Wind turbine wake inflow over a heterogeneous forest - comparison between measurement and LES simulation

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Abstract. In this work a new step in understanding the wind turbine (WT) wake behavior on forested areas is made. For this analysis, a pair of real scale WTs located on a site with moderately complex terrain and heterogeneous forest is simulated using Large Eddy Simulation (LES). This simulation is compared with met mast and power output measurements of two WTs in Ryningsnäs, Sweden, considering near neutral stratification in the atmospheric boundary layer (ABL). Three validation steps are followed; first, the undisturbed wind profile is compared with met mast data and another similar LES code. Then, the wake for each WT impacting on the met mast at different directions is addressed. A feature of this pair of WTs is that these have different hub heights, but the same rated power and rotor diameter, which helps provide insight into how the tip clearance over the forest affects the operation and wake characteristics. Finally, power output deficits when the WTs are operating in each others wakes are compared to observed power deficits. For these simulations SOWFA, the OpenFOAM project for wind farms simulation in ABL, is used. In this code, three new additions are made; the forest model, the mesh modification for complex terrain and the representation of the WT using an actuator disc model with local force adaptation for wind farm flows. The simulation results show a good performance on quantitatively and qualitatively capturing the velocity in the wake, but for TKE the simulation underestimates the magnitude, and fails to match the measured structure of the wake for one of two WTs. The power deficit on the impacted WTs is well captured, despite the complexity related to turbines with different hub heights. This study makes one of the first steps on validating LES simulations for wind farms in forest.

1. Introduction

The high-fidelity Large Eddy simulation (LES) of wind farms has made it possible to carry out several studies on the wind turbines (WTs) wakes within the atmospheric boundary layer (ABL) [1–3]. For countries covered with a large share of forest, like Sweden with a 70 % forest cover [4], one of the main interests to study is how the forest interacts with the ABL and the WT wake [2, 3]. In the modeling of traditional wind energy sites, the land or sea surface is modeled with a boundary condition characterized through the roughness-length parameter, \( z_0 \) [5]. On the other hand, the trees that integrate the forest land cover represents an elevated momentum absorption that differ from traditional surfaces since the exchange may be distributed at several model heights [6]. Thus, the presence of the forest increases the interaction between the air and the surface, remarking the importance of a proper surface characterization for wind power modelling; for example, both the strong wind increase with height (vertical wind shear) and high
turbulence level associated with flow above forests magnify the uncertainty in the production of WTs. In addition, the high ambient turbulence intensity affects the shape and recovery rate of the wake [2] and increases the fatigue loads [7].

Previous studies have approached the LES simulation of wind farms in forested environments on different levels of detail. Shaw and Schumann [8] were pioneers in proposing a canopy model for LES, considering the forest as a porous media which depends on the Plant Area Density (PAD) and a constant drag coefficient. Subsequently, other authors have extended the model analysis; for example [9] reveals the influence of a three-dimensional structure in PAD compared to a two-dimensional structure on the mean velocity field as well as on the turbulent quantities. Studies on how the forest density impacts the flow were also done by [10]. More recently, [6] presented a benchmark for modelling flow in heterogeneous forests which highlighted a large spread in model results despite the use of the same PAD fields and concluded that RANS closure constants and upstream domain size are important factors for accurately representing the footprint of the forest.

In contrast to bare forest model analysis, few works have addressed the simulation of WTs in forests. For example, [2] was the first to analyze the wake of a single turbine with and without forest using LES, considering a constant PAD profile and flat terrain. Another similar example with LES is the work of [3], using OpenFOAM with six WTs. There is currently a lack of studies on the interaction of WT wakes with the ABL over forest and its validation with field measurements in the literature. Given the amount of wind turbines actually built in forested regions, it is crucial to understand the wake impact on the production.

That is why in this work we undertake the simulation and validation of individual WT wakes and the interaction between WTs using LES in neutral ABL. We apply the study to the Ryningsnäs site [11], where a met mast and two WTs are installed. A feature of this pair of WTs is that these have different hub heights, but the same rated power and rotor diameter, which helps provide insight into how the tip clearance over the forest affects the operation and wake characteristics.

2. Site and measurements
This study is performed on data from the Ryningsnäs site, which has been extensively analyzed, for example, on characterizing the flow with the measurements [5, 11] and model validation [6, 12, 13]. The location of the site is in south west Sweden at 57°16’34.26” N, 15°59’12.23” E coordinates, 122 m altitude and 30 km from the south-eastern coast. The surface is characterized by a non-uniform forest land cover and moderately complex terrain. With data from the Swedish national airborne laser scanning campaign [14], the terrain topography as well as the PAD of the forest were determined, with the method of [15], both with a horizontal resolution of 10m and a vertical resolution of 1m for PAD.

The site has a meteorological mast and two WTs (WT1 and WT2). Figure 1 shows the terrain elevation relative to the altitude of the met mast and the tree heights for a region of 4.8 km x 4.7 km centered on the met mast location. This region is used for the simulation in section 3.2. The base of WT1 and WT2 are 0.55 m and 2.15 m higher than the met mast, respectively. The forest has several clearings, particularly one located in the south east of the met mast with a dimension of 400 m x 400 m [5, 6].

Regarding the WTs, the manufacture model is Nordex N90 2.5 MW. In Figure 2 the positions of the two WTs are plotted relative to the position of the met mast. Despite the fact that both WTs have the same diameter ($D = 90$ m), WT1 has a hub height ($H$) of $H = 100$ m, while WT2 has $H = 80$ m. Analyzing the relative positions of WTs and the met mast, the maximum wake impact of the WT1 and WT2 on the mast occurs at $54^\circ$ and $181^\circ$, respectively. Furthermore, the maximum wake impact of WT1 on WT2 appears at $26^\circ$ degrees, while the opposite case is at $206^\circ$. The spacing between the WTs and the met mast is quite close and similar, being
Figure 1. Study area of 4.8 km x 4.7 km. (left) terrain elevation, in relative to the particular value at met mast position, and (right) canopy height. Both maps have a horizontal resolution of 10 m.

Figure 2. (left) WT and met mast positions. (center and right) WT hub heights in relation with the sonic anemometers height.

2.05D for WT1 and 2.50D for WT2. The distance between the WTs is greater and close to the usual distances for onshore wind farms, being 4.29D for this particular case.

The mast instruments used in this work consist of six sonic anemometers located at heights of 40, 59, 80, 98, 120, and 137.7 m as well as six cup anemometers at heights of 40.1, 60.5, 80.1, 95.85, 120.75, and 137.6 m, see [5, 11] for details. 10-minute measurements are available for a total period of approximately 1 year (Nov 2, 2010 to Nov. 14, 2011). Regarding WT data, the period that overlaps with the met mast measurement is used, which corresponds to 9 continuous months (Nov 2, 2021 to Oct 1, 2011).

For the data measured in the met mast, post processing was done in the same way as described in [11], but with an averaging time of 10 minutes instead of 30. This decision is motivated by the lack of cases in the directions when wake impact occurs. From the sonic anemometers, the variables used are the average wind speed \(U\), the wind direction of the average wind \(Dir\), the turbulent kinetic energy \(TKE\), the vertical temperature flux \(w' t'\) and the friction velocity \(u^* = \left( \frac{1}{2} u' w'^2 + \frac{1}{2} v' w'^2 \right)^{1/4}\). In addition, in the cup anemometers the average wind speed \(U\) was used as well. The reference temperature \(\Theta\) was taken from the temperature sensor at 40 m.

To characterize the atmospheric stratification and single out neutrally stratified conditions the Monin–Obukhov similarity theory parameter \((z - d)/L\) is calculated at the lowest height [11], where \(z\) is the height, \(d = 11\) m is the displacement height, and \(L\) the Obukhov length,
evaluated from

\[ L = \frac{u_3^2 \Theta \kappa g w'}{\kappa gw' L}, \]  

where \( g = 9.81 \, \text{m/s} \) is the acceleration due to gravity and \( \kappa = 0.4 \) the von Kármán constant. A range of \(-0.5 < (z - d)/L < 0.2\) was used to filter the data. The uneven limits were adopted to avoid a bias towards stable stratification. The rather wide criteria was selected to limit the dependence on individual cases. The use of this particular wide criterion gives averages \((z - d)/L\) values of 0.0018, 0.0030, 0.0043, 0.0054, 0.0068 and 0.0079 at 40, 59, 80, 98, 120 and 138m height, respectively. The mean values correspond to a maximum deviation from the neutral relationship between momentum flux and wind gradient of 4 % according to the stability expressions of [16].

From the analysis of the power output in the two WTs (\(P_1\) and \(P_2\)) as a function of the upstream reference velocity, \(U_{ref}\), at each hub height (not present in this work), it was found that both WTs show a similar measured power curve for the open wind directions. When comparing these curves with the manufacturing power curve, it was found that there is a good agreement for the speed range of \(7 \pm 1 \, \text{m/s}\). More in detail, the WT1 measured power curve have differences of 11.3, 5.0 and 0.9% compared to the manufacturing power curve for \(U_{ref} = 6, 7\) and \(8 \, \text{m/s}\), respectively. In the case of the WT2 measured curve, the differences are 3.5, -6.2 and -10.1%, respectively.

3. Methodology

3.1. Wind turbine model

To simulate the WT wake, the Actuator Disc (ADM) is used, which has shown similar results compared to measurements for WT power deficit due to wake impact in a real wind farm [17]. Since only basic manufacture information is available from the WT operation, such as the thrust \(C_T\) and power \(C_P\) coefficient as a function of a reference speed \(U_{ref}\), the ADM can only includes the thrust force, \(f_n\) [18], distributed on the WT swept area, as:

\[ f_n = \frac{1}{2} \rho C_T U^2. \]  

Here, \(\rho\) is the air density and \(U_\infty\) the upstream velocity that can be assumed equivalent to \(U_{ref}\) for uniform incoming flows. From the developments made in [17, 18], this model can be improved with a numerical adaptation for complex flows, such as ABL profile and total or partial wake impact, without the need of more manufacture information. In order to do that, \(C_T\) must be estimated from the global WT working regime and \(U_\infty\) from the local conditions on the disc. This process is done by using two calibration tables previously created for the specific WT, in order to first interpolate \(C_T\) and then \(U_\infty\). The procedure to create the calibration tables can be found in [18].

The ADM forces are calculated in nodes, separated at \(\Delta_b\) along the blade, distributed in multiple artificial lines over the entire disc. The separation \(\Delta_b\) is recommended to be \(\Delta_b = 2\Delta\) [19]. The amount of lines \(n_l\) is calculated as \(n_l = \frac{2\pi R}{\Delta}\), where \(R\) is the total radius of the rotor and \(\Delta\) is the horizontal mesh resolution. Then, the force in each node, \(F_n\), is calculated as:

\[ F_n = \frac{f_n}{n_l}. \]  

To avoid numerical instability, the force in the node is then distributed on the cells (\(F_{cell}\)) using the Gaussian distribution [1],

\[ F_{cell} = \frac{1}{\varepsilon^{3/2}} \exp \left( -\left( \frac{s}{\varepsilon} \right)^2 \right), \]  

where \(s\) is the distance between the node and the center of the cell and \(\varepsilon\) is the smearing factor, which commonly is fixed as \(\varepsilon = 2\Delta\) [20].
3.2. Software configuration
The simulations are performed using the open source code OpenFOAM (version 2.3.1) and the SOWFA project [21], developed at the U.S. National Renewable Energy Laboratory (NREL). SOWFA is designed to simulate ABL flows using LES, including WTs, capping inversion of potential temperature, Coriolis force and the possibility to run neutral or other ABL stability. For this study only neutral conditions are considered and a capping inversion starting from 700 m above ground is fixed. The inclusion of the capping inversion follows the recommendation by [21], who remarks that the capping inversion in neutral conditions helps to slow the vertical growth of the boundary layer with time. A one equation eddy viscosity Sub-Grid Scale (SGS) model is chosen [22]. In this work three new features are added to the standard version of SOWFA: the forest model, the mesh adaptation for nonuniform terrain and a new ADM (in section 3.1). The forest model is based on the same formulation for LES simulation present in the Rynningsnäs modelling benchmark [6].

The simulation of each case is performed in two stages, precursor and farm [21]. The total domain size is the same for both stages, 4.8 km x 4.9 km horizontally and 1 km vertically.

(i) The precursor is first carried out with periodic conditions in order to develop the turbulent solution of the flow in the whole domain and record the inlet turbulent condition for the farm stage. It is computed in flat terrain and a horizontally uniform forest distribution with a representative vertical PAD profile from the area of interest, calculated using the horizontal average PAD at each height. The roughness length is adopted from [6], as $z_0 = 0.03m$. The mesh has an horizontal resolution of $\Delta = D/4.5 = 20 m$ and a vertical resolution that stretches with height, starting with 2.5 m, similar to [3, 6], and finishing with 60 m at the top. This horizontal resolution is similar to the one used in [6] for LES. The time step is fixed in 0.5 s, with a maximum Courant number of 0.69. The average velocity and direction in a horizontal plane at WT1 hub height is forced to match the desired value for each case and is computed for 5 hours (18000 s), following the recommendations in [23] to obtain a quasi-steady state. In the next hour and 10 min the values at the corresponding inlet faces are recorded for each time step, in order to use it for the farm.

(ii) In the farm stage, the domain is divided in two zones, the analysis and buffer zones (Figure 3). The analysis zone is determined with a margin distance of 10D from the position of the WT, being the area where the wake solution is analyzed. A buffer margin zone of 10D width is created next to the inlet and outlet faces, in order to obtain a good compatibility between the analysis zone and the border conditions. A transition margin of 5D is placed between the analysis and buffer zone. This square domain allows a minimum and maximum fetch for the met mast position of 2.3 km and 3.3 km, respectively, depending on the wind direction. In the farm the terrain, forest distribution and ADM are included, following the next steps:

(a) two mesh refinements, one in the analysis zone and another one at the ADM locations. The refinement mesh details can be seen in Figure 3. The final horizontal resolutions are $\Delta = D/18 = 5m$, $\Delta = D/9 = 10m$ and $\Delta = D/4.5 = 20m$ in the WT, analysis and outer zones, respectively. The resolution in the ADM is 18 cells along the diameter in the horizontal direction, matching a similar resolution from a previous ADM study [18]. The time step is reduced to 0.1 s, with a maximum Courant number of 0.7.

(b) non-uniform vertical and horizontal distribution of the forest PAD. This field is written using horizontal and vertical resolutions of 20 m and 2.5 m, respectively.

(c) terrain inclusion, in which the nodes in the mesh are vertically translated in order to copy the non-uniform terrain, using the process from [17]. In the buffer zone the topography is linearly vanished up to reach a constant elevation in the borders. This height is defined as the average elevation in the buffer zone, in contrast to the minimum
Figure 3. (left) terrain elevation in CFD domain, indicating the buffer and analysis zones. The elevation in the borders is defined as the average terrain elevation in the buffer zone before modification. (right) mesh refinement zones near WT1 location, using horizontal resolutions of $\Delta = 20$, 10 and 5 m for the outer, analysis and turbine zones, respectively. The cells are colored with the PAD field on a horizontal resolution of 20 m.

4. Results
Five cases with different flow directions and increasing level of complexity are simulated and compared with met mast or power output measurements. First, in section 4.1 a direction free of WT wakes is simulated, in order to validate the simulation setup compared with external results from the benchmark in [6]. Then, in section 4.2 the wake impact on the met mast for each WT case is analyzed. Finally, in section 4.3 the wake impact on the two WTs is studied, analysing the power output deficit.

4.1. Undisturbed wind profile
In this section the direction of $240^\circ$ is analyzed, comparing the average velocity $U$ and $TKE$ at the met mast position between the simulation and original measurement extracted from benchmark in [6]. This strategy allows to also compare with results from other participants of the benchmark. For this particular work, the results of the UUCG code are included [6, 13], which had the best performances in the benchmark. This in-house code is based on OpenFOAM (version 3.0.1) LES solver and some libraries from SOWFA, having many similarities with the OpenFOAM-SOWFA code used in this study. A major difference of the UUCG simulations compared to this work is the long domain size upstream the met mast (14 km) used in UUCG, that allows for a considerable forest and topography footprint on the ABL vertical profile.

In the precursor, $U = 7.4 m/s$ and $Dir = 240^\circ$ are forced at 100 m, following the case specifications from the benchmark. In the farm simulation the average velocity in the mast at 100 m is closer to the target velocity but slightly different due to terrain and forest influence, being 7.23 m/s. To facilitate comparison, $U$ is divided with the velocity in the mast closer to 100 m, $U_{100}$, following [13]. In Figure 4 (left) the average velocity plane at 100 m above the local ground is shown, where the wakes of each WT can be clearly identified. In Figure 4 (center and
Figure 4. (left) average velocity field at 100 m above local ground height, divided with the value at met mast position. (center and right) vertical profile of velocity and TKE at met mast position, comparing with measurements and LES results for strictly neutral ABL conditions extracted from [6]. Error bars indicate the 95% confidence level for the mean value.

right) the velocity and TKE from simulations is compared with the measurements at the met mast position. Despite the differences in domain size and resolution there is a close agreement between the results of this work and UUCG, with main differences found near the forest. As was shown in [9, 12], that difference may be due to the PAD resolution and distribution closer to the probe line. In [13] it was found that the low spatial resolution in UUCG made difficult to correctly predict the large shear close to the canopy top. The measurements have a closer match in the velocity profile, but for the TKE profile the simulations are under predicting the turbulence magnitude. We can see a good match between the two codes for heights related to the WT rotor sweep area, despite the fact that in this work the non uniform PAD field footprint is only 2.5 km while for UUCG it is larger, about 14 km. This finding highlights the need for a future study on the importance of the highly detailed forest foot print on the velocity and TKE vertical profiles. In [12] it was also reported that the forest density does not have a strong influence in U and TKE profiles at heights between 50 and 200 m.

4.2. Single wake

For each single wake impact of WT1 and WT2 over the met mast the measurements are filtered for the periods when the WT output is related to $U_{ref} = 7 \pm 1$ m/s in addition to the selection on $(z - d)/L$. Then, cup and sonic anemometers average velocity $U$ is plotted for a direction range of $\pm 50^\circ$, every $5^\circ$ with an average window of $\pm 2.5^\circ$, centered in the direction of maximum wake impact. The velocity $U$ is divided by the reference velocity at hub height $U_{ref}$. The direction is extracted from the sonic measurements at hub height. Also the TKE from the sonic anemometer is shown, using the same filtered data set. 95% confidence level for the mean value are added to the sonic measurements.

For the simulations, only one direction is simulated for each case and the variables are extracted in points distributed in arcs at the instrument heights for the met mast. The precursor is set in order to force $U = 7m/s$ and $Dir = 54^\circ$ at $H = 100$m for the WT1 case, while for the WT2 case $U = 7m/s$ and $Dir = 181^\circ$ at $H = 80$m are forced. In the farm stage, the velocity in the mast at 100 m is $U_{ref} = 7.09m/s$ for the WT1 case and $U_{ref} = 6.93m/s$ at 80m for the WT2.

Figure 5 presents the comparison when the WT1 wake impacts the met mast. The maximum measured velocity deficit at hub height is 35 %, taking into account a $\pm 5^\circ$ range. It can be noticed that there is a good agreement in the velocity deficit between measurements and the simulation with most of the simulated values falling within or close to the 95 % confidence interval.
of the measurement average. When $TKE$ is compared, more differences are found, especially in the wake where the measurements indicate a larger $TKE$, with a more pronounced difference between the middle and the edge of the wake. The corresponding comparison for WT2 is shown in Figure 6. The maximum measured velocity deficit at hub height is 47 %, a larger velocity deficit compared to the observation in the wake of WT1. This difference is related to the closer distance between the WT2 hub height and the forest, changing the wake recovery. The velocity deficit from the simulation is slightly underestimated for heights closer to the hub height ($H = 80$ m). Similar to the WT1 case, the underestimation of $TKE$ in the wake is also seen, but the structure is closer to the observed, with the simulations tending towards two distinct peaks at heights close to the hub height.

4.3. Wind turbine power deficit in the wake

The WT power deficit in the wake is analyzed by comparing the power output between WT1 ($PT_1$) and WT2 ($PT_2$) for the directions where the WTs are aligned. The measured periods are selected when the output of the undisturbed WT is corresponding to an inflow within $7 \pm 1$ m/s. The direction is obtained from the sonic anemometer at the hub height of the upstream turbine. The deficit values are averaged every $5^\circ$ with an average window of $\pm 2.5^\circ$. For the simulations, the precursor is forced to $U = 7$ m/s and $Dir = 26^\circ$ at $H = 100$ m when WT1 is upstream, and $U = 7$ m/s and $Dir = 206^\circ$ at $H = 80$ m when WT2 is upstream. The results are shown in Figure 7. Due to the fact that the WT1 hub height is 20 m taller than WT2, the ratio in the undisturbed directions $PT_1$ is not 1, but rather 0.78 for $PT_2/PT_1$ and 1.28 for $PT_1/PT_2$. For $PT_2$, the wake impact is observed in a $40^\circ$ wide direction range, with a maximum measured $PT_2$ reduction of 53.0 %. For $PT_1$, the wake impact occurs in a narrower $30^\circ$ wide direction range, with a maximum measured $PT_1$ reduction of 35.2 %. The results obtained from the simulations for both the magnitude and direction of the maximum wake impact has a good agreement with the measurement for both of the WTs.
5. Conclusions
In this work a novel study on wind turbine wakes is carried out for a real site covered with forest. Large Eddy Simulations are compared with met masts and two wind turbines power output measurements for different directions, including open and wake impact cases. The simulation results show a good performance on capturing the velocity profile on the wake, but underestimating the $TKE$. The power deficit on the impacted wind turbine is close to measured values, despite the complexity related to turbines with different hub heights. As future steps, it is necessary to address the possible sources that produce the discrepancy between the measured and simulated $TKE$ in the wake region. Between the possible causes, we can list the mesh resolution, the PAD foot print, and the normal forces distribution in the actuator disc model.
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