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3D-simulation of the turbulent wake behind a wind turbine

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Abstract. The paper relates to the simulation of the airflow around a wind turbine (WT) of the type ENERCON E66 with emphasis on the turbulent wake. The simulations were undertaken with the Computational Fluid Dynamics (CFD) software ANSYS FLUENT 6.3 using the LES technique for turbulence modeling. It is the aim of the work to capture the full three-dimensional turbulent flow behind a WT in a sufficient spatial and temporal resolution to generate information for wind loads of WTs in wind farm configuration. This information shall help to optimize wind farm layouts in the future. Using an incoming wind field that matches the requirements of the IEC-61400 for wind fields used in load calculations it was possible to simulate a full meandering turbulent wake. The turbulent features of the WT wake could be reproduced with numerical methods not using further assumptions but solely based on the WT geometry and the solution of the governing physical equations. The project is supported by ENERCON GmbH, Germany.

1. Introduction
The international IEC standard 61400-1 [1] defines wind turbine (WT) classes in terms of wind speed and turbulence parameters. The intention of the classes is to cover most applications. The main parameters are the reference wind speed average over 10 minutes (v_{ref}) and the expected value of the turbulence intensity at 15 m/s (I_{ref}). The latter one is defined as ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed and in this context defined over a 10 minute period of time.

Within wind farms WTs are subject to the influence of nearby turbines, which may affect their loading, durability and operation. The assessment of the suitability of the wind turbine at a site in a wind farm shall take into account the deterministic and turbulent flow characteristics associated with single or multiple wakes from upwind machines, including the effects of the spacing between the machines, for all ambient wind speeds and wind directions relevant to power production.

The increase in loading generally assumed to result from wake effects may be accounted for by the use of an effective turbulence intensity, which shall include adequate representation of the effect on loading of ambient turbulence and turbulent wake effects. For fatigue calculations the standard gives an empirical formula to calculate the effective turbulence intensity as a superposition of wake and non-wake situation using the Wöhler (SN-curve) exponent for the considered material.

Calculation of the turbulence intensity inside the wake is based on the common approach that the ambient turbulent energy and the additional turbulent energy generated by the turbine are additive. The maximum centre-wake, hub height turbulence intensity typically depends on wind speed, WT thrust coefficient and distance to the neighboring turbine.
The empirical formula to calculate the effective turbulence intensity as given in the standard is designed to cover most applications and should result in conservative loads in cases where the effective turbulence intensities within the wind farm exceed the design values and the fatigue loads need to be recalculated. However, the load calculation process requires a three vector component turbulent wind velocity field. No model exists at the moment to describe a turbulent wind field within the full extent of the wake. Measured data are typically collected with a single mast to hold the anemometers. This means no information is given to account for the spatial correlation structure of the velocity components. As the turbulent wind model may affect the loads significantly further information need to be obtained.

It is the general approach of this work to validate a Computational Fluid Dynamics (CFD) model of a single wake in order to close this lack on information. Calculations are focused on a wind turbine (WT) of the type ENERCON E66 to compare to data collected by ultrasonic anemometers during a research project of the “Deutsche Institut für Bautechnik” [2], which is the German authority that draws up the technical rules in the field of civil engineering.

2. CFD-Model
The CFD-model contains the full geometry of the WT which is tower, nacelle and the rotor. The blade geometry itself is based on a set of 2D-profiles and gives a reasonable representation of the aerodynamic relevant structure. However, it was not the intent to generate a full aerodynamic model of the blades, which would be able to reproduce lift, drag and overall power coefficients, as the computational effort needed would have been to expensive in the context of this work. The aerodynamic forces can therefore not be used to calculate rotor speed. The rotor speed was instead fixed at a constant value, which corresponds to the mean wind speed at hub height of the incoming wind field.

The computational domain extends from approximately one rotor diameter upwind to three rotor diameter downwind of the WT, which is sufficient for the validation process with the data of [2] taken at 2.06 rotor diameter behind the WT. The rotating part of the nacelle and the rotor are inserted in a dynamically meshed volume with sliding interfaces to the rest of the computational domain. The boundary layer on the blades is meshed with several layers of prismatic cells. As pointed out before, the boundary layer does not sufficiently resolve the flow field within the high speed areas of the blade. However the computational effort would have not been reasonable with respect to the impact on the flow field downstream, although this should be kept in mind as one area of possible improvement. Outside the boundary layer polyhedral cells are used for meshing. An impression of the computational grid is given in figure 1. The total number of computational cells amounts to 4.05 million.

The simulations were undertaken with the Computational Fluid Dynamics (CFD) software ANSYS FLUENT 6.3 using the LES technique for turbulence modeling at a time step size of 0.1 seconds. The Smagorinsky-Lilly model was chosen as subgrid scale model. The incoming flow field was specified using a three component von-Karman turbulent wind model including wind shear, which is common praxis in BEM-based (blade element momentum theory) modeling of WT for load calculations. The ten minute averaged turbulence intensity was set at 0.1 in correspondence to measured mean values of ambient turbulence intensity on the site. Mean wind speed at hub height was 10m/s.
3. Results - qualitative

A total of 470 seconds of physical time have been simulated. Approximately the first 50 seconds which have not been used for analysis but they were needed to establish the wake in the model. Figure 2 and 3 give a snapshot of the unsteady turbulent wake and show contour plots of velocity magnitude ranging from 4 to 14m/s. White areas denote wind speeds outside this range, which in figure 2 and 3 are areas of low wind speed in the vicinity of the walls and close downstream of the tower.

Although the qualitative behavior of the wake can best be visualized in an animation the figures can serve to point out the main results:

- The wake meanders horizontally and vertically and is sufficiently smaller than known from measurement data averaged over ten minutes. I.e. the broadening of the wake as observed in this data is a consequence of the meandering and not present on smaller time scales.

- Tip or nacelle vortices are only slightly present in the near wake area. However there is a region downstream of the nacelle with hardly any or only slight wind speed reduction. The extent of this region varies significantly with time. The wake is accompanied with areas of wind speed acceleration as can be expected of a structure, which despite of its visually light appearance forces part of the flow to pass around. The relatively high velocity gradients experienced at either the outer and inner edges of the wake in conjunction with the meandering contribute much to the turbulence intensity observed on a ten minute time scale.

These points will be further demonstrated in the next chapter.
Figure 2: Contours of velocity magnitude in m/s at an average $v_{in}$ of 10m/s at hub height (snapshot in a vertical plane).

Figure 3: Contours of velocity magnitude in m/s at an average $v_{in}$ of 10m/s at hub height (snapshot in a horizontal plane).
4. Validation
Longitudinal, vertical and horizontal components of wind speed have been measured in [2] at hub height, hub height minus half rotor radius and hub height minus one rotor radius 2.06 rotor diameter downstream of the WT. However only data at hub height in the range of 4 to 8 and 8 to 12m/s wind velocity were available for validation. The latter set of data was used for comparison with the simulation at 10m/s.

In figures 4 to 7 every point denoted with a red cross represents one ten minute mean value of either velocity magnitude or local turbulence intensity. The abscissa denotes wind direction, with the met mast and thus the center of the wake located at 305°.

Figure 4: Measured data of velocity magnitude at hub height, incoming velocity 8-12m/s. Comparison of 10-minute mean values to 20-second mean values of simulated data (incoming velocity 10m/s).

Figure 5: Measured data of local turbulence intensity at hub height, incoming velocity 8-12m/s. Comparison of 10-minute mean values to 20-second mean values of simulated data (incoming velocity 10m/s).
Figure 4 and 5 show a comparison of these values to the 20 second mean values taken from the simulation. It can be seen that the extension of the wake as well as the turbulence level is significantly smaller compared to the ten minute measured mean values as pointed out in the previous chapter.

With increasing the time used for averaging velocity magnitude and turbulence intensity in the simulation data the differences gradually diminish.

Figure 6 and 7 show a comparison of measured values to the 7 minute mean values taken from the simulation.

**Figure 6**: Measured data of velocity magnitude at hub height, incoming velocity 8-12m/s. Comparison of 10-minute mean values to 7-minute mean values of simulated data (incoming velocity 10m/s).

**Figure 7**: Measured data of local turbulence intensity at hub height, incoming velocity 8-12m/s. Comparison of 10-minute mean values to 7-minute mean values of simulated data (incoming velocity 10m/s).
The shape of both curves smoothly fit to the measured data, although only the lower values of wind speed deficit and turbulence intensity are represented. This difference may result from different sources:

- **Limitations of the model:**
  - The computational grid is still rather coarse. No grid sensitivity check could be carried out due to the limitations of computer resources. The influence of this effect is therefore unknown.
  - Both tower and blade are perfectly stiff within the simulation. The influence of this on the wake is hard to estimate.
  - Rotor speed and pitch are kept constant during simulation and are not adjusted according to the control system of the WT. The authors believe that this will significantly change the results especially in situations where pitch regulation comes into effect.

- **Inlet boundary conditions:**
  - The three component von-Karman model does not represent the state of the art of turbulent wind field modeling as recommended in [1]. It is not known to what extent the model differs from the real wind field properties. But it is quite obvious, that an increase in wind direction changes will both broaden the wake and raise the turbulence level on a ten minute time scale.

- **Measured data:**
  - The measured data represents a much broader range of flow conditions concerning ambient turbulence intensity and average wind speed compared to the single simulation test case. However no clear or only little trend was visible when limiting the range of wind speed to the range of 9.5 – 10.5m/s or the measured ambient turbulence intensity to the range of 0.09 – 0.11.
  - Some of the more extreme points of measured turbulence intensity in figure 4 – 7 might result from situations with a wind speed trend during the ten minute interval. To our knowledge no detrending of data was performed.

![Figure 8: Example of measured (left) and calculated (right) time series of velocity components at hub height, hub height minus half rotor radius and hub height minus rotor radius (v and x = longitudinal, u and y = lateral)](image)
Figure 8 shows a first promising comparison of measured and calculated time series of the longitudinal and lateral velocity components at hub height, hub height minus half rotor radius and hub height minus one rotor radius. A detailed analysis of this data concerning frequency spectrum etc. has not yet been performed.

5. Conclusion
Using an incoming wind field that matches the requirements of the IEC-61400 for wind fields used in load calculations it was possible to simulate a full meandering turbulent wake. A few minutes of physical time have been calculated and compared to measurements. The local values of turbulence intensity and velocity magnitude inside the wake match the measurements quite well.

A limitation of the model at the current stage is the manual adjustment of pitch angle and rotor speed to the incoming wind, which itself may still deviate from the real turbulent wind. These points probably account for the differences left in comparison to the measurements. The main results extracted from the simulation so far are:

- The wake meanders horizontally and vertically and is sufficiently smaller than known from measurement data averaged over ten minutes.
- Tip or nacelle vortices are only slightly present in the near wake area. The relatively high velocity gradients experienced at either the outer and inner edges of the wake in conjunction with the meandering contribute much to the turbulence intensity observed on a ten minute time scale.
- The analysis of the data shows that a time span of at least five minutes is recommended, if the averaged values shall be compared to measured ten minute mean values.

The model of the full three-dimensional turbulent flow behind a WT can provide enough data on a spatial and temporal resolution to predict the loads in wake situations more precisely. This will help to optimize wind farm layouts in the future.

6. References

[1] IEC 61400-1 ED. 3: WIND TURBINES - PART 1
[2] Deutsches Institut für Bautechnik DIBt; Untersuchung des Nachlaufes von Windenergieanlagen und dessen Auswirkung auf die Standsicherheit der benachbarten WEA in Parkaufstellung; Forschungsvorhaben P 32-5-3.78-1007/02