Comparison of the Actuator Line Model with Fully Resolved Simulations in Complex Environmental Conditions

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Abstract. In the present paper the actuator line method is compared with fully resolved wind turbine simulations in offshore and complex terrain applications. In such flow fields, which are characterized by non-homogeneous and unsteady velocity distributions in the rotor plane, unsteady aerodynamic effects are likely and it is unclear how these characterize the wake development and load behavior of the wind turbine. The wake properties and loads are therefore compared for the case of a 5 MW wind turbine operating in a typical maritime atmosphere and a 2.4 MW onshore turbine located at a complex terrain site downstream of an escarpment. It was found that the actuator line predicts the wake structure, wake deflection and wake deficit in good agreement with the fully resolved simulation. However, an overestimation of velocity fluctuations was observed.

1. Introduction
The massive extension of wind power use calls for clustering of wind turbines in wind farms and for establishing sites of relatively lower wind speed in complex terrain. Especially for the latter, as summarized by Alfredsson and Sagalini [1], the aerodynamic modeling is multidisciplinary and challenging, involving effects of orography, roughness or stratification on the turbulent atmospheric boundary layer or the question on how to model the turbine itself. The present paper shall contribute to the assessment of turbine modeling by evaluating the actuator line method (ACL) in offshore and complex terrain conditions. The ACL has been widely used in the wind turbine community for the prediction of turbine performance, wake and the loads [2, 3]. Particularly, with focus on wind farms it seems to be reasonable that details from the rotor geometry as for example viscous wake effects of the flow around the airfoil are probably irrelevant for the development of the wake state multiple rotor diameters downstream of the turbine. This gives the rationale to shift the time and length scales to the order of the airfoil’s chord by representing those with an appropriate source term distribution. This follows both a significant reduction of computational effort, as well as a massive simplification in the preparation of a fully resolved (FR) simulation. In close to design conditions, the blade element momentum theory which serves as the foundation of the ACL provides reliable results in the industrial framework. However, in complex environmental conditions like in the turbulent atmosphere or in the case of misalignments of the wind vector with the rotor axis, the spatial and temporal distribution of the velocity components in the rotor plane is far from uniform and unsteady aerodynamic effects
are likely [4, 5, 6]. These effects which can be summarized as a phase shift between the change in angle of attack and the responding loads are naturally taken into account when conducting a FR turbine simulation. It is not clarified how these flow fields affect the wake properties. Besides of inter and intra code comparisons conducted in MexNext projects [7] where the wake is compared in controlled uniform conditions, the work of Troldborg et al. [8] contrasts actuator techniques with FR simulations in non-sheared inflow conditions and obtain an overall good agreement for turbulent inflow. The current study, as the latter, shall use both models within the same code and shed more light into the scope of application of the ACL, particularly, for non-uniform sheared turbulent flows. Therefore, the wake development, as well as the load prediction are compared with FR simulations for an offshore case with atmospheric turbulence and a case in complex terrain.

In the next section the numerical modeling and code is described, followed by the presentation of the test cases, the meshing and the numerical settings in Sec. 3. The results are discussed thereon in Sec. 4 and conclusions are drawn in Sec. 5.

2. Numerical modeling

The simulations in the present work have been performed using the code FLOWer which has been developed by the German Aerospace Center (DLR) and has been extended by the Institute of Aerodynamics and Gas Dynamics (IAG). The code solves the compressible Navier-Stokes equations on block-structured grids using the finite volume method. Convergence is accelerated by a three-level multi-grid method. For unsteady simulations, time discretization is conducted using the dual-time stepping algorithm by Jameson [9], whereas the convective fluxes are discretized by default with the central Jameson-Schmidt-Turkel (JST) scheme [10]. In order to improve conservation of vortical structures, the latter has been extended in Schäferlein [11] by the fifth-order weighted essentially non-oscillatory (WENO) scheme in conjunction with a HLLC or $l^2$-Roe [12, 13] Riemann solver, respectively. For the FR rotor simulations the relative movements of the body conforming grids are applied utilizing the overset grid technique and taking into account the corresponding whirl fluxes.

The basic implementation of the actuator line method is aligned with literature [14, 15], where the source term distribution representing the two dimensional lift and drag forces of each blade element are distributed over the surrounding grid cells using a three dimensional Gaussian smearing with a radially constant factor $\epsilon$. Tait-Bryan angles transform the inertially sampled velocities into the airfoil coordinate system by taking into account the turbine kinematics of yaw, tilt, cone and the current azimuthal position of the blade. It is to be noted, that for the approximation of the angle of attack (AoA), the sampling points of the velocities do not coincide with the locations of the actuator points. Theoretically, the up- and down-wash in the center of a potential vortex is discontinuous. In reality, at least high gradients can be expected. In order to circumvent the problem that the sampled velocity might be deteriorated by the induced velocity of the bound vortex, the sampling is applied at some distance upstream of the airfoil and is then corrected iteratively by the induced velocity of the bound vortex applying Biot-Savart’s law.

The procedure is as follows: The initial value of the AoA is determined from the velocity triangle in the sample point, from which the lift distribution $\Gamma$ is calculated. With Biot-Savart’s law
law the induced velocity from the actuator point on the sampling point is determined and the effective velocity is obtained from which the inflow angle is recalculated. After five to ten iterations usually a converged AoA value is found. The nacelle can be modeled as an extraction of momentum within the volume of the nacelle. In FLOWer, this has been implemented based on the nacelle geometry and a user specified drag coefficient for that shape. From which the integrally estimated drag force of the body volume force increments are calculated and imposed to the flow field in those cells found within the nacelle. It was refrained from using the Gaussian smearing again, as the compressible framework of FLOWer does not show pressure velocity decoupling. For bluff nacelle shapes, where vortex shedding of the wake is likely, an orthogonally to the local wind vector acting side force is superposed which follows a simple sinusoidal signal

$$F_{sf} = k_f F_{D,nc} \sin 2\pi \frac{Sr U_{\infty}}{L} t.$$  

where $F_{D,nc}$ is the drag force of the nacelle. The frequency is calculated from the Strouhal number the length of the nacelle $L$ and the free stream velocity. The amplitude $k_f$ and can calibrated using literature values [16]. Figure 1 shows the wake behind an isolated nacelle simulation in uniform inflow. The geometry is a cuboid of $20 \times 6.5 \times 6 m^3$ that is later employed in the offshore turbine simulation. The actuator type simulation is compared with a FR representation of the nacelle and shows overall good agreement for the near and farther wake. Particularly, the deflection can be mimicked. The tower is represented as a single actuator line with cylindrical profile. Here again the mentioned side force is applied.

All simulations have been carried out using the Spalart-Allmaras turbulence model and a zonal detached eddy simulation approach, where the ambient turbulence is resolved in LES mode and the actual turbine meshes of the FR simulations are treated in URANS mode [13, 17, 18].

3. Test cases and numerical setup

3.1. The wind turbines and their operating points

In the present work two cases are investigated that cover important environmental conditions of wind farms, namely the maritime atmospheric boundary referred to as caseOffshore, as well as high turbulence and shear found in complex terrain (caseTerrain). For caseOffshore a 5 MW wind turbine of 126 m diameter and a hub height of 95 m is considered. The tilt angle is $6^\circ$ and the cone angle $-4^\circ$. The turbine is operating in partial load at a constant rotational speed of 10.3 rpm which corresponds to a tip-speed ratio (TSR) of 8.5. The pitch angle is $-1^\circ$.

For caseTerrain a turbine of 2.4 MW with a rotor diameter of 109 m, and tilt and cone angles of $5^\circ$ and $-2^\circ$, respectively is considered. The turbine is sited on a plateau downstream of an escarpment that is located close to Stötten in southern Germany (cf. Fig. 3). Details on the site can be found in [19]. The TSR is 6.64 and the pitch angle 4.41°.

It should be noted, that both turbines are commercial, hence the scaling of the load results has to be suppressed.

3.2. Inflow conditions

The atmospheric conditions for caseOffshore are fed from a precursor simulation conducted at the University of Oldenburg using the meteorologic LES solver PALM [20]. This run was driven by WRF and LiDAR data that were obtained upstream of the turbine. The atmosphere was almost neutrally stratified with an averaged wind speed at hub height of $\approx 8 m/s$ and a turbulence intensity of 4.5%. A time series of 58 s was extracted and ramped according to Meister et al. [21] to obtain temporal periodicity. The inflow data set was prescribed more than 2.5 D upstream of the turbine using a Dirichlet Boundary condition.

For caseTerrain a steady, homogeneous boundary layer profile is superposed with synthetic turbulence generated from the Mann model [22]. The underlying boundary layer follows power law with an exponent $\alpha = 0.14$. The model parameters for the Mann box were $L = 40 m$, $\Gamma = 3.9$, $\alpha c^2/\beta = 0.035$. The standard deviation of the stream-wise velocity component was $\sigma_u = 0.9 m/s$. The turbulence is introduced with body forces similar to Troldborg [23] ca. 1 km
upstream of the turbine. At the virtual turbine position this results in an inflow velocity of around 11 m/s at a turbulence intensity of about 10%. Details on the inflow generation and the propagation through the orography can be found in Schulz [19].

3.3. Meshing
For the FR simulations the relevant turbine components as tower, nacelle, spinner and the blades are meshed with body conforming grids. The blade meshes were created automatically using the IAG script Automesh in a C-H topology with locally adapted $y^+$ spacing of $\approx 1$ in the boundary layer. The blade of caseOffshore is discretized by $256 \times 100 \times 192$ cells in circumferential, wall normal and span-wise direction. For caseTerrain $220 \times 100 \times 140$ cells were used. All other component grids were created manually in Pointwise with resolved boundary layers. Each component was then assembled within FLOWer using the overset grid technique as shown in Fig. 2. In both cases the area of the wake and the inflow is discretized by $1 \text{ m}^3$ volumes. Away from that, the mesh is coarsened stepwise using hanging nodes. In total caseOffshore consists of ca. 80M cells, whereas in caseTerrain ca. 180M cells were used.

For the ACL simulations the blades are represented in both cases by 100 points. The airfoil polars were generated in XFOIL in the AoA range $-180^\circ < \alpha < 180^\circ$ using Viterna’s extrapolation. For sections near the root interpolation is conducted between the airfoils. For caseOffshore the tower and the nacelle are modeled as actuators as described in sec. 2. In caseTerrain the tower and nacelle meshes of the FR simulation were used. In both cases no tip corrections have been applied.

![Figure 2. caseOffshore: Assembly of the component meshes with the overset grid technique.](image)

![Figure 3. caseTerrain: Integration of the Turbine in the background domain [24].](image)

3.4. Numerical Parameters
The low dissipative resolution of turbulent structures in the atmosphere and the wake is important in order to capture unsteady loads as well as the turbulent fluctuations induced by the turbine. Therefore, the fifth order WENO scheme is applied in the background mesh, while the more robust second order JST scheme is applied in the component structures. For the ACL simulations of caseOffshore the low low-Mach number Riemann solver $l^2$-Roe was employed [12, 13]. All other simulations use the HLLC Riemann solver. The time step in caseOffshore and caseTerrain was set equivalent to $1.5^\circ$ and $2^\circ$ azimuth increment, respectively, for both the FR and ACL simulations. Each physical time step was iterated towards a pseudo steady state using 40 sub-iterations. The simulation were run until periodicity of the flow field
and the thrust was obtained. Data was then extracted for 10 revolutions in caseOffshore and 12 in caseTerrain.

4. Results
To accurately predict wakes by means of actuator type methods the generation of appropriate airfoil polars is crucial. To be able to interpret the wake results presented below, the sectional thrust loading of the rotor shall be discussed in Fig. 4 before. In each case the force is normalized by the span-wise mean value of the FR simulation. For caseTerrain the ACL distribution coincides very well with the results from the FR, except for a slight overestimation between 0.2 ≤ r/R ≤ 0.5. Compared to caseTerrain, the thrust distribution in caseOffshore is linear over a wide range with a highly loaded tip, which is significantly overestimated by the ACL. There, it could be observed that the airfoils operate close to the beginning of flow separation revealing thick boundary layers and XFOIL predicts higher lift coefficients compared to CFD. Therefore, it can be expected, that in caseOffshore the ACL predicts a higher induction compared to the FR simulation.

To assess whether unsteady aerodynamic effects play a role, time series of the angle of attack are plotted v.s. the lift coefficient at different radial positions of caseOffshore in Fig. 5. In the inner part of the rotor, a strong non-linearity of the load response is present, which reduces further outboard, but is still pronounced in the mid portion of the rotor. As expected, the ACL reproduces the 2D airfoil polar. The AoA range is similar as for the FR. For the outer region the mean value of the AoA in the ACL is even slightly smaller compared to the FR. Nevertheless, the predicted lift coefficient is higher which stresses the fact that inaccurate airfoil polars are responsible for the higher loading of the ACL rotor.

Turning to the characterization of the wake, first the instability mechanisms shall be discussed for the different cases. For caseOffshore the parameters that define the wake state are of meteorologic as well as turbine specific kind. The shear of the wind profile as well as the tilt angle of the turbine result in an inhomogeneous azimuthal loading of the rotor. The tilt results in higher thrust for the 270° position compared to the 90° position as shown for the considered turbine by Meister et al. [21]. Further, the blade digs deeper into the wake when passing the upper rotor half. Particularly, at high TSR this results that the blade is affected by higher induction there. This effect is superposed by the shear of the wind profile which increases the loading with increasing height. The ambient turbulence adds to these effects that result in an azimuthally inhomogeneous strength and distance of the trailing vortices and favors the relative movement of those. As the tip vortices are already close to each other due to the high

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**Figure 4.** Time averaged sectional thrust. Each normalized by the spanwise mean value of the corresponding FR simulation.

**Figure 5.** Characterization of unsteady aerodynamics for caseOffshore. Solid: FR; Symbols: ACL.
TSR mutual inductance becomes very likely as shown in Fig. 6. Vortex pairing starts about one rotor radius downstream of the turbine in the ACL and the FR simulations. However, the tip vortices of ACL are more elliptic compared to the FR, which is related to the smearing of the force terms. From $2 \leq x/R \leq 4$ the vortices roll up to larger sub-structures that are finally soaked into the wake center at around $x/R = 3.25$. Due to the presence of the ground, this process occurs with preference in horizontal direction constricting the wake. In reaction to that, fresh outer fluid of higher kinetic energy fills the deficit and longitudinal vortices emerge. As the velocity of the incoming fluid is inhomogeneous a large scale motion of the entire wake is triggered. Once, the shear layer is broken up the mixing with the surrounding air is enhanced. Therefore, with increasing distance the coherent structures loose their directionality and become more and more isotropic. The instability process is captured by the ACL and the FR in similar way. The wake structure in the hub region is closely mimicked by the hub model. Further, it can be observed, that the ACL simulation resolves smaller structures, which is a consequence of the lower dissipation of the employed $l^2$-Roe Riemann solver compared to the HLLC.

![Figure 6](a) caseOffshore: ACL vertical slice $y/R = 0$ (b) caseOffshore: ACL horizontal slice $z/R = 0$

![Figure 6](c) caseOffshore: FR vertical slice $y/R = 0$ (d) caseOffshore: FR horizontal slice $z/R = 0$

Figure 6. Wake instability mechanisms visualized by vorticity magnitude for caseOffshore.

The vorticity contours of the flow around the turbine in caseTerrain are shown in Fig. 7. Compared to caseOffshore the considerably higher turbulence intensity can immediately be noticed showing vorticity levels of the same order as the tip and root vortices generated by the turbine. Further it can be observed that the incoming flow is rather homogeneous. Both facts result in a quicker disordering of the coherent structures in the wake. Vortex pairing can be observed at about one rotor diameter downstream of the turbine showing brake-up of the wake at around $x/R \geq 4$, especially in vertical direction. Hereby the upward deflection is larger as the inclination angle of the incoming flow. Overall, the role up process of the tip vortices that leads to global instability is less pronounced as for caseOffshore. When comparing the ACL with the FR, the wake structure is similar. However, stronger smearing of the tip vortices is present.
compared to the FR. It should be noted that as opposed to caseOffshore both simulations use the same spatial discretization scheme.

![Diagram](image1)

**Figure 7.** Wake instability mechanisms visualized by vorticity magnitude caseTerrain.

In order to evaluate the development of the wake more quantitatively the profiles of the mean velocity and their standard deviation $\sigma$ are shown for caseOffshore in Fig. 8. The near wake is characterized by a linearly increasing velocity deficit in radial direction which is closely aligned with the rotor loading observed in Fig. 4. The high axial induction which reduces the free stream velocity by up to 50% in the outer part indicates that the turbine is operating close to the turbulent wake state [25]. This supports the findings made before regarding the entrainment of fluid from outside into the wake. The recovery process of the wake coincides well with the instability discussed before. When looking at the local maximum of the velocity in the wake center, this is phased out towards $x/R = 4$ showing a fairly uniform distribution and can be explained by the horizontal contraction of the wake. At $x/R = 6$, this shape is also present in the vertical profile, whereas in horizontal direction the wake is further rounded. Overall, the wake is deflected in positive $z$-direction and negative $y$-direction. The reasons for that is a slight negative mean $v$-component and positive $w$-component, as well as a rotor loading which is maximum in the fourth azimuthal quadrant. The ACL compares quite well with the FR capturing the shape and the levels of the wake deficit. The slightly higher deficit is connected with the mismatch of the loads in the outer part discussed in Fig. 4.

When looking at the velocity fluctuations it can be observed, that the ACL brings in higher perturbations into the flow field. In the near wake the FR simulation shows only peaks in the surrounding of the tip- and root vortices, whereas the ACL indicates enhanced fluctuations also in the middle part of the rotor. Similar observations were also made in Troldborg et al. [8] for turbulent non-sheared inflow. A possible explanation, is that due to the force smearing the bound vortex which trails helically into the flow field is larger than the viscous wake of the airfoil of the
FR simulation. Both lead to velocity variations that travel over the fixed observer. However, the thin viscous wake of the FR dissipates quicker as it requires a significantly finer mesh to be preserved. When looking further downstream, both turbine models predict a spatially blurring of the velocity fluctuations in the tip region which is a consequence of the breaking shear layer and mixing with the surrounding turbulent boundary layer. The entrainment of fluid into the wake center raises the level of turbulence there and diminishes the turbine footprint.

For case Terrain, the corresponding profiles are shown in Fig. 9. At first glance it is apparent, that the wake is more rounded compared to case Offshore which is consistent to the higher loading in the mid portion of the rotor shown in Fig. 4. The escarpment in the terrain yields higher velocities near the ground and a negative shear with increasing height [19, 24]. This results in a stronger tower effect compared to case Offshore. Particularly, in the very near wake the velocity fluctuations do not decay towards the ground. Still further downstream the fluctuations are more pronounced in the lower part of the wake which leads to a faster recovery of the wake there. Compared to case Offshore the higher turbulence intensity is responsible for the fact that the footprint of the turbine is getting blurry after around two rotor diameters behind the turbine resulting in a Gaussian shaped wake deficit. Regarding the averaged deflection of the wake, the vertical profiles indicate an upward deflection in the near wake due to the inclination of the inflow, followed by a successive alignment to the orography further downstream. In horizontal direction the wake is slightly deflected to the negative $y$-axis which follows from a terrain induced small yaw angle in combination to an azimuthally asymmetric rotor loading due to the turbine tilt and cone angle. A more detailed discussion on the wake development in case Terrain can be found in [24]. Comparing the wake deficit between the modeling techniques, good agreement of both can be found with a slight tendency of the ACL to extract more momentum from the flow field as the FR, although both had very similar force distributions. The comparison of the velocity fluctuations shows as for case Offshore mostly higher standard deviations for the ACL compared to the FR simulation.
For the determination of fatigue loads on a fictive turbine located in the wake, it is important to break down the velocity fluctuations into the different frequency shares. Hence, spatially averaged velocity spectra of the axial component are displayed in Fig. 10 for the different models and cases. In case Offshore the fluctuations show similarly to Meister [26] distinct peaks at the $3P$ frequency and its higher harmonics. As for the ACL only a single vortex system is injected into the flow field the energy is concentrated in the rotor frequency where the peaks are somewhat sharper and the amplitudes slightly higher. In the FR simulation velocity fluctuations are more diverse resulting for example from the viscous wake of the airfoil or flow separation and therefore resulting in a more broadband spectrum. In case Terrain the situation is different. As already seen in Fig. 7 the wake structure is less dominated by the turbine features than in case Offshore (Fig. 6) but more by the higher amount of atmospheric turbulence that directly enters the near wake. It seems that here the vortices induced by the ACL get disintegrated more easily as in the FR case, yielding the spreading of the $3P$ peaks. This seems to hold also further downstream as shown in the higher amplitudes of small scale turbulence at $x/R = 7$. In case Offshore the high frequency regime at $x/R = 6$ is further amplified for the ACL, since a lower dissipation scheme was employed.

5. Conclusions
Simulations on the wake properties have been conducted for typical wind turbines sited in on- and offshore wind farms with different turbine modeling techniques, namely the actuator line method and the fully resolved representation of the rotor. The objective was to assess the modeling accuracy of the actuator line method in complex environmental conditions where different levels of turbulence, shear and orography effects apply. Therefore, two cases have been investigated, an offshore case where a 5 MW wind turbine was subject to the maritime boundary layer and a 2.4 MW turbine sited in complex terrain. For the offshore case precursor LES data from the PALM code has been used revealing positive shear and a mean velocity of 8 m/s with a
moderate $Ti$ of 4.5% at hub height. For the complex terrain case synthetic turbulence has been generated with the Mann model. The orography yields a negatively sheared wind profile at the turbine position with wind velocities of 11 m/s and turbulence intensities of about 10%.

It could be shown that in the cases considered unsteady aerodynamic effects are present for the rotor loads. Regarding the wake instability, distinct wake meandering was observed for the high induction offshore rotor. In complex terrain no such large scale motion of the wake was observed. The actuator line simulations showed good agreement for the mean wake properties but over predicted velocity fluctuations in the mid portion of the wake. It can be concluded that for wind farm optimization and power forecasts the actuator line seems accurate enough, even in complex terrain. However, the specification of accurate airfoil polars is essential. If the interest lies on the detailed load behavior of a turbine within a wind farm the actuator line model could certainly provide the disturbed inflow for the turbine of interest which is then simulated in the fully resolved fashion.

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References
[1] Alfredsson P and Segalini A 2017 Introduction wind farms in complex terrains: an introduction
[2] Nilsson K, Shen W Z, Sørensen J N, Breton S P and Ivanell S 2015 Wind Energy 18 499–514
[3] Troldborg N 2008 Actuator Line Modeling of Wind Turbine Wakes Ph.D. thesis Technical University of Denmark
[4] Huyer S A, Simms D and Robinson M C 1996 AIAA journal 34 1410–1419
[5] Leishman J G 2002 ASME 2002 Wind Energy Symposium (American Society of Mechanical Engineers) pp 141–167
[6] Schepers J G 2012 Aerospace Engineering. Delft University of Technology
[7] Schepers J and Snel H 2007 ECN report
[8] Troldborg N, Zahle F, Réthoré P E and Sørensen N N 2015 Wind Energy 18 1239–1250
[9] Jameson A 1991 AIAA paper 1596 1991
[10] Jameson A, Schmidt W, Turkel E et al. 1981 AIAA paper 1259 1981
[11] Kowarsch U, Oehrle C, Keßler M and Krämer E 2013
[12] Oßwald K, Siegmund A, Birken P, Hannemann V and Meister A 2015 International Journal for Numerical Methods in Fluids
[13] Weihing P, Letzgus J, Bangga G, Lutz T and Krämer E 2017 Notes on Numerical Fluid Mechanics and Multidisciplinary Design (to be published) (Springer)
[14] Mikkelsen R 2003 Actuator Disc Methods Applied to Wind Turbines Ph.D. thesis Technical University of Denmark
[15] Tossas I, A M and Leonard S 2013 Wind turbine modeling for computational fluid dynamics Tech. Rep. NREL/SR-5000-55054 National Renewable Energy Lab., Golden, CO (US)
[16] Limley J 2016 Implementierung eines modells zur berücksichtigung von gondeleffekten bei der actuator line methode im strömungslöser flower
[17] Weihing P, Meister K, Schulz C, Lutz T et al. 2014 Journal of Physics: Conference Series vol 524 (IOP Publishing) p 012143
[18] Schulz C, Klein L, Weihing P and Lutz T 2016 Journal of Physics: Conference Series vol 753 (IOP Publishing) p 032016
[19] Schulz C, Hofsäi M, Anger J, Rautenberg A, Lutz T, Cheng P W and Bange J 2016 Journal of Physics: Conference Series vol 753 (IOP Publishing) p 082017
[20] Raasch S and Schrotter M 2001 Meteorologische Zeitschrift 10 363–372
[21] Meister K, Lutz T and Krämer E 2014 Journal of Physics: Conference Series vol 555 (IOP Publishing) p 012071
[22] Mann J 1994 Journal of fluid mechanics 273 141–168
[23] Troldborg N, Sørensen J N, Mikkelsen R and Sørensen N N 2014 Wind Energy 17 657–669
[24] Schulz C 2017 Numerische Untersuchungen des Verhaltens von Windenergieanlagen im komplexen Gelände unter turbulenter atmosphärischer Zuströmung Ph.D. thesis Institute of Aerodynamics and Gas Dynamics, University of Stuttgart
[25] Hansen M O 2015 Aerodynamics of wind turbines (Routledge)
[26] Meister K 2015 Numerische Untersuchung zum aerodynamischen und aeroelastischen Verhalten einer Windenergieanlage bei turbulenter atmosphärischer Zuströmung (Shaker Verlag)