the blade.

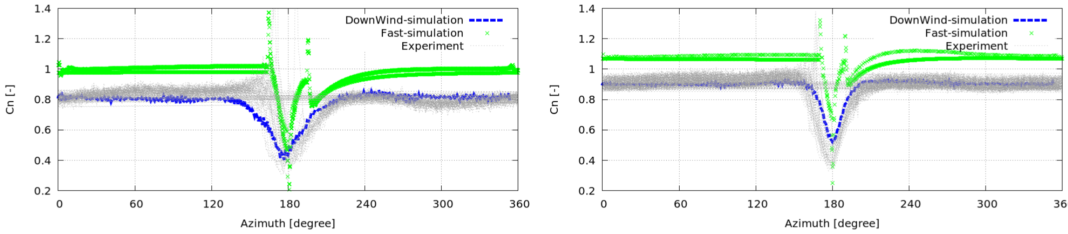

Figure 2. Normal coefficient for 30% (left) and 47% (right) of span for wind speed of 7 m/s

Figures 2 shows a comparison of the lift coefficient at two different sections along the blade span. The results from FAST shows an approximately 20% higher value for the lift coefficient compared to CFD results. The CFD simulations show a drop of 50% compared to the FAST simulation which has a drop of 70%. In the full paper the results of other wind velocities and also the results of power and thrust forces will be presented.

5. Standstill case

One critical load case in the phase of the wind turbine design is the standstill case which can occur during the erection of a wind turbine or during operation due to failure in the control system.

According to the IEC 61400-1 guideline [13], in this load case the blades have to withstand extreme wind speeds from different directions. Due to high angles of attack and therefore often fully separated flows in combination with a strong interaction of the flow and the structure, the standstill load case is numerically complex to simulate. In this work we use a fluid-structure coupled solver, which combines the open source CFD code OpenFOAM with an inhouse structural beam solver. Using the Geometrically Exact Beam Theory (GEBT) [14] for the structural part and a Delayed-Detached Eddy-Simulation for the fluid part, the coupled solver allows a high fidelity analysis of complex aeroelastic problems.

Figure 4 shows a comparison of the developed high fidelity solver with the standard BEM-based engineering tool FAST for the NREL 5MW reference wind turbine [15] during stand still. The inflow angle corresponds to 90, the wind speed is set to 40 m/s. While the flapwise deflections are similar for both approaches, the CFD based solver predicts clear edgewise vibrations of the blade, while in FAST the fluctuation of the edgewise deflections are computed much smaller.

6. Learning objectives

While BEM will give in most general load cases sufficient good results, care needs to be taken at cases leading to flow separation. CFD methods can help to get a more complete picture of the aerodynamics even in complicated cases.

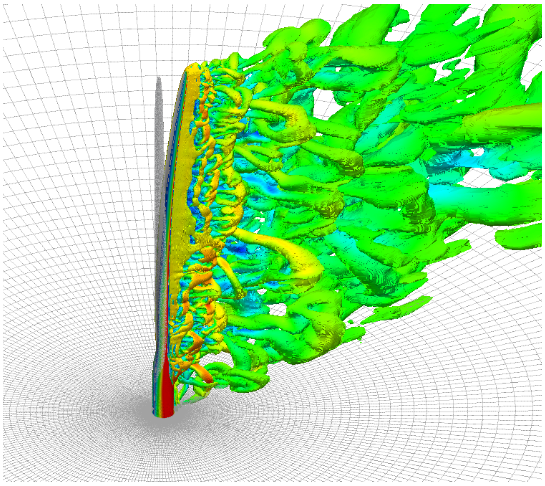

Figure 3. Instantaneous isosurface for Q coloured by velocity magnitude. Inflow speed: 40 m/s, physical time: 2s. The initial blade geometry is shown in grey.

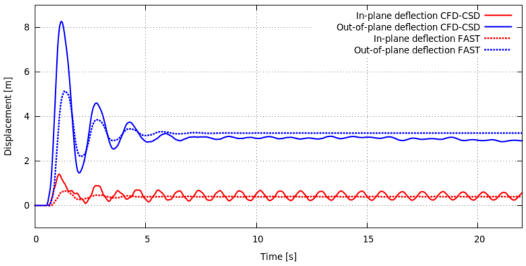

Figure 4. flapwise and edgewise deflections

References

[1] Schepers J 2012 *Engineering models in wind energy aerodynamics* november ISBN 9789461915078

[2] Micallef D 2012 *3D flows near a HAWT rotor :* (Technische Universiteit Delft) ISBN 9789995703127

[3] OpenCFD 2015 Openfoam®- the open source computational fluid dynamics (cfd) toolbox accessed 29 July 2015 URL `http://OpenFOAM.com`

[4] Jonkman J M and Buhl Jr M L 2005 *National Renewable Energy Laboratory, Golden, CO, Technical Report No. NREL/EL-500-38230*

[5] Schepers J 1998 *An engineering model for yawed conditions, developed on the basis of wind tunnel measurements*

[6] Hand M M, Simms D, Fingersh L, Jager D, Cotrell J, Schreck S and Larwood S 2001 Unsteady aerodynamics experiment phase vi: wind tunnel test configurations and available data campaigns Tech. rep. National Renewable Energy Laboratory

[7] Spalart P, Deck S, Shur M, Squires K, Strelets M and Travin A 2006 *A New Version of Detached-eddy Simulation Resistant to Ambiguous Grid Densities* vol 20 (Springer-Verlag)

[8] Moriarty P J and Hansen A C 2005 *AeroDyn theory manual* (Citeseer)

[9] Fairley P 2003 Two-bladed wind turbines make a comeback accessed 29 March 2016 URL `https://www.technologyreview.com/s/528581/two-bladed-wind-turbines-make-a-comeback/`

[10] Hagen T R 2011

[11] Rahimi H, Daniele E, Stoevesandt B and Peinke J 2016 *Wind Engineering*

[12] Menter F and Esch T 2001 *16th Brazilian Congress of Mechanical Engineering* pp 26–30

[13] IEC 2005 *Wind Turbines - Part 1: Design Requirements, IEC 61400-1 (3rd edn.)* (Genova) ISBN 2-8318-8161-7

[14] Cardona A and Geradin M 1988 *International Journal For Numerical Methods in Engineering* **26** 2403–2438 ISSN 0029-5981

[15] Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW reference wind turbine for offshore system development Tech. Rep. February