CFD Studies on Wind Turbines in Complex Terrain under Atmospheric Inflow Conditions

Christoph Schulz, Levin Klein, Pascal Weihing, Thorsten Lutz, Ewald Krämer
Institut für Aerodynamik und Gasdynamik (IAG) Universität Stuttgart, Pfaffenwaldring 21, 70569 Stuttgart, Germany
E-mail: \{schulz, levin.klein, weihing, lutz, kraemer\}@iag.uni-stuttgart.de

Abstract. This article presents various detached eddy simulation (DES) results of a commercial wind turbine under multiple inflow conditions in complex and flat terrain. Challenges regarding the meshing process of wind turbines in complex terrain are described and an approach to overcome those is presented. The main focus of the evaluation is blade load and power response to inflow turbulence and terrain effects, e.g. the change of the inclination angle or the speed-up due to a hill. To separate the different influences, the complexity of the simulation setup is increased stepwise. Starting with a baseline simulation in flat terrain and uniform inflow over adding atmospheric turbulence to a complex terrain simulation of a fully meshed rotating 3D wind turbine under atmospheric inflow.

1. Introduction

The growing importance of environmental aspects as a public concern has led to basic changes in politics within the last decade and an increase of the importance of regenerative energies. A major part of these energy sources is wind power which is already wide-spread in many countries. As classical flat terrain sites are rare and offshore wind parks gain as high risks as they do costs — complex terrain sites step into to the focus. These sites are characterized by different features influencing the atmospheric boundary layer and as a consequence loads, life time, maintenance cycles, power output and financial benefit of wind turbines or parks. As described in \[1–3\] wind turbulence is one of the key influences on power output of single wind turbines and wind farms. This highlights the need for a deeper understanding of the interaction between atmospheric inflow turbulence and turbulence generated by orographic changes as well as of the interaction between wind turbine and atmospheric turbulence in case of wind farm considerations \[4\]. A lot of articles have been published studying the turbulent wind structure and orographic effects on wind turbine inflow conditions. \[5\] examined in experiments the influence of hills with applied roughness elements on the flow field and derived a power estimation of a generic wind turbine. Other studies focused on long term analysis of data received from a met mast sited in complex terrain in order to investigate the interaction between atmosphere and orography \[6\]. Numerical approaches mainly focused on meso- and micro-scale atmospheric simulations using different tools and statistical features to create power predictions. \[7\] describes a nesting method to get a link between the scales of atmospheric simulations and the scales needed to get detailed regional information for turbine power predictions, whereas \[8\] uses statistical downscaling to get
similar information. Nevertheless, none of these investigations focuses on capturing interaction
effects between wind turbine, atmospheric inflow and complex terrain. Covering these multiple
components is a time and cost consuming challenge. Therefore, different approaches with
contradictory priorities can be made which differ in the grade of complexity and consequently
simplification of the real flow behaviour. In [9] an overview and structuring of various techniques
for turbine simulations is given. The range varies from Blade Element Momentum (BEM) theory
based models [10] over actuator disc models [11] and actuator line models [12–14] up to direct
modelling of wind turbines [15–17]. The BEM method deals basically with calculating two
dimensional load distributions along the blade using tabulated airfoil data. As a consequence,
3D effects, root and tip losses as well as dynamic stall, wake and inflow dynamics have to be
considered using corrections or models. Its main advantage is the easy implementation. In the
studies of [4] analyses of wind farms in complex terrain have been performed using this method
and compared to a more sophisticated one — the actuator disc method. Actuator disc and line
methods increase the degree of complexity compared to BEM and get rid off wake and inflow
models. Both of the methods are a part of a Computational Fluid Dynamics (CFD) simulation.
The actuator disc method represents the wind turbine by an actuator disk transmitting body
forces into the flow field. These forces can be spread non-uniformly over the disc by using e.g. a
pre-defined distribution. The actuator line goes a couple of steps further and considers the blade
positions by distributing the forces in the rotor plane non-uniformly along lines representing
the different blades. As a result, the actuator line only smears the forces around each line,
whereas the actuator disc also smears the forces in the azimuthal direction. The highest grade
of complexity among the mentioned methods is reached by the so-called direct modelling, which
is also the most expensive approach. The blade is discretized completely and the 3D flow field is
calculated. Hence, 3D dynamic stall effects as well as the interaction between the turbine blade
geometry itself and the atmospheric turbulence can be taken into account without the use of
additional modelling. This approach will be used for the simulations presented in this article.

2. Numerical Aspects
Within the last years, the Institut für Aerodynamik und Gasdynamik (IAG) has developed a
process chain to analyze the aerodynamics of wind turbines by means of CFD [15]. The process
chain can be divided into two main parts. The first one is the commercial grid generation
software Gridgen® by Pointwise, Inc. supporting scripting capabilities and therefore, the
automation of the meshing process. Second is the block structured flow solver FLOWer provided
by the German Aerospace Center (DLR) [18]. To consider different inflow conditions an inflow
boundary condition has been developed giving the ability to use measured, artificial or simulated,
steady or unsteady data with a wide range of time a spatial resolutions for the simulation [19].

2.1. Numerical Schemes
All presented simulations were performed as detached eddy simulations (DES 97) with Spalart
Allmaras turbulence model. In this simulations a number of 35 inner iterations per time step were
chosen using a dual-time stepping method as temporal descretization [20]. Further information
on the time steps are given in section 2.5. For the calculation of the convective fluxes a second
order Jameson-Schmidt-Turkel (JST) method was used [21].

2.2. Turbine Grids
In the presented simulations the commercial K110 2.4 MW wind turbine manufactured by
Kenersys was used having a hub height of 95 m and a rotor diameter of 109 m. The rotor
plane is tilted by 5°, the precone angle is -2° and the pitch angle was constant at 4.41°. At the
chosen operational point the turbine had a rotor frequency of 12.81 RPM. In order to perform
the simulations, the turbine was divided into different geometrical parts which were meshed
separately and overlapped during the simulations by FLOWer using the chimera technique [22].

Alltogether, the turbine model consists of four different grids: tower including nacelle, hub, blade hub joints and blades. The blade grid was created based on an .iges file using a proven blade grid generation script developed at the IAG [16]. Its resolution was well kept below a value of $y^+ = 1$ (figure 1). As the outcome of a grid convergence study a blade grid consisting of approx. 5.4 million cells was created and the blade treated as rigid. The other grids were created manually with an $y^+ \approx 1$ for the first boundary layer cells using the software Pointwise® by Pointwise, Inc.. An overview of the used grids and their sizes is given in table 1.

| Name                | Cells (Mio.) | No. type | Comments                                      |
|---------------------|--------------|----------|-----------------------------------------------|
| Tower/Nacelle       | 3.75         | 1 steady | Has a fully resolved boundary layer.          |
| Hub                 | 2.15         | 1 rotating | Has a fully resolved boundary layer.          |
| Joint               | 0.3          | 3 rotating | Have fully resolved boundary layers.          |
| Blade               | 5.4          | 3 rotating | Have fully resolved boundary layers.          |
| BG flat terrain     | 19           | 1 steady | Used for flat terrain simulations.            |
| BG complex terrain  | 45           | 1 steady | Used for complex terrain simulations.         |
| Support             | 3            | 1 steady | Used for refinement around turbine.           |

### 2.3. Terrain Data Preparation

The terrain data used for this simulation were provided by the State Agency for Spatial Information and Rural Development Baden-Württemberg (LGL) in Gauss-Krüger coordinates. A main issue of complex terrain simulations is a well shaped joint between tower and terrain surface. As described in [23] an overlap of different surfaces requires identical surface positions and in an ideal case grid representations in order to minimize errors caused by chimera. Small differences in the surface discretization and the overlap could result in a misalignment in the wall distance calculations of the overlapping grids. Larger deviations regarding the surface alignment will result in more severe problems like orphaned points or blanking walls in the surfaces [22, 24]. In case of flat terrain a good overlap is easy to manage — the foot of the tower grid is created with a flat surface at the ground and a friction boundary condition (figure 2a). This friction wall is overlapped with another flat friction wall of the background grid. Reaching the tower foot using the same meshing approaches as before for a complex terrain situation two cases are likely (figures 2b). First of all, the tower grid foot could lay above the terrain surface causing a gap between the two surfaces and non-physical results. In the second case the tower grid would be beneath the terrain surface and as consequence the defined tower chimera holes would cut out surface parts of the terrain. In order to get a good chimera connection some adaptations have to be made. Figure 2c shows an approach modifying the tower grid at the tower foot by a projection of the tower friction wall on the ground of the terrain database. Another way to overcome the described chimera issues is the the modification of the terrain as displayed in figure 2d. Therefore, a pre-processing script has been developed creating a foundation for the tower inside a given terrain database. The script levels the terrain in the tower area smoothly.
Figure 2: Four different approaches for handling the tower terrain joint by using the chimera technique. (a) displays the standard situation valid for flat terrain cases. (b) shows the result of using the same approach unchanged in complex terrain. (c) and (d) suggest solutions by adapting either the tower grid or the surface database of the complex terrain. Tower grid lines are drawn in red on yellow ground and background grid lines are black on white ground. Tower surface and the friction wall at the ground are highlighted in red and terrain surface in grey. Chimera overlap regions show a mixture of the different grid line and background colours.

The result is an even plateau that fits well to the tower grid at the foot and results in zero orphaned chimera points or errors. Due to the script, it is possible to site the whole wind turbine in the complex terrain by just making minimal adaptations in the grid generation process. An advantage compared to the first approach is that the flat surface allows the use of the whole flat turbine grid setup without any changes between flat and complex terrain. Furthermore, it is closer to a real turbine in complex terrain needing a foundation and terrain adaptation. The overall dimensions of the database are 750 m streamwise, 600 m horizontal and the highest point of the included hill is 124 m.

2.4. Background Grids

The flat terrain background grid has a total size of approx. 500 m $\times$ 400 m $\times$ 475 m and a constant grid width in horizontal direction of 2 m. In vertical direction the boundary layer is resolved for the DES which was performed. Afterwards the cell size is kept constant at 1.5 m. In downstream direction the grid is designed for a width of 2 m but is refined at the turbine to a cell size of 1 m in order to get good chimera overlap regions and avoid interpolation errors. The chosen values of the domain size and grid spacings emerged from several grid convergence studies.

Regarding the complex terrain grid it was not possible to get the same high grid resolution at all points of the grid as for the flat terrain. This can be traced back to computational resource limits. Hence, the focus was to keep the grid resolution as high as for the flat terrain with respect to the inflow towards the turbine and in the near turbine region and coarsen the grid approaching the outlet and the sides of the computational domain. In addition to this, for the turbine simulation in complex terrain a cubic supporting grid around the turbine was used and overlapped by chimera to increase the grid resolution locally. Overall the complex terrain grid is divided into three different regions as illustrated in figure 3. At the inflow boundary an even surface is required to use the implemented inflow boundary condition by [19]. This region with a length of 16 m and the same height as the flat terrain background grid, since the same inflow
data should be used, is followed by the orographic data provided by the LGL. Downstream of the orographic database an extension 600 m streamwise has been made to capture the subsiding of the main disturbances inside the computational domain. Smaller domain sizes showed non-physical behaviour in the flow field. The transitions between the regions are created by spline interpolation. The boundary conditions in both grids were chosen similarly — inflow at the front plane, no-slip walls at the ground, farfield boundary conditions at the sides, the top and downstream as depicted in figure 3.

2.5. Test Cases
In order to get a stepwise insight into the effects of terrain and inflow turbulence four different simulations have been performed (table 2). For all test cases a DES and a combination of the grids described above was used. In Case I a baseline simulation of the wind turbine under uniform inflow conditions was carried out. This simulation was taken for validation against the manufacturer data provided. As a second step, in Case II a 60 s periodic time signal with a resolution of 0.25 s based on the data used by [19] was chosen as inflow condition and propagated towards the turbine. Due to the limitation of computational resources and the small time step required for wind turbine simulations, it was not possible to chose a longer time series. The whole 60 s signal was transported through the computational domain ten times before the evaluation data were extracted. In order to capture the full periodic inflow signal at least once, it was necessary to simulate nearly 13 revolutions of the turbine afterwards. The chosen time step was based on an azimuthal movement of approx. 2.5° and corresponds to approx. 0.0325 s. In the third step the complex terrain was simulated with turbulent inflow (Case III) aiming at getting information about the terrain–inflow–interaction. The time step for this simulation was aligned with the resolution of the inflow data and therefore chosen to 0.25 s. In Case IV the turbine was sited at x=457 m downstream and y=300 m in the complex terrain. Again the 60 s signal was propagated ten times through the whole domain using a time step of approx. 2.5° before the evaluation started and 13 revolutions have been monitored afterwards. All simulations have been carried out on the High Performance Computing Center Stuttgart (HLRS) with AMD Interlagos processors.

| Case | Inflow   | Turbine | Terrain  | Time step | Wind speed | Tilt  | Precone | Pitch |
|------|----------|---------|----------|-----------|------------|-------|---------|-------|
| I    | uniform  | yes     | flat     | ≈ 2.5°    | 11.01 m/s  | 5°    | -2°     | 4.41° |
| II   | turbulent| yes     | flat     | ≈ 2.5°    | 11.01 m/s  | 5°    | -2°     | 4.41° |
| III  | turbulent| no      | complex  | 0.25 s    | 11.01 m/s  | —     | —       | —     |
| IV   | turbulent| yes     | complex  | ≈ 2.5°    | 11.01 m/s  | 5°    | -2°     | 4.41° |
3. Results
As for confidentiality reasons it is not possible to show blade profile evaluations like $c_p$–distributions in the following subsections. Additionally, all power and force values have been normalized. For the power this was done by using the manufacturer value for the given reference case determined by BEM computations. Since no load data were provided by the manufacturer all force values have been normalized with the mean value of Case I of the corresponding force.

3.1. Wind Turbine Under Uniform Inflow
Figure 4 depicts the normalized aerodynamic power of the given operating point over the azimuth position of blade 1. The red line represents the mean power over one revolution and shows a deviation of less than 1% compared to the reference. At $60^\circ$, $180^\circ$ and $300^\circ$ the influence of the tower blockage becomes visible by power reduction of four percentage points. The normalized axial blade forces illustrated in figure 5 show that the curves of the three blades cover each other quite well. In addition, the impact of the tower blockage can be seen. This time it is visualized by a decrease of the normalized axial force of about ten percentage points in an area between $150^\circ$ and $215^\circ$. Furthermore, the effect of the tilt angle is apparent in a shift of the normalized axial force to the left side of the diagram. Similar observations have been made by [19].

![Figure 4](image1.png)  
**Figure 4:** Normalized power over one revolution of Case I (black) and its mean (red).

![Figure 5](image2.png)  
**Figure 5:** Normalized axial force of all blades over one revolution for Case I. Lines cover up.

3.2. Wind Turbine Under Turbulent Inflow
Case II aimed at the investigation of the impact of turbulent inflow on the axial force before the complex terrain is added to the setup in the following cases. Figure 6 depicts the normalized power over 13 revolutions averaged at each azimuthal step and the corresponding standard deviations $\sigma$ related to this average (mean±$\sigma$). In figure 7 the normalized axial force of blade 1 analyzed over 13 revolutions can be seen. The mean normalized power decreases by four percentage points compared to Case I and displays large fluctuations visible in standard deviations of up to six percentage points. Furthermore, the normalized force shows large fluctuations around the values gained from Case I. Both effects are a result of the permanently varying inflow velocities and atmospheric turbulence. Nonetheless, the influence of the tower blockage as well as the shift due to the tilt angle of the rotor plane can be detected as clearly as in Case I by looking at the power decrease of around $60^\circ$, $180^\circ$ and $300^\circ$ and the axial force decrease between $150^\circ$ and $215^\circ$. 

![Figure 6](image3.png)  
**Figure 6:** Normalized power over 13 revolutions averaged at each azimuthal step for Case II.
In the spectra determined by a FFT of the normalized axial force $s$ (figure 8) changes in comparison to Case I in the frequency range up to 1 Hz are apparent. As a consequence of the atmospheric boundary layer and the lower wind speeds at low heights in comparison to uniform inflow the tower influence is less intense, but noticeable. At the first harmonic of the blade passing frequency a decrease of 20% and at the second a decrease of 30% compared to Case I appears. At the other harmonics the decrease is about 20%. At the upper right corner of figure 8 a detail of the spectra using linear scale is placed to give a better insight into this. Above all, the spectrum of Case II is higher than for Case I over the whole frequency range due to the influence of the atmospheric turbulence. Similar observations have been made by [19] investigating the influences of an atmospheric boundary layer on different frequency ranges regarding blade loads. The trends shown for the normalized axial force can be seen in the spectrum of the normalized power (figure 9). The impact of the tower passage is less strong than in Case I, whereas the spectrum is higher.

**Figure 6:** Mean normalized power at each resolved azimuthal point over 13 revolutions for Case II (black) and its related standard deviation range ($\text{mean} \pm \sigma$) in red and blue.

**Figure 7:** Normalized axial force of blade 1 over 13 revolutions for Case II (black) and of the same blade for Case I over one revolution (red).

**Figure 8:** Normalized axial force spectrum of Cases I (black), II (red) and IV (blue). Upper right corner shows a detail of the spectra.

**Figure 9:** Normalized power spectrum of Cases I (black), II (red) and IV (blue). Upper right corner shows a detail of the spectra.
3.3. Complex Terrain Simulation

Case III has been performed without turbine to separate the interaction effects between turbulent inflow and complex terrain from other influences. Figure 10 shows the instantaneous estimated normalized maximum power output in complex terrain. The data were created by interpolating the wind speeds of the volume solution on a circular plate covering the rotor disc. The latter was placed at hub height considering the tilt angle [25]. Afterwards the data were normalized by the maximum power output possible under uniform inflow of 11.01 m/s. Thin black lines in the figure indicate different height levels with a difference of 10 m each. The tower position is highlighted by a black dot and the swept area of the blades by two black straights. It can be figured out that at the designated turbine position an increase of power of about 1.7 to 2 times the reference can be achieved whereas in the flat areas the power is nearly equivalent the reference case. Obviously, speed-up effects due to the hill step into focus and also a blade load increase would be expected. Furthermore, the turbulence intensity at the designated turbine position increases from up to 2% in the inflow to a value of about 5%, which means that the terrain leads to an increase of the ambient turbulence of factor 2.5. Prominent is the large area of high turbulence intensity downstream the hill. The turbine is sited very close to the edge of this area. In case of slightly steeper terrain a larger separation at the hill top could appear and catch parts of the turbine influencing load and power fluctuations enormously. Taking into account the mentioned data, higher fatigue compared to a flat terrain position is likely. The distribution of the turbulence intensity over the height above ground emphasises this hypothesis. The turbulence intensity increases compared to Case II from about 4.5% to a maximum value of 15% in the swept area of the rotor blades (figure 12). The distribution shows clearly the effect of the hill up to a height of 100 m above ground with a peak of turbulence intensity at 35 m. Apart from that, other interesting points at a complex terrain site are the inflow angles [2, 3]. For the given conditions an angle of about 16° in positive z-direction (inclination angle) and of 2° in negative y-direction (yaw angle) could be figured out. As a consequence, a reduction of power can be expected as the projected rotor area decreases [26]. The combination of this contradictory effects impedes giving a final statement on the later turbine behaviour at the given site. Load and power increases are likely as well as a obvious influence of the inflow angles.

Figure 10: Normalized estimated power output at the complex site. Black symbols indicating the designated turbine position.

Figure 11: Turbulence intensity at hub height. Black symbols indicating the designated turbine position.

Figure 12: Turbulence intensity over height above ground at inflow and designated turbine position. Black dot and bars indicating hub and blade area.
3.4. Wind Turbine In Complex Terrain

As it has been estimated in the previous investigations, power and axial force increase in the designated complex terrain situation. Usually, a turbine would change the pitch angle or stop operation under these conditions. For these analyses the pitch angle and rotational speed has been kept constant in order to keep the comparability of the investigations. The study of these effects is part of still ongoing investigations performed by the authors. The normalized power and axial force distributions are not shown here, as there are no new effects compared to the previous Cases. Looking at the spectral analysis of both quantities in figure 8 and 9 some new effects are evident. The tower blockage has in general a stronger influence on power and axial force fluctuations than in Case II. For the first harmonic an increase of 40% can be determined. Except for some local areas both spectra are located at a higher level compared to Case II with a prompting difference up to 0.5 Hz. Nonetheless, the influence of the terrain on the spectra is less than expected from Case III turbulence intensity investigations, whereas the general trend of axial force and power increase is equivalent to the estimations made before.

Illustrating the inclination angle $\alpha$ and a comparing the normalized power and axial forces of Case II and Case IV, figure 13 and 14 cover one sequence of the inflow data. As mentioned above, the mean power of Case IV is about 1.8 times the reference value and about 0.75 percentage points higher than for Case II. The normalized axial forces increase about 0.35 percentage points in comparison to Case II. These effects emerge from the mean wind speed increase due to the hill and the higher turbulence in the turbine inflow. The power increase fairly well agrees with the Case III estimation, that predicted an increase by a factor of two. Differences might be caused by interaction effects influencing the turbulent boundary layer. Black lines in the figures symbolize the inclination angle over time. Case II shows a slight variation over the sequence with an end point equal to the starting point because of signal periodicity. The angles are within a range of -2° and 2.5° showing only a little impact on axial force and power. The already in Case III mentioned impact of an anti-proportional behaviour of power output and inclination angle is visible, but not striking. In contrast, Case IV highlights the anti-proportionality much stronger. The mean inclination angle is as already estimated in Case III about 16° but varies between 14° and 22°. The increasing inclination angle leads to a power and axial force reduction which is visible in the larger scale trend of the curves. For Case IV, a periodicity of the inclination angle can not be detected hinting at the presence of low frequency or non-periodic effects that have not been captured completely in the current investigations.

![Figure 13: Normalized power of Case II and IV as coloured lines and the corresponding inclination angle $\alpha$ as black lines.](image1)

![Figure 14: Normalized axial force of Case II and IV as coloured lines and the corresponding inclination angle $\alpha$ as black lines.](image2)
4. Conclusion
This article presented different approaches of integrating a wind turbine setup including tower, nacelle, hub and fully meshed blades into a complex terrain site. An approach to adapt the terrain by including a tower foundation as probably done in reality was finally chosen for the simulations. Moreover, the article analyzed different influences on rotor blade loads and power output of a commercial wind turbine as well as simple methods of site assessment for estimations of designated turbine locations. Starting from a uniform inflow situation, influences of tilt angle and tower blockage have been shown. Adding atmospheric turbulence to the simulation, an increase of load and power fluctuations became visible likewise the decrease of the tower blockage. The atmospheric turbulence led to a prominent change in the spectral analyses of loads and power. An increase of the amplitudes in the low frequency range was the most eye-catching. Furthermore, it was pointed out that simple methods of site evaluation make it possible to extract estimations on later turbine behavior. A good correlation between the estimations gained from this analyses and the performed turbine simulation has been illustrated. Especially, the speed-up estimation and the inclination angle determination showed good agreements. The complex terrain situation evinced overall three major effects: 1) A mean wind speed increase and as a result load and power increase. 2) An increase of turbulence and consequently of load and power fluctuations. 3) A correlation between the inclination angle and load and power behavior.

5. Acknowledgements
The authors thank the German Federal Ministry for the Environment, Nature Conservation & Nuclear Safety for funding this studies, the State Agency for Spatial Information & Rural Development Baden-Württemberg for providing terrain and Kenersys for providing turbine data. The computational resources were contributed by the High Performance Computing Center Stuttgart.

References
[1] Milan P, Wächter M and Peinke J 2013 Physical Review Letters 110
[2] Hau E 2006 Wind Turbines: Fundamentals, Technologies, Application, Economics (Springer, New York)
[3] Emeis S 2013 Wind Energy Meteorology (Springer, New York)
[4] Pedersen T, Gjerding S, Enevoldsen P, Hansen J K and Joergensen H K 2002 Wind turbine power performance verification in complex terrain and wind farms
[5] Ruck B and Gruber M 2013 Proceedings: 8th International Conference on Energy and Environment 123128
[6] Pauscher L, Hagemann S, Klaas T, Callies D, Langenmayer C, Kühn P and Lange B 2012 Proceedings: German Wind Energy Conference, DEWEK
[7] Martí I, San Isidro M J, Cabezon D, Loureiro Y, Villanueva J, Cantero E and Perez I 2004 Proceedings: The Science of Making Torque from Wind 316–327
[8] Mengelkamp H T 1999 Theoretical and Applied Climatology 63 129–139
[9] Sandere B, van der Pijl S and Koren B 2011 Wind Energy 799–819
[10] Hansen M O L, Sørensen J N, Sørensen N and Madsen H A 2006 Progress in Aerospace Sciences 285330
[11] Sørensen J N and Myken A 1992 Journal of Wind Engineering and Industrial Aerodynamics 139149
[12] Mikkelsen R 2003 Actuator Disc Methods Applied to Wind Turbines Ph.D. thesis
[13] Sørensen J N, Troldborg N and Mikkelsen R 2007 Journal of Physics: Conference Series
[14] Troldborg N 2008 Actuator Line Modeling of Wind Turbine Wakes Ph.D. thesis
[15] Meister K, Lutz T and Krämer E 2010 Proceedings: German Wind Energy Conference, DEWEK
[16] Meister K, Lutz T and Krämer E 2012 Wind Energy and the impact of turbulence on the conversion process
[17] Bechmann A, Sørensen N N and Zahle F 2011 Wind Energy 677689
[18] Kroll N, Rossow C C, Becker K and Thiele F 2000 Aerospace Science and Technology 4 223–237
[19] Meister K, Lutz T and Krämer E 2012 Simulation of a 5MW wind turbine in an atmospheric boundary layer
[20] Jameson A 1991
[21] Jameson A, Schmidt W, Turkel E et al. 1981 AIAA paper 1259
[22] Benek J A, Steger J L, Dougherty F C and Buning P G 1986 Chimera. A Grid-Embedding Technique.
[23] Schwarz T, Spiering F and Kroll N 2010 Second Symposium "Simulation of Wing and Nacelle Stall"
[24] Dietz M 2007 Simulation der Aerodynamik von Hubschrauberkonfigurationen unter Berücksichtigung von Strömungs-Struktur-Kopplung und Trimmung Ph.D. thesis University of Stuttgart
[25] Schulz C and Lutz T 2013 IEA Topical Expert Meeting No. 75
[26] Pedersen T 2004 Wind Energy 7 163–176