Investigation of the validity of the Blade Element Momentum Theory for wind turbine simulations in turbulent inflow by means of Computational Fluid Dynamics

S. Ehrich¹, C.M. Schwarz¹, H.Rahimi¹,², B. Stoevesandt² and J. Peinke¹,²

¹ ForWind, Institute of Physics, University of Oldenburg, Oldenburg, 26129, Germany
² Fraunhofer IWES, Oldenburg, 26129, Germany
E-mail: sebastian.ehrich@uni-oldenburg.de

Abstract. In this work three different numerical methods are used to simulate a MW class wind turbine under turbulent inflow conditions. These methods are a blade resolved Computational Fluid Dynamics (CFD) simulation, an actuator line based CFD simulation and a Blade Element Momentum (BEM) approach. For all three methods sectional and integral forces are investigated in terms of mean, standard deviation, power spectral density and fatigue loads. It is shown that the power spectral densities of integral forces are in good agreement in the low frequency range for all methods. However, deviations are observed from 2 Hz onward. Although the fatigue loads of the CFD based methods are similar for the torque, the loads from BEM differ by 22%. For the thrust BEM only deviates by 4.5% from the blade resolved case. Nevertheless the actuator line based simulation differs by up to 7.3%. The standard deviations of sectional forces for all three methods relate very well to the standard deviation of integral forces. Nevertheless, a similar relation for the fatigue loads could not be observed.

1. Introduction

One of the most common tools in wind turbine design and load calculation is the Blade Element Momentum method (BEM). Although BEM based tools are very efficient, they are based on many simplifications like stationary environment, 2D airfoil characteristics and inviscid fluid behavior [1]. While preserving its efficiency, over the years a lot of correction models have been developed to improve the accuracy, e.g. by using tip loss models or dynamic stall models. However, especially for turbulent inflow scenarios the reliability of such predictions is still unknown. This is mainly due to the relatively coarse discretization of wind fields and rotor blades, the dynamic aerodynamic response to complex inflow, the unresolved flow field but also the assumption of inviscid and stationary flow [1]. Nevertheless, turbulent inflow scenarios are relevant to the design and certification process, e.g. to the design load cases 1.1-1.3 of the IEC standard [2]. One of the limited work in this field is done by Madsen et al. [3] where for turbulent inflow conditions differences for the spectra of sectional forces between BEM and Blade Resolved (BR) Computational Fluid Dynamics (CFD) simulations were shown. However, global quantities like thrust and torque, and the corresponding fatigue loads were not investigated.

This work aims to assess the validity of BEM based simulations for turbulent inflow conditions comparing them to two higher fidelity CFD methods, namely the BR simulation and the Actuator
Line (AL) model. New in this comparison is the investigation of spectra of integral forces, the analysis of fatigue loads and a bridge between BR and BEM calculations, namely the AL method. This work is organized as following. The basic setup of the turbine, the turbulent wind fields, the CFD and BEM simulations, and the fatigue load estimation are addressed in section 2. In section 3 key aerodynamic quantities of the turbine such as power, thrust and sectional forces and the corresponding equivalent fatigue loads as well as spectral properties are investigated. Finally a conclusion including future work is presented in section 4.

2. Methodology

In this section the basic methodology used in this work as well as the fatigue load estimation is presented.

2.1. The turbine

The numerical studies are performed on the NREL-5MW reference wind turbine with a rotor diameter of 126m [4]. This three bladed horizontal axis wind turbine with a blade length of 61.5m was designed by the National Renewable Energy Laboratory. It is close to the current average rotor size of newly installed wind turbines which accounts to 100-120m. More details on the reference turbine can be found in Table 1. Because there is a lack of experimental data for large wind turbines, and the NREL-5MW turbine has been investigated many times, it can be considered as one of the most important wind turbine design which are available within the wind energy research community.

Table 1. Overview of NREL-5MW turbine.

| Parameter                     | Value       |
|------------------------------|-------------|
| Number of rotor blades       | 3           |
| Rotor diameter               | 126m        |
| Rated aerodynamic power      | 5.3 MW      |
| Rated wind speed             | 11.4 m/s    |
| Rated rotational speed       | 12.1 rpm    |
| Blade cone angle             | 2.5°        |
| Shaft tilt angle             | 5.0°        |
| Blade length                 | 61.5m       |
| Blade mass                   | 17740 kg    |

2.2. The wind fields

As the findings are believed to be general and only weakly dependent on wind modelling details a simplified model for the wind fluctuations is used. For the sake of simplicity the wind profile is uniform, i.e. shear is not taken into account. Velocity fluctuations are represented by a Gaussian process realized at the inflow patch of the CFD domain. In particular, coupled stochastic Ornstein-Uhlenbeck processes of the form

$$\frac{du_i^{(k)}(t)}{dt} = -\gamma (u_i^{(k)}(t) - \bar{u}^{(k)}) + \sqrt{D} \sum_j H_{ij} \Gamma_j^{(k)}(t)$$  \hspace{1cm} (1)$$

with an exponentially decaying spatial and temporal correlation function for all wind components are used. In this stochastic differential equation each subscript $i, j = 1\ldots N$ denotes a specific cell on the inlet patch where the turbulence is generated and each superscript $k = x, y, z$ corresponds to the longitudinal, lateral or vertical velocity component. $\gamma = 0.97 \, s^{-1}$ is a damping factor, $\bar{u}^{(x, z)} = 0 \, m s^{-1}$
and \( \bar{u}(x) \) the mean velocities in \( x, y \) and \( z \) direction, \( D = 0.62 \, m^2 \, s^{-3} \) a diffusion constant, \( H \) the lower Cholesky-decomposed correlation matrix and \( \Gamma \) a Gaussian, delta-correlated random noise vector with variance 2.

Fields with a mean wind speed of \( \bar{u}(x) = 11.4 \, ms^{-1} \) corresponding to the rated operating condition of the wind turbine and a Turbulence Intensity (TI) of 20% are fed into the CFD domain. This relatively high TI had to be chosen, because of the natural decaying process leading to much smaller turbulence intensities in the vicinity of the turbine in the absence of shear. To make the comparison between different codes in a similar manner, the pitch and rotor speed are fixed and the effect of structural deformations, tilt and cone as well as the tower and nacelle are neglected.

2.3. Numerical methods

In the following the BR, AL and BEM method are described in more detail:

- **BR:** The blade resolved simulations are performed with the open-source CFD software OpenFOAM V4.1 [5], which is an open-source CFD package with a collection of modifiable libraries written in C++. The simulation domain is discretized using the bladeblockMesher [6] and WindTurbine mesher tools [7] with a combination of structured and unstructured grids consisting of a total of 36M cells. The mesh of the complete simulation domain and the rotating part are shown in Figure 1 with a sectional view on the blade mesh in Figure 2. In order to limit the cell aspect ratio in radial direction, adaptive wall functions are being applied. The solution for the flow field is achieved on solving the incompressible Delayed Detached Eddy Simulations (DDES) equations where the flow is assumed to be fully turbulent, i.e. the laminar-turbulent transition in the boundary layer is not considered. The closure problem is treated by use of the Sparlart–Allmaras (SA) turbulence model [8]. In order to solve the pressure-velocity coupling, the PIMPLE algorithm, is used, which is a combination of the loop structures of SIMPLE [9] and PISO [10]. Integration in time was performed using an implicit second order backward scheme together with a second order linear upwind scheme for discretizing the convection terms. For these simulations 360 cores were used for approximately 20 days resulting in 600 seconds simulation time.

- **AL:** The rotor is simplified by an AL model [11], where all rotor blades are reduced to rotating lines with a radial distribution of body forces at 60 positions along the lines. A Gaussian filtering kernel with smoothing parameter \( \varepsilon \) equal to 4 was used to obtain well fitting sectional forces to the BR case. Based on the angle of attack at the given positions on the line, body forces are gained from lookup tables containing polars of two dimensional airfoils. Except for a coarser resolution in the vicinity of the rotor the domain is exactly the same as for the BR case leading to a domain size of 22M cells. The flow field is simulated by Large Eddy Simulations (LES) with a Smagorinsky subgrid-scale model [12]. These simulations have been conducted on 360 cores for 25 hours real time reaching 600 seconds simulation time.

- **BEM:** This method uses wind fields recorded in the CFD domain on an equidistant \( 31 \times 31 \) grid with a grid size of 4.5m. In this case the fields are obtained at the position of the rotor from the same mesh as for the AL method but in an empty CFD domain. This seems to be a reasonable choice, because the TI at the rotor is expected to be comparable for the CFD and BEM simulations. The BEM based tool FAST v8 [13] in combination with AeroDyn v15 [14] with the Beddoes Leishman type unsteady aerodynamics model [14, 15] is used in this work. The BEM model relies on the very same airfoil data as the AL.
2.4. Fatigue load estimation

One of the most important quantities relevant for wind turbines are the fatigue loads on different parts of the turbine measured by damage equivalent loads also known as Equivalent Fatigue Loads (EFL) which will play a role in the load analysis of the three methods analysed here. In general EFL are defined as

$$EFL = \left( \sum \frac{n_i r_i^m}{N} \right)^{\frac{1}{m}}$$

with the specific load ranges $r_i$, the corresponding amount $n_i$ of load ranges, the reference number of ranges $N$ and the Wöhler exponent $m$. More information on the estimation of the EFL and the underlying rainflow algorithm can be found in [16] and [17].
3. Results
In this section the results of the study are presented. The focus lies on the wake structure, average and standard deviation of sectional and integral forces, as well as fatigue loads and power spectral densities.

3.1. Wake dynamics
Snapshots of the velocity magnitude for the BR and AL cases are shown in Figure 3. Despite the differences in the methods both simulations show very similar fields in terms of the velocity magnitude upstream of the turbine. This leads to the conclusion that the induction zone of the turbine is also similar for both simulations. The wake structure is also in very good agreement. However, the BR simulation is resolving the tip and root vortex in a more physical way which results in smaller structures in the near wake. The missing nacelle in the AL method leads to a jet like behavior at the center of the rotor, but the influence on the far wake is negligible.

![Figure 3. Snapshots of the velocity magnitude for BR (left) and AL (right) simulations.](image)

3.2. Sectional forces
All three simulation methods (BR, AL and BEM) are compared based on averaged sectional quantities and their standard deviation. As most important aspects we select sectional axial and tangential forces on the blade, which do not reveal big differences for the average between all cases in the mid-span as shown in Figure 4. However at the root (up to 30% of span) and the very tip (from 80% of span onwards) some differences can be observed. BEM and AL rely on similar root and tip correction models and very same airfoil data which explains their good agreement. But in contrast to the BR case, where 3D effects are modelled physically, the forces at the root section are far off supporting the well known issues for BEM and AL.

The standard deviations for the tangential and axial force distributions, explicitly shown in Figure 5, are very similar for the BEM and AL methods but with a bit larger values for the BEM case in most sections. With the BR case as the reference the standard deviations of sectional forces tend to be lower at the root of the blade for the BEM and AL methods whereas they are larger in the mid-span. Close to the tip of the blade the standard deviations for the AL method are much smaller while BEM is in good agreement with the BR simulation at the outermost section.
Figure 4. Radial distribution of axial (left) and tangential (right) forces for BR, AL and BEM cases. The shaded areas illustrate one standard deviation of the fluctuations.

Figure 5. Radial distribution of standard deviation of axial (left) and tangential (right) forces for BR, AL and BEM cases.

3.3. Integral forces
As presented in Table 1, the integral aerodynamic thrust and torque, show a very close agreement between all the methods. The AL method shows up to 8.3% difference in thrust and 2.5% in torque with respect to BR method. The BEM simulation shows 4.2% and 1.8% difference in the thrust and torque compared to BR method, respectively.

Analog to the relation between mean sectional forces and mean integral forces, the standard deviation of sectional forces corresponds to a standard deviation in the thrust and torque. The standard deviation for the AL case is for both quantities approximately 10% smaller than for the BR simulation. In contrast to that, out of the BEM simulation an approximately 20 to 30% increase in the standard deviation is obtained.
Table 2. Thrust and torque comparison between BR, AL and BEM.

|                  | BR   | AL   | BEM  | AL/BR [%] | BEM/BR [%] |
|------------------|------|------|------|-----------|------------|
| **Thrust [kN]**  | mean | 761  | 698  | 729       | 91.7       | 95.8       |
|                  | std  | 37.9 | 33.9 | 49.7      | 89.4       | 131.1      |
| **EFL**          | mean | 147.6| 136.8| 141.0     | 92.7       | 95.5       |
| **Torque [MNm]** | std  | 0.495| 0.452| 0.599     | 91.3       | 121.0      |
|                  | EFL  | 1.904| 1.897| 1.486     | 99.6       | 78.0       |

3.4. Fatigue loads

To give a more detailed description of the effect of forces on the rotor blades, fatigue loads at each section have been investigated. Compared to the AL case, increased fatigue loads of axial forces at each radial position were observed for the BEM case as can be seen in Figure 6. In contrast to that, the EFL of tangential forces are smaller for the BEM case except at 20% span. Nevertheless the effect on integral forces like thrust and torque are different to what one would expect out of the radial force distributions as seen in Table 2. On the one side, the EFL of thrust are in good agreement for all three methods, while we would expect a higher value for the BEM case. On the other side, the loads of torque are almost the same for the BR and AL method, but the BEM approach gives a 22% lower estimation. It can be concluded that in contrast to the standard deviation, the EFL of thrust and torque can not be estimated directly out of the EFL of sectional forces. This highlights the fact that the dynamics of global forces are in general different to the dynamics of sectional forces and the output of the rainflow counting algorithm is not easily predictable for complex time series.

Figure 6. Radial distribution of axial (left) and tangential (right) equivalent fatigue loads for BR AL and BEM methods.

Further analysis of EFL by the underlying range histograms in Figure 7 shows that for the thrust force all three methods have in general a similar behaviour. At low ranges BEM is following the AL trend and in the mid range BEM has a bit higher counts as AL and BR. Because of their large weight the most important part for the EFL are the high thrust ranges which almost equally often occur for all three cases leading to similar EFL.
The range histogram of the torque in Figure 7 is also very comparable for all three cases but the AL as well as the BR cases show ranges much higher than the highest one for BEM at approximately $2.4 \cdot 10^6 \text{Nm}$. This leads to the 22% difference in the EFL of torque shown in Table 2.

3.5. Power spectral densities
For a analysis of the dynamics of torque and thrust power spectral densities are investigated in Figure 8. All three methods show a very good agreement for low frequencies up to 2 Hz including the 3P frequency and the first two harmonics. For higher frequencies up to approximately 5 Hz BEM and AL are very similar but the BR method drops up to this point. The reason for the power spectral density drop might be the RANS model working in the boundary layer of the blade while the AL uses LES everywhere and therefore does not smooth out the wind field in the vicinity of the blade. Additionally, the time step could be too large for the fine grid resolution in the blade region for the BR simulation. The difference between BEM and AL in the high frequency range could be according to the missing damping and filtering effects in the BEM case, while AL uses a Gaussian filter to smooth out the forces along the blade. The noisy behavior of the power spectral density of the AL method at high frequencies is part of every AL simulation and is also a result of the convolution of the forces given at the airfoil sections with a Gaussian kernel.

4. Conclusions
Out of this work it can be concluded that the AL, BR and the BEM method with extracted wind fields at the rotor plane from an empty domain are very similar with respect to averaged tangential and axial forces, except close to the root and the tip. However differences are observed when looking at the standard deviations of the forces. For the integral quantities thrust and torque BEM tends to overestimate the standard deviation compared to the other two methods. This leads to the conclusion that either the wind fields have to be extracted downwind of the rotor position from the empty domain simulation or a correction of wind fields for the BEM case has to be considered.
The question, why the standard deviation of the global quantities investigated here are much higher for the BEM than for the other two cases, while the EFL are comparable or less, is still unsolved. One reason could be the missing wake effects of BEM simulations which could increase the EFL but do not necessarily increase the standard deviation. Additionally in the AL method the 60 airfoils used are linearly interpolated between known sections and the forces are smoothened with a Gaussian kernel. FAST does not smooth out the sectional forces and along a blade are only 13 airfoils available, leading to different dynamics in the forces. A good starting point for further analysis might be looking at higher order statistics of the forces, because the spectra do not seem to capture the fatigue loads. Further studies on this point have to be done in the future work to find the reason for this behavior. Nevertheless, BR and AL simulations result in very similar results for the average, standard deviation and EFL of thrust and torque, which is also the result of tuning the parameters of the AL to the BR results. The power spectral densities of thrust and torque for all three methods show good agreement on lower frequencies but it is still not very clear what leads to the large differences on high frequencies. Finally it is also not clear which of all the results are most realistic, because no experiments for comparison were performed.

Acknowledgments

The simulations were performed at the HPC Cluster EDDY, located at the University of Oldenburg (Germany) and funded by the Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie) under grant number 0324005.

References

[1] Schepers J G 2012 Engineering Models in Wind Energy Aerodynamics Ph.D. Thesis Delft University of Technology URL https://repository.tudelft.nl/islandora/object/uuid:92123c07-cc12-4945-973f-103bd744ec87/datastream/OREJ/download
[2] International Electrotechnical Commission 2005 IEC 61400-1 Standard International Electrotechnical Commission
[3] Madsen H A, Sørensen N N, Bak C, Trolldborg N and Pirrung G 2018
[4] Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW Reference Wind Turbine for Offshore System Development Tech. Rep. TP-500-38060 National Renewable Energy Laboratory 15013 Denver W Pkwy, Golden, CO 80401, USA
[5] OpenCFD 2007 OpenFOAM - The Open Source CFD Toolbox - User's Guide OpenCFD Ltd. United Kingdom 1st ed
[6] Rahimi H, Daniele E, Stoevesandt B and Peinke J 2016 Wind Engineering 40 148–172 ISSN 0309524X URL https://doi.org/10.1177/0309524X16636318
[7] Rahimi H 2018 Improving Aerodynamic Engineering Models for Wind Turbines by means of Computational Fluid Dynamics Ph.D. Thesis University of Oldenburg
[8] Spalart P and Allmaras S 1992 439
[9] Patankar S and Spalding D 1972 International Journal of Heat and Mass Transfer 15 1787 – 1806 ISSN 0017-9310 URL http://www.sciencedirect.com/science/article/pii/0017931072900543
[10] Issa R 1986 Journal of Computational Physics 62 40 – 65 ISSN 0021-9991 URL http://www.sciencedirect.com/science/article/pii/0021999186900999
[11] N Sørensen J and Shen W Z 2002 124 393
[12] Smagorinsky J 1963 Monthly Weather Review 91 99–164
[13] Jonkman B and Jonkman J 2016 Fast v8.16.00a-bjj Tech. rep. NREL URL https://wind.nrel.gov/nwtc/docs/README_FAST8.pdf
[14] Jonkman J, Hayman G, Jonkman B and Damian R 2016 AeroDyn v15 User’s Guide and Theory Manual (draft version) Tech. rep. NREL URL https://wind.nrel.gov/nwtc/docs/Aerodyn_Manual.pdf
[15] Leishman J G and Beddoes T S 1989 Journal of the American Helicopter Society 34 3–17
[16] Madsen P H 1990 Recommended practices for wind turbine testing and evaluation. 3. Fatigue loads
[17] Rychlik I 1987 International Journal of Fatigue 9 119 – 121 ISSN 0142-1123 URL http://www.sciencedirect.com/science/article/pii/0142112387900545