Numerical simulation of the impact of atmospheric turbulence on a wind turbine in complex terrain

Christoph Schulz, Patrick Letzgus, Pascal Weiheing, Thorsten Lutz, Ewald Krämer
Institute of Aerodynamics and Gas Dynamics (IAG) University of Stuttgart, Pfaffenwaldring 21, 70569 Stuttgart, Germany
E-mail: \{schulz, p.letzgus, weiheing, lutz, kraemer\}@iag.uni-stuttgart.de

Abstract. In this study, which was part of the project AssiSt, numerical analyses of wind turbine power, loads and wake development in the extreme wind conditions found on a complex terrain site in northern Spain have been performed. The turbine is located near the edge of a characteristic cliff. Realistic atmospheric inflow conditions are prescribed by propagation of highly resolved meteorologic data of the LES code PALM in the aerodynamic solver FLOWer. The global features of the flow field in the complex terrain site were investigated showing significant inclination angles, high turbulence intensities and a characteristic mixing mechanism of high and low momentum velocity layers. Further, the wake development and its deflection and deformation was analyzed. Finally, the turbine’s load response was investigated, showing severe fatigue loading as consequence of the highly unsteady inflow conditions.

1. Introduction
The exploitation of complex terrain sites is important to increase the onshore wind power capacities, particularly in regions of relatively lower wind speed, in order to study the impact of the complex site specific inflow conditions on the loads and the wake development of the turbine. Without doubt, it can be taken advantage of the local over-speed when siting the turbine on a hill to increase the power production [1, 2, 3]. However, complex topography usually involves complex inflow conditions that may increase the fatigue loading and potentially reduce the turbine life time. Within the research project AssiSt, the influence of such extreme conditions have been investigated. The terrain examined is located in northern Spain and shows a characteristic escarpment with a cliff on top of the hill.

Within the last years various simulations and experiments have been performed on complex terrains with different focus and different scale resolved, as well. A lot of studies are performed on the well known Askervein hill or the small peninsula Bolund. In the small scale Bolund experiment, the flow over a cliff has been thoroughly studied by [4] and served as validation test case for micro scale flow models of different complexity. Applying the RANS approach to flows in complex terrain, general features as overspeed and inclination can be estimated [5]. By hybridization of RANS and LES the energy containing eddies detached from the wall can be temporally resolved [6], [7], while maintaining attached, wall bounded turbulence in RANS mode. Using e.g. immersed boundary methods, the flow in complex terrain can also be simulated entirely by LES [8], allowing the direct simulation of turbulent structures that are larger than the employed filter.
In the present case, certain flow characteristics of the Bolund experiment, namely speedup, flow inclination and high turbulence intensities can be expected, as well. Britter et al. [9] analyzed and explained the effects of speedup and turbulence development using rapid distortion theory for a two-dimensional hill. The effect of inclination angles for wind turbine performance and wake has been investigated experimentally e.g. by [10]. Therefore, characteristic load variations are present in the rotor plane, going along with an also characteristic wake deflection [7, 11].

The objective of the present project was to examine the local atmospheric flow field for wind energy on this specific site from a meteorological and aerodynamic point of view. In the course of this work, highly resolved CFD simulations of the complex terrain with a wind turbine at the edge of the cliff are performed. The data of the inflow conditions is provided from the Institute of Meteorology and Climatology (IMUK) of the Leibniz University in Hannover and simulated by PALM [12], which is a meteorological LES solver. Within the project a coupling of PALM and the aerodynamic CFD code FLOWer has been pushed forward.

Via this coupling the local atmospheric flow field is shown, as well as the interaction with the turbine generating the wake structure. Importantly for fatigue and turbine's life time are the unsteady loads, which will be analyzed and associated with effects imposed by the complex orography.

In the next section computational details of solver, atmospheric inflow and grids are provided. The results of the flow field are shown first, before its impact on the turbine loads will be discussed. Lastly, the major findings are summarized in the conclusions.

2. Methodology and Computational Details

2.1. Flow Solver and Atmospheric Inlet Boundary Condition

For the present study the flow solver FLOWer [13] of the German Aerospace Center (DLR) has been used and specifically extended for wind turbine applications at the authors’ institute. The basic code is a compressible block-structured code of second order accuracy with overset moving grid capabilities. It was extended by a fifth order WENO [14], [15] scheme to improve preservation of vortical structures which is important for accurate propagation of atmospheric turbulence and the wind turbine wake [16]. This is of particular importance for the present approach, when propagating turbulence data stemming from a LES code, that is naturally designed for low dissipation. For the code PALM [12] for example, inviscid fluxes are discretized using a sixth order central scheme with fifth order upwind stabilization. Previous investigations [17] propagating atmospheric turbulence originating from that code using the standard second order Jameson scheme [18] were affected by severe numerical dissipation.

The boundary conditions to feed in atmospheric turbulence implemented in FLOWer, can be either of Dirichlet type by imposing flow data from precursor simulations [17], or by using body forces and applying synthetic turbulence forces [19], [20], [7]. For the present study the first approach has been used. The Dirichlet condition initially transfers all conservative variables from the first inner layer to the first ghost cell and then uses the corresponding $u, v, w$-velocity components to overwrite the momentum $\rho u, \rho v, \rho w$. With that procedure, e.g. the turbulence variables can adapt iteratively to the incoming flow field. Regarding the coupling of the extracted LES data, a tool has been written that transforms the staggered PALM data to cell centered quantities in the requested FLOWer coordinate system applying bicubic interpolation. Generally, it would also allow the scaling of the velocity field to match desired turbulence levels at the turbine position, but this has not been conducted here. The extracted velocity time series corresponds to 13 rotor revolutions and has been modified according to [17] in order to obtain a periodic signal. In both, the PALM simulations and in FLOWer, the atmosphere is treated with neutral stratification.
2.2. Computational Setup
The terrain in covers an area of $15 \times 10 \text{km}^2$ and reveals a very distinct rim on which an array of 15 wind turbines is sited. The entire domain has been simulated by the project partner IMUK using the LES code PALM with focus on meteorologic effects in complex terrain. For one of the prevailing wind directions which is approximately oriented perpendicular to the rim, highly resolved flow data of $2m$ resolution have been extracted from PALM in a plane $800m$ upstream of the turbine and is fed into FLOWer using the previously described Dirichlet boundary condition. The domain cutout used for the wind turbine simulation in FLOWer is shown in Fig. 1 (a). It is $800m$ long and $400m$ wide. At the turbine position the domain height above ground is around $250m$. The considered wind turbine is a generic redesign of original turbines installed on site. The rotor diameter is $44m$ and the hub height $49m$. The overset mesh design of the wind turbine in the complex terrain depicted in Fig. 1 b). The terrain is meshed using a hanging grid node approach and grid deformation to adapt the local terrain contour. The resolution in the wake and upstream of the turbine is $1m$. The nacelle and the tower are meshed in O-type topology, whereas the blades use C-H-type meshes. The latter employ high quality boundary layer refinement assuring $y^+ \approx 1$ in the first grid cell and consists of around 15M cells, each. In total, the setup comprises 76 million cells. Apart from the Dirichlet inflow condition, all surfaces are treated with no-slip conditions. For the other outer boundaries farfield conditions are applied. The simulations are conducted unsteady, using the dual-time stepping method of [21] and a physical time-step equivalent to $2^\circ$ azimuth movement and 40 sub-iterations. The simulation assume fully turbulent conditions in the wall boundary layers and use the SAE turbulence model [22]. In the background mesh it is switched to DES mode [23] to lower possible damping of resolved eddies caused by the turbulence model. With the same purpose the higher order WENO scheme is applied there, as well. The whole turbulence field was propagated twice through the domain before, data was extracted over 13 revolutions.

![Computational domain.](image1)

![Overset turbine mesh.](image2)

Figure 1. Computational domain and overset mesh integration.

3. Results
The following section gives an overview of the computational results of the unsteady simulations with FLOWer. First, the flow field upstream and downstream of the wind turbine will be analyzed, followed by a discussion on the unsteady load response of the turbine on the turbulent inflow.

3.1. Flow field
The instantaneous flow field of the atmospheric boundary layer in the complex terrain interacting with the turbine is visualized in Fig. 2 using volume streamlines and various stream-wise cross
Figure 2. Visualization of the instantaneous flow field using volume streamlines and cross-cuts at $x/D = [-9; -5; 1; 2]$ colored by axial velocity.

cuts ($x/D = [-9; -5; -1; 2]$) indicating the axial velocity. The local flow field in the complex terrain is divided in five significant areas. Area 1 visualizes a high speed area of the flow high above ground with nearly negligible changes of the axial flow direction. The second characteristic of the flow field can be seen in area 2. There, the low speed flow near ground exhibits relatively high yaw angles compared to area 1, because of the lateral slope shape of the terrain. The vertical and horizontal shear results in a mixing area 3, where low speed flow of the lower part of the terrain mixes with high speed flow regions of the upper part of the atmospheric boundary layer by global longitudinal vortex-system, which is determinable in the cross cuts -1D and -5D by the spirally shape of the streamlines. The horizontal gradient seems to be driven, first by the hanging terrain in flow direction to the left as already described for area 2 and secondly by the fact that rim is not perpendicular to the main inflow direction, revealing an angle of up to $30^\circ$ at the right end of the domain. The mixing of the high speed flow in the upper regions and the low speed flow of the lower regions of the field leads to smaller absolute velocities in that height compared to lower areas above ground and therefore to negative shear at the location of the turbine. The wind turbine wake with its low speed and elliptical shape is visible in area 4. Area 5 highlights the flow separation area downstream of the turbine near the ground. When looking in flow direction, generally, the left part of the flow field of the terrain shows significantly lower wind velocities compared to the right part because of the yawed inflow and orographic effects. The yawed inflow near the ground leads to a non axial flow over the step of the terrain, which becomes apparent by taking a closer look on the streamlines at the -1D cross-cut.

Figure 3 illustrates the local flow field in a vertical cut at turbine position for the axial mean velocity $u$ in Fig. 3 (a) and the standard deviation of axial velocity $\sigma$ in Fig. 3 (b). The complex terrain exhibits large slopes and a large step on top of the hill near the wind turbine position, which leads to high inflow velocities and to a characteristic flow field in the wake of the turbine. Despite the time averaging, small scale spatial variation of the local velocity field can still
be seen. This clarifies the high turbulence intensity on the one hand but it must be also stated that the simulations might not have been run for long enough to cover also the largest scales in the atmospheric boundary layer. Typically for the latter 10min signals are used for statistics which is however very expensive to resolve in the manner of the scales considered for blade aerodynamics.

Because of the escarpment, resulting in high inclination angles of the flow, the wake of the wind turbine separates near the ground, which has already been analyzed in area 5 of Fig. 2. The interaction of the flow with the wind turbine influences the area near the ground to a large degree. This effects a flow separation, which appears to remain on the same position. The reason for this flow separation bubble is linked with a positive pressure gradient on top of the hill due to the inclination of the plateau, combined with a strong shear layer which is further stressed by momentum extraction of the wake. The high velocities on the upper half of the flow field (analogous to area 1 in Fig. 2) can be justified from the meteorological inflow data of PALM. Downstream of the turbine a characteristic wake deflection downwards can be seen. In complex terrain, particularly when a plateau follows a steep escarpment, the effect of inclination on the wake deflection is different compared to what would be expected from a corresponding yaw misalignment. The latter commonly deflects the wake beyond the pure inflow angle [11]. The same would occur for inclination without plateau, similarly as shown by the experiments of Tsalicoglou et al. [10]. In the present case, however, inclination pushes the wake downwards, since the flow realigns to the global orography. The wake additionally deformed, due to the flow over the flow separation area, which represents lower static pressure and leads to a suction of the wake flow downwards. Another characteristic of the local flow field can be seen in Fig. 2, as well. Negative shear appears in the domain along the slope of the hill. A minimum of the local mean velocity is recognizable on hub height upstream of the wind turbine.

Figure 3 (b) shows high standard deviations of the velocity u in the whole field. This verifies the statement of Barthelmie et al.[24], that the standard deviation of the flow becomes increased in complex terrain. Because of the vortex systems the standard deviation σ increases drastically in the near wake of the turbine, see Fig. 3 (b). Downstream of the separation bubble, the standard deviation σ decreases rapidly. Troldborg [25] investigated the decrease of the standard deviation in the wake and argues that the turbulent fluctuations are decaying in the wake but remain significantly important for such analyses. At the slope escarpment the standard deviation increases again, an effect that has already been analyzed by Stull [26]. The high standard deviations in these areas are the reason for the flow deflection upstream and downstream of the turbine and lead to an area of high velocity gradients in z-direction.
Figure 4. Turbulence intensity of the axial velocity fluctuations (left), lateral fluctuations (mid) and vertical fluctuations (right) in a slice one rotor diameter upstream of the turbine. The polar diagram indicates the rotor area.

Focusing on the direct inflow of the rotor, corresponding turbulence intensity is plotted for the three velocity components, in a plane located, one rotor diameter upstream of the turbine in Fig. 4. The virtual rotor area is depicted for reference. The left border of these plots is located adjacent to the main vortical mixing structure denoted by 3 in Fig. 2. The core of this vortex is characterized by high turbulence intensity of more than 20%. The present clipping is affected by the end portions of that region with streaks of high velocity fluctuations passing the rotor plane. Higher fluctuations of axial velocity are found in the upper left rotor portion and in a diagonal streak at 240°, whereas vertical fluctuations are found for the lower rotor half. Significant lateral fluctuations are present in the lower left quadrant of the rotor plane.

Figure 5. Mean axial velocity in the wake at $x/R = [1; 2; 5]$.

Figure 5 visualizes the mean axial velocity $u$ in the wake at several positions downstream of the turbine in the wake. From left to right the normalized positions of the cuts through the wake are $x/R = 1$, $x/R = 2$ and $x/R = 5$. The circular shape of the wake just downstream of the rotor becomes increasingly deformed due to the separation bubble near the ground.
Furthermore, the wake area in each cut is smaller than the rotor diameter. The reason for this effect was given by Troldborg [25]. It appears to be a combination of large scale out of plane motion and wake stretching, because of the flow separation area. At the position $x/R = 5$ the wake breaks up because of mixing with ambient turbulence, which could already be seen at the position $x/R$ in Fig. 5. Figure 6 shows the standard deviation of the axial velocity in the wake.

![Figure 6. Standard deviation of axial velocity in the wake at $x/R = [1; 2; 5]$.](image)

The standard deviation in the separation bubble near the ground satisfies the assumption, that this recirculation area displays low temporal fluctuations. Besides, there is no flow mixing in this area. On the other hand $\sigma$ demonstrates the increasing deformation of the wake. The elliptical deformation of the wake and increasing interaction of the wake and the surrounding area is clearly visible in the standard deviation. The asymmetric shape of the wake and the area of flow separation in yz-direction is due to the asymmetric inflow conditions and the special shape of the plateau. Especially the area on the right, downstream of the wind turbine becomes separated near the ground in the wake of the turbine in contrast to the left side.

### 3.2. Loads

The previous sections showed, that the flow dynamics altered by the escarpment revealed high inclination angles, local over-speed and significant, anisotropic velocity fluctuations approaching the rotor. These effects bear the detrimental potential of high fatigue loads for the rotor.

The thrust of one rotor blade is plotted in Fig. 7 (a) vs. azimuth position. The force is normalized with the averaged value of a flat terrain reference simulation in uniform inflow having the same averaged wind speed as found in the terrain. To include the presence of the ground, a slip boundary condition was applied there. Apart from the tower blockage effect, the reference simulation shows a fairly constant load distribution over the whole azimuth range, since the generic turbine has no tilt or cone angles. In complex terrain, the speedup near the ground increases the loads for the lower rotor area. The obvious shift of the loads towards to the right rotor half can be explained by the inclination angle. In general, the inclination angle alters the effective rotational velocity component seen by the blade section, as the inflow wind vector already reveals a certain component in chord-wise direction. For a vertically positive inclination angle as found in the present terrain this naturally means an augmentation of the tangential velocity component for the downward moving blade and respectively a smaller relative velocity on the upward moving side. In addition it must be kept in mind, that the angle of attack is accordingly reduced when the rotational speed is increased, assuming the horizontal component...
of the wind velocity stays constant. As both effects are working in opposite direction with respect to the generated lift, an a priori statement on the azimuthal shift of the rotor loading is difficult. Inboard, the angle of attack effect might prevail, whereas outboard it is more likely that the change in relative velocity is dominating. In the present case, the integrated thrust is shifted towards the right rotor area, which indeed suggests that the effect of changing relative velocity predominates. The variations in the magnitude of the polar diagram for a constant azimuthal position are a consequence of the interaction with turbulent gusts.

At first glance, the distribution of rotor power shown in Fig. 7 (b) seems rather chaotic. However, certain correlations can be made to the thrust distribution discussed before. When focusing for example on the \([0;120;240)^\circ\) azimuth positions, power is markedly higher. For that situation two of the blades dive into the local over-speed near the ground, while the third blade is in vertical direction, where it comes close to region \([1]\) shown in Fig. 2, where wind speed is also relatively high, and inclination angles small. For an azimuth angle of 270\(^\circ\) power is about average. At that position thrust is minimum, however, the other blades being at 30\(^\circ\) and particular the blade at 150\(^\circ\) compensates this. When one blade is at 90\(^\circ\) azimuth, overall power is lowest, although thrust for that blade is higher compared to the 270\(^\circ\) position. The reason can be again attributed to the inclination angle which results in smaller loads for 210\(^\circ\) compared to 150\(^\circ\) and smaller loads for 330\(^\circ\) compared to 30\(^\circ\), respectively.

![Figure 7](image_url)

**Figure 7.** Loads and power for 13 revolutions. The black curve denotes results from a flat terrain reference simulation in uniform inflow with slip boundary condition on the ground. The terrain case (gray curves) are normalized by the averaged value of the flat terrain case.

In order to assess the turbine’s load response more locally, the radial distribution of the thrust force shall be discussed in Fig. 8. Phase averaged quantities have been computed over 13 revolutions, although it is clear, that these results are far from being statistically converged. However, those can still be helpful for the understanding about the changes happening at the same azimuthal positions from revolution to revolution. The phase averaged thrust presented in Fig. 8 a) shows its maximum value at around 140\(^\circ\) azimuth and \(r/R = 0.8\). As previously discussed this is caused by the over-speed and the largest inclination angles closely above the rim. For the corresponding position on the left, the load is smaller as the inclination has the opposite effect, and further the blade needs some time to build up circulation after passing the tower. As already suspected from the integral loads, inclination shifts the loading to the right for the outer part of the rotor, but for the inner 50% the left half of the rotor is higher loaded.
This clearly suggests that there, the effect of increasing angle of attack compensates the lower relative velocity.

Turning to the corresponding phase averaged fluctuations (Fig. 8 b), two major spots can be seen in the polar diagram. The first is found in the upper left rotor portion and can be connected to angle of attack variations imposed by fluctuations in axial velocity observed in the turbulence intensity in the $x$-direction. The other hot spot prevails between 120° and 150°. For those positions, no distinct axial velocity fluctuations were seen. However, for these azimuth positions, the relative velocity acting in chord-wise is composed of the lateral and vertical components, respectively. As the superposition of both is particularly strong in that region, this might be an explanation for the high load fluctuations. At around 90°, the velocity variations in axial and vertical direction, that would lead to angle of attack and relative velocity changes, were very small, and so are the load fluctuations, which are minimum in that section. Directly in front of the tower, where the mean loads collapse, the standard deviations are small, as well, as this effect is purely periodic, being absent for phase averaging. When the blade recovers from the tower passage, strips of high standard deviation are present which can be linked to the wavy pattern seen in Fig. 7 a) and Fig. 8 a) in the azimuth range between 180° and 230°. As these are absent in the flat terrain case, they must be caused by effects coming from the atmospheric inflow. A possible explanation could be the excitation of an angle of attack oscillation superimposed by the increasing bounded circulation due to high lateral velocity fluctuations present in that region resulting in an unsteady aerodynamic response of the blade.

![Diagram](image)

(a) Phase averaged thrust force.
(b) Standard deviation of phase averaged thrust.

Figure 8. Phase averaged radial thrust distribution vs. azimuth angle averaged over 13 revolutions.

4. Conclusions
In the present study, the effects of atmospheric turbulence affected by a highly complex terrain site is numerically investigated by means of CFD, with respect to the unsteady load behavior of a wind turbine. The numerical approach is based on a coupling of results obtained from the meteorologic LES code PALM and the aerodynamic code FLOWer. The complex terrain and its special shape involving a steep rim on top of a ramp yields over-speed and significant inclination angles and is further responsible for generation of strong vertical and horizontal shear layers that causes a coherent mixing zone of high and low momentum layers. This results in very high turbulence levels upstream of the rim. The turbine which is sited closely downstream of that rim
is affected by the border of this highly turbulent structure and already shows significant load fluctuations compared to a reference case in flat terrain. A lateral shift of the turbine into that highly turbulent region could extremely enhance fatigue loading. Regarding the wake, it seen to be deformed to an elliptical shape and disintegrates about five diameter behind the rotor. In vertical direction it was observed to be deflected downward and to induce a recirculation area beneath. Future work is dedicated to different wind directions, where particularly the opposed wind direction could be interesting for comparison. In addition, a comparison of FLOWer and PALM is planned, in order to quantitatively assess the propagation of LES turbulence in FLOWer.

Acknowledgments

The authors acknowledge the PALM group of S. Raasch of IMUK Hannover for providing the inflow data set, the German Federal Ministry for Economic Affairs and Energy for funding this study as part of the project "AssiSt" (grant number 0325719A) and the High Performance Computing Center Stuttgart for providing computational resources.

References

[1] Schulz C, Klein L, Weihing P, Lutz T and Krämer E 2014 Journal of Physics: Conference Series vol 524 (IOP Publishing) p 012134
[2] Wegley H L, Ramsdell J V, Orgill M M and Drake R L 1980 Siting handbook for small wind energy conversion systems Tech. rep. Battelle Pacific Northwest Labs., Richland, WA (USA)
[3] Emeis S 2012 Wind energy meteorology: atmospheric physics for wind power generation (Springer Science & Business Media)
[4] Berg J, Mann J, Bechmann A, Courtney M and Jørgensen H E 2011 Boundary-layer meteorology 141 219
[5] Brodeur P and Masson C 2008 Journal of Solar Energy Engineering 130 031020
[6] Bechmann A and Sørensen N N 2010 Wind Energy 13 36–50
[7] Schulz C, Klein L, Weihing P and Lutz T 2016 Journal of Physics: Conference Series vol 753 (IOP Publishing) p 032016
[8] Shamsoddin S and Porté-Agel F 2017 Boundary-Layer Meteorology 163 1–17
[9] Britter R, Hunt J and Richards K 1981 Quarterly Journal of the Royal Meteorological Society 107 91–110
[10] Tsaligoglou C, Barber S, Chokani N and Abhari R S 2012 Journal of engineering for gas turbines and power 134 122601
[11] Lutz T, Schulz C, Letzgus P and Rettenmeier A 2017 Journal of Physics: Conference Series vol 854 (IOP Publishing) p 012029
[12] Raasch S and Schrotter M 2001 Meteorologische Zeitschrift 10 363–372
[13] Kroll N, Rossow C C, Becker K and Thiele F 2000 Aerospace Science and Technology 4 223–237
[14] Shu C W 1998 Advanced numerical approximation of nonlinear hyperbolic equations (Springer) pp 325–432
[15] Kowarsch U, Keßler M and Krämer E 2013
[16] Weihing P, Schulz C, Lutz T and Krämer E 2017 Journal of Physics: Conference Series vol 854 (IOP Publishing) p 012049
[17] Meister K, Lutz T and Krämer E 2014 Journal of Physics: Conference Series vol 555 (IOP Publishing) p 012071
[18] Jameson A, Schmidt W, Turkel E et al. 1981 AIAA paper 1259 1981
[19] Troldborg N, Sørensen J N, Mikkelsen R and Sørensen N N 2014 Wind Energy 17 657–669
[20] Mann J 1994 Journal of fluid mechanics 273 141–168
[21] Jameson A 1991 AIAA paper 1596 1991
[22] Edwards J R and Chandra S 1996 AIAA journal 34 756–763
[23] Weihing P, Letzgus J, Bangga G, Lutz T and Krämer E 2016 Symposium on Hybrid RANS-LES Methods (Springer) pp 309–380
[24] Barthelmie R, Wang H, Doubrawa P, Giroux G and Pryor S 2016 Wind Energy
[25] Troldborg N, Sørensen N, Norkaer J and Mikkelsen R F 2008 Dissertation
[26] Stull R B 2012 Springer Science and Business Media 13