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Power deficits due to wind turbine wakes at Horns Rev wind farm

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Abstract

The wind turbine operational characteristics, power measurements and the meteorological measurements as 10 minute statistical data from Horns Rev offshore wind farm have been identified, synchronized, quality screened and stored in a common database. A number of flow cases have been identified to describe the flow inside the wind farm and the flow deficits along rows of wind turbines have been determined for different inflow directions and wind speed intervals. Furthermore the maximum power deficit has been determined as function of ambient turbulence intensity.

Keywords: wind farms, offshore, measurements, power deficits.

1 Introduction

A detailed analysis of the atmospheric conditions and the flow deficit due to wind farm wakes has been investigated inside the Horns Rev offshore wind farm in Denmark as part of the EU funded research project UPWIND, WP8: FLOW. Although the flow conditions inside Horns Rev wind farm have already been investigated [1], recent release of two years additional data have increased the database size and enabled an examination of wakes with a higher resolution in terms of wind speed, wind direction and stability.

Data are analyzed for different directions, which results in varying numbers of aligned turbine and different turbine spacing. Results of the analysis documents the dependence of the power deficit magnitude of the ambient turbulence and how the power deficit varies for 7D and 10D spacing. Further data processing has been undertaken to identify potential flow cases, which are applicable for evaluating CFD models or with engineering park flow models e.g. WAsP® and WindFarmer®. Recent analysis has been initiated to evaluate the impacts of atmospheric stability and turbine spacing on the magnitude of the power deficit induced by wind turbine [4].

2 Wind farm layout

Horns Rev is a 160 MW wind farm, 14 km from the west coast of Denmark as shown on Figure 1, with a water depth of 6-14 m. The wind farm comprises 80 wind turbines, which are arranged in a regular array of 8 by 10 turbines.

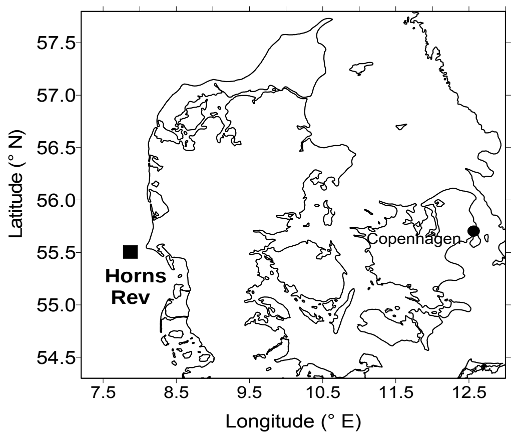

Figure 1: Location of the Horns Rev wind farm in Denmark.

The Horns Rev (HR) has a shared ownership by Vattenfall AB (60%) and DONG Energy AS (40%). The wind turbines are installed with an internal spacing along the main directions of 7D, as shown on Figure 2. The diagonal wind turbine spacing is between 9.4D and 10.4D. Figure 2 furthermore illustrates the location of the offshore masts associated to the wind farm. Mast M2 was installed prior to the wind farm installation to document the wind conditions [2], while M6 and M7 were installed as part of the Horns Rev wind farm wake measurements program [3]. This investigation is mainly based on top mounted cup anemometers corresponding to the wind turbine hub height of 70 m.

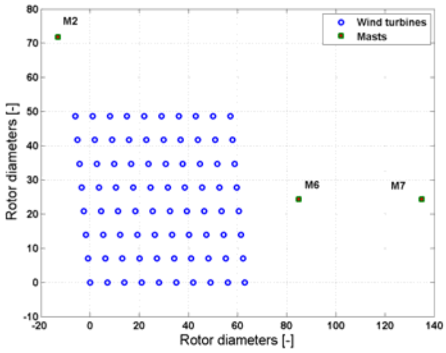

Figure 2: Layout of Horns Rev wind farm including location of three nearby offshore masts: M2, M6 and M7.

The meteorological measurement setup has been detailed in these references and a huge database with synchronized meteorological and wind turbine measurements has been established. The wind conditions prior to the installation of the wind farm have been documented in [2]. The analysis will focus on flow situations where the wind comes from a western direction with very large fetch (>500km).

2.1 Wind turbines

The wind farm comprises VESTAS V80, which are a 2MW pitch controlled, variable speed wind turbines with a diameter of 80m and 70m hub height. Huge amount of channels are recorded continuously on each turbine with the SCADA system. Afterwards a limited number of channels have been extracted from the SCADA database and stored as 10 minute statistics to investigate the operational behavior and wind farm flow together with the [external] meteorological observations. From each wind turbine the following data are available to describe the wind turbine operational conditions: Electrical power, rotor speed, pitch angle, yaw position, yaw misalignment and the wind speed measured on the nacelle as 10 minute statistical values.

The [official] power and thrust coefficient curves as function of wind speed are shown on Figure 3. The operational mode is characterized with a variable rotor speed and variable pitch angle, as shown on Figure 4.

The operational characteristic on Figure 4 includes an indication of the operational characteristics for two wind turbines, where the [wake] wind turbine operates in the wake of the [upwind] wind turbine. The figure illustrates the difference in operational characteristics due to the speed deficit, which need to be taken into consideration when simulating flow cases.

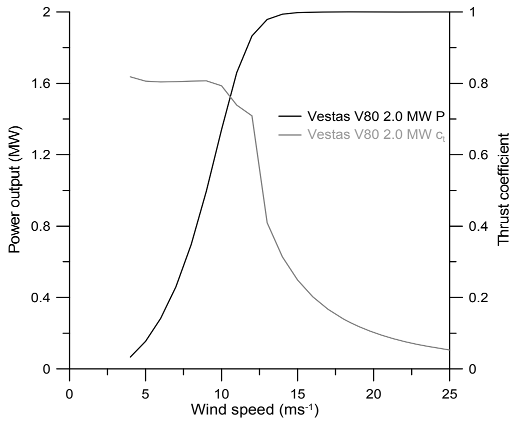

Figure 3: Power curve and thrust coefficient curve for the VESTAS V80 2MW wind turbine.

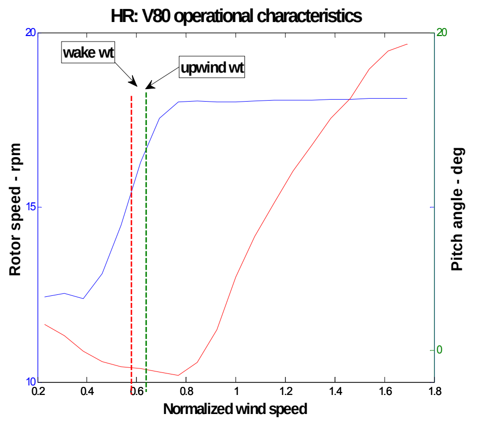

Figure 4: VESTAS V80 rotor speed and pitch as function of normalized wind speed.

2.2 Quality of measurements

The Horns Rev measurement systems have been in operation for several years and not all instruments have been calibrated or even quality controlled regularly. This means that signal quality control is highly required and some of the procedures presented in [5] have been implemented in this project. Below is a summary of potential problems or uncertainties related to the measurements.

Mast M2, height 62m: The instrumentation has been in operation since 1999 with regular calibration and inspections, but the signal control has decreased during the recent years and the data acquisition system was stopped completely in the beginning of 2007. Furthermore many periods of wind direction measurements have been erroneous from 2005 to 2007, which results in a lack of reliable wind direction measurements for the western inflow sector.

Mast M6, height 70m: The instrumentation has been in operation since 2004 with regular calibration and inspections.

Mast M7, height 70m: The instrumentation has been in operation since 2004 with regular calibration and inspections.

Wind turbines, hub height 70m: Most instruments are part of the SCADA system and have been regular supervised, but the exact calibration information has not been distributed. None of the wind turbine yaw position signals have been calibrated and include large offset errors. Due to a lack of wind direction measurements, it has been necessary to derive a wind direction signal based on wind turbine yaw position and the power deficit distributions. This results in an increased uncertainty, because the result depends both on the wind turbine control algorithm and an acceptable yaw misalignment. The total uncertainty on the wind direction signal includes contributions from the instrument, the wind turbine control settings and the skewed wake flow along the nacelle and has been estimated to be at least than 5 degrees.

2.3 Database

The Horns Rev database includes 10 minute statistics of wind speeds, directions and other meteorological parameters both from mast M2 and two 'wake masts' 2 and 6 km to the west of the array. Data from individual wind turbines include power values and operational wind turbine signals eg. rotor speed and pitch angle. All the statistical data are organized in a database and have undergone quality screening before use.

2.4 Flow conditions

The flow conditions expressed in term of atmospheric stability classes, have been difficult to establish due to lack of high quality temperature measurement. During the initial measuring period the atmospheric stability classification were based on 3D sonic measurements, recorded during 2003 – 2005 at 50 m height on M2 [2]. Unfortunately it has not been possible to merge these stability measurements with the wind farm production data due to a lack of time overlap. This requires another approach, which will be tested and presented as part of another investigation [4].

The Obukhov length, L has been derived from the sonic measurements and the atmospheric stability classification has been determined according to the definitions given in Table 1.

Table 1: Definition of stability classes based on Obukhov length, L .

Obukov length interval [m]	Atmosperic stability class
-100 <=L <= -50	Very unstable (vu)
-200 <=L <= -100	Unstable (u)
-500 <= L <= -200	Near unstable (nu)
|L|>500	Neutral (n)
200 <= L <= 500	Near stable (ns)
50 <= L <= 200	Stable (s)
10<= L <= 50	Very stable (vs)

The resulting stability distribution, based on 3D sonic measurements, is show in Figure 5. The figure shows a dominant occurrence of near neutral/unstable (nu) conditions for the western inflow sector.

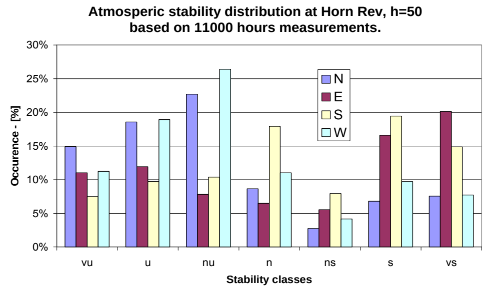

Figure 5: Stability distribution for Horns Rev M2, z=50m, for 2003 – 2005.

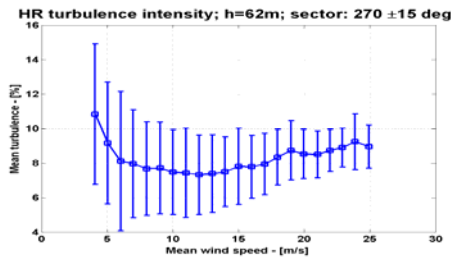

Figure 6: Turbulence intensity, binned as function of mean wind speed for Horns Rev M2, h=62m. Sector = 270 ±15 deg.

The turbulence intensity representing westerly inflow to the wind farm at 8 m below hub height is shown in Figure 6. The turbulence distribution represents a limited inflow sector of 270 ±15 deg and measurements have not been detrended. Preliminary studies of the turbulence conditions around Horns Rev indicate a small increase in the turbulence intensity from 8 to 10 % in the wake of the wind farm according to [1].

3 Flow characterization

The flow deficit is determined on three different levels 1) interaction between two neighboring wind turbines; 2) flow along a row of turbines and 3) for different atmospheric conditions.

The flow deficit is defined as the power deficit due to a lack of representative wind speed measurements from inside the wind farm. The power deficit (η_p) is defined in (1),

$$\eta_p = \left[1 - {P_{wake}}/{P_{free}}\right] \qquad (1)$$

And ranges between 0 and 1. The deficit is determined as function of flow direction based on 10 minute mean power values for two [neighboring] wind turbines (wt07 & wt17). The power values are filtered to exclude periods where either of the turbines have been offline or partly offline (eg inside start or stop sequences). Due to a lack of nearby reliable wind speed signal, the power value from the free wind turbine is used with reference to the power curve (Figure 3) to define the wind speed interval.

3.1 Flow interaction between two neighboring wind turbines

The power deficit values averaged with a 5 degree moving window technique have been extracted as function of the wind direction and have been fitted with an expression:

$$f(\theta) = a_0 + (a_1 + a_2 \times \theta + a_3 \times \theta^2) \times \exp(-a_4 \times \theta^2) \qquad (2)$$

The fitted function is shown on Figure 7 for a 7-9 m/s wind speed interval. This deficit expression is characterized with 2 descriptors; 1) the maximum deficit (0.41) and 2) the wake width of 28 deg, which is determined as the 95% confidence level.

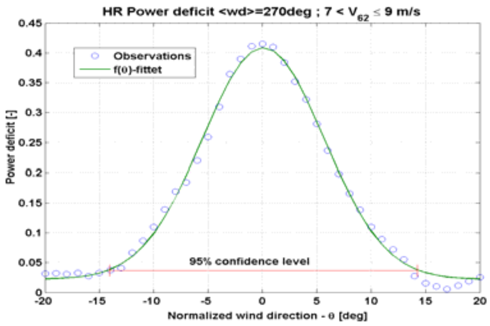

Figure 7: Horns Rev power deficit, as function of normalized wind direction for wind turbines 17 and 07 with a spacing of 7D.

Table 2 summarizes the main flow characteristics for 5 different wind speed intervals and it is important to highlight the correlation between the wind turbine operational speed ratios and the flow characteristics.

Table 2: Horns Rev flow characteristics for 7D spacing. Sector = 270±20 deg.

V_{hub}	Max {deficit}	Wake width
3-5 m/s	0.50	29 deg
5-7 m/s	0.41	30 deg
7–9 m/s	0.41	28 deg
9–11 m/s	0.36	25 deg
11–13 m/s	0.31	25 deg

3.2 Power deficit as function of turbulence

The maximum power deficit and the wake size in Table 2 depends on the ambient turbulence intensity and the wind turbine thrust. The thrust highly depends on the wind speed as shown on Figure 3 but also on the rotor speed and the pitch angle setting.

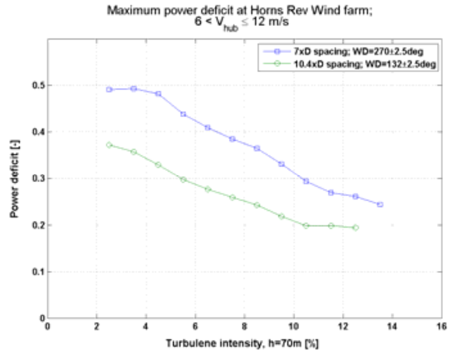

Figure 8: Maximum power deficit for 7D and 10.4D spacing at Horns Rev – as function for turbulence intensity.

The large amount of recordings enables a determination of the power deficit as function of the ambient turbulence intensity. Figure 8 demonstrates a strong correlation between the ambient turbulence, maximum deficit and the internal spacing. The curves on Figure 8 represent two different spacing, which seems to converge above 18-20% turbulence intensity. The number of available measurements are limited both at low turbulence (<4%) and at high turbulence (>12%); but it has been possible to determine the flow deficit distribution as function of direction for the medium turbulence interval (8 – 12%) - as shown on Figure 9. The figure demonstrates how the wake size increases with the turbulence, demonstrating increa-sed turbulent mixing of the wake.

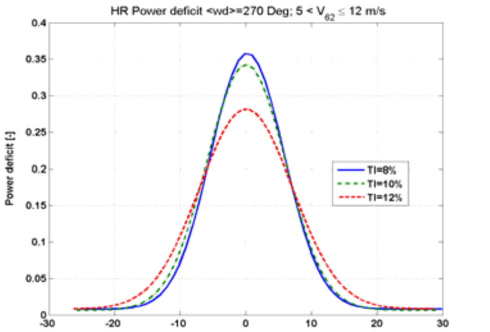

Figure 9: Power deficit as function of normalized wind direction for different turbulence levels.

3.3 Power deficit along rows of wind turbines

A number of flow cases have been formulated to enable a validation of the engineering codes and the commercial CFD models towards measurements as reported in a previous paper [6].

The flow cases are limited to a western inflow sectors (wdir=255, 260,,.., 285±2.5 deg.) and to three distinct wind speed intervals: 6±0.5 m/s, 8±0.5 m/s and 10±0.5 m/s to avoid modeling the power controller. All flow simulation models assume wind turbine operation with constant rotor speed and constant pitch angle in these wind speed intervals, despite what is documented on Figure 4.

The power deficit along a row of turbines has been determined for 7 x 3 different flow cases. The total inflow sector of 270±15 degrees is applicable for the engineering models, the default is a wind direction range of 30 degrees and this can be modified e.g. in WAsP the maximum number of sectors is 36 giving a minimum 10 degree wind direction range. Before the measurements can be included, a number of filtering criteria have been implemented:

i) Reference wind turbine wt07 is grid connected 100%,

ii) Object wind turbine is grid connected 100%,

iii) All upwind, wake generating wind turbines are grid connected 100%

iv) Flow stationarity throughout the whole wind farm.

Where clause iv) flow stationarity is reached when two consecutive observations belongs to the same flow case e.g. $7.5 < V_{hub} \leq 8.5$ m/s & $277.5 < W_{dir} \leq 282.5$ deg. The second period will then be acceptable for our analysis.

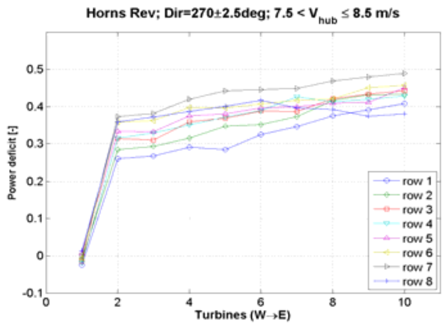

Figure 10: Power deficits along a row of 10 wind turbines for a small inflow sector of 5 deg.

The flow deficits are shown on Figure 10 for 8 rows. Row 1 is the northern W→E row with wt01 as the free wind turbine. All deficits are determined with reference to wt07 and include all stability situations. Figure 10 shows a distinct power deficit between col 1 and col 2 turbines of 35%, while the deficit increases moderately up to 45% through the remaining columns. There is a small lateral shear along the inflow column of turbines, because these values are not exactly 0 as seen on Figure 10.

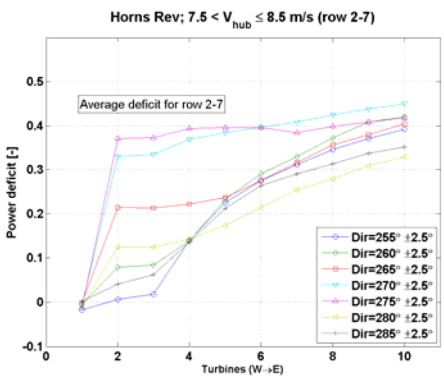

Figure 11: Averaged power deficits for 7 inflow sectors, V_{hub} =8 m/s.

Figure 11 shows the averaged deficit for each inflow sector at 8 m/s. Dir= 270±2.5° represents the averaged flow along row 2-7 shown from the previous figure. Row 1 and row 8 have been excluded to avoid "wall" effects from the border rows, which increases when flow sectors differs from 270 degrees.

Figure 11 illustrates how the power deficit decreases with inflow sectors deviating from 270°, but the power deficit along col 10 always tend to be 40±5% for this wind speed.

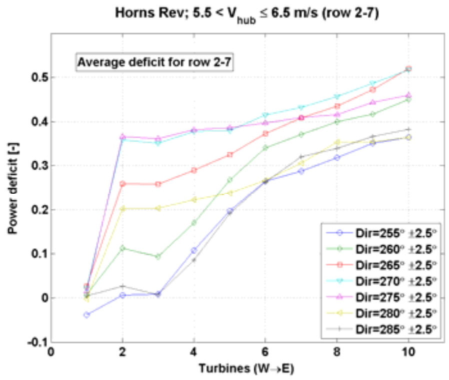

Figure 12: Averaged power deficits for 7 inflow sectors, Vhub = 6 m/s.

Figure 12 and Figure 13 shows the averaged power deficit for 6±0.5 and 10±0.5 m/s wind speed intervals respectively. The maximum deficit for each wind speed interval decreases with increasing wind speed.

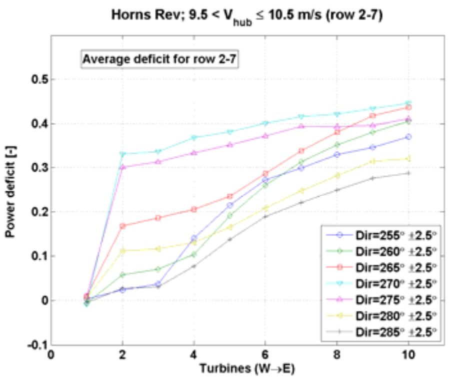

Figure 13: Averaged power deficits for 7 inflow sectors, V_{hub} = 10 m/s.

4 Conclusions

Characterization of the power deficit for westerly inflow to the Horns Rev wind farm shows that each wind turbine generates a flow deficit sector of 25-30 degrees, where sector size depends both on the mean wind speed and the turbulence. The analysis shows a distinct linear relation between maximum deficit and the turbulence intensity where the slope highly depends on the wind turbine spacing. The mean power deficit along wind turbine rows is similar in the wind speed interval from 6 to 10 m/s and for the same inflow direction, but the maximum deficit decreases with increasing wind speed.

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