Heat and Flux

Analysis of field measurements

K. Boorsma

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Abstract

This report gives a description of the work done within the framework of the FLOW project on Heat and Flux. Hereto available field measurements at the ECN wind turbine test site EWTW are analyzed.

Acknowledgement

This work is subsidized by the FLOW programme under project number 5.1440. Leo Machielse is acknowledged for providing his analysis of the measured field data. Edwin Bot, Arno vd Werff and Gerard Schepers are acknowledged for their assistance during interpretation of the results.

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Introduction

ECN holds a patent for the 'Heat and Flux' concept. This concept aims at maximizing the power output of a wind farm by adjusting the axial induction of the windward turbines below their individual optimum for power production. This will reduce the velocity deficit and turbulence in the wake and increase the output of the downwind turbines. Other benefits are decreased average loading of the upwind turbines and decreased fatigue loading of the turbines in the wake.

The reported activities aimed at the quantification of the effects of 'Heat and Flux' farm control. To this means field measurements at the ECN Wind Turbine Test Site Wieringermeer (EWTW) are analyzed from December 2004 until April 2009. These field measurements have been analyzed before in [7, 2]. Questions regarding the validity and usability of these results have initiated the current study.

First the test site is described in section 2. The adopted data reduction procedure is highlighted in section 3. The results are discussed in section 4 followed by conclusions and recommendations.

2

EWTW

The EWTW farm [5] consists of a row of five 2500 kW turbines with variable speed-pitch regulated control. These turbines have a diameter and a hub height of 80 m and are placed at mutual distances of 3.8 rotor diameters. The EWTW farm is very well suited for investigation into effects at full scale because of its state of the art turbines and the comprehensive and reliable measurement infrastructure for turbine and meteorological data.

The farm is orientated from west to east (95-275°), Figure 2.1. Turbine 5 and 6 have been used for the analysis in this report as turbine 5 is exposed to the prevailing westerly winds. Turbine 6 has been instrumented with blade root strain gauges and hence is used for the loads analysis. In addition to that a variety of signals is measured on all turbines, including electric power, nacelle wind speed and direction (both absolute nacelle direction as well as the direction of the wind vane), rotor speed and blade pitch angle. The wind characteristics are measured with the meteorological tower at 3.5D distance south-east of turbine 5 and 2.5D south-west of turbine 6. This mast measures wind speed and direction at three different heights including hub height. Also air pressure and temperature are measured at this height. The measurements at the EWTW are analyzed from December 2004 until April 2009.

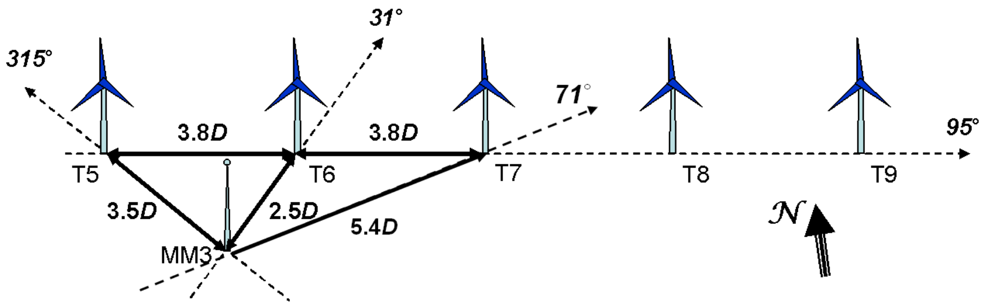


Figure 2.1: Main dimensions and directions in the EWTW farm. T5 to T9 are the turbine positions, MM3 indicates the measurement mast.

3

Data reduction

The signals of turbine 5 and 6 together with the meteorological data from mast 3 have been used for the analysis in this report. 2-, 5- and 10-minute statistics have been retrieved from the data base. The 2-minute SQL-scripts for this purpose can be found in appendix A. Wind direction (between 200 and 300°), operational mode (between 10.5 and 14.5) and minimum power ($>$25 kW) of turbine 6 are used as filter criteria in these scripts.

3.1 Filtering

After retrieving the statistics from the database, a second data reduction step is performed to filter out erroneous samples and outliers. These steps are outlined below. For more details, please consult appendix B which contains a summary of the results of this procedure.

Non-numeric values The misalignment of the turbine is calculated by means of subtracting the average wind direction measured by the meteo mast from the average nacelle direction. In some cases the nacelle direction is not recorded, resulting in a non-numeric value (NaN). These values are excluded from the dataset. The same holds for samples with NaN values of air pressure ('Pair') and flat and edgewise moments ('Mflat' and 'Medge').

Power Only normal operation conditions below rated wind speed are considered. Although the operational mode and minimum power for turbine 6 has already been filtered by the SQL script, the minimum average power of turbine 5 is also filtered to be larger than 25 kW.

Nacelle direction standard deviation The standard deviation of the nacelle direction indicates to what extent the turbine has been yawing during the sample. Samples have been excluded for standard deviation exceeding 15°.

Average wind speed Although operational mode and minimum power filters should have excluded unsuitable samples, the average wind speed has also been restricted between 5 and 15 m/s.

Nacelle to wind speed ratio The wind speed is measured at the meteo mast located 3.5 diameters distance from the turbine. There can be differences between the wind that is experienced by the turbine and the meteo mast. Since the wind speed at the meteo mast is used to correlate with the turbine measurements, ratios between average nacelle and wind speed are restricted between 0.85 and 1.15.

Turbulence intensity The turbulence intensity can be calculated by dividing the standard deviation of the wind speed over its average, both measured at the meteo mast. Extremely low and high values are filtered out by restricting this value between 1% and 20%

Pitch angle and variation Even during normal operation pitch angles can vary. The difference between the maximum and minimum pitch angle of a data set is restricted to 0.2°.

3.2 Correction for atmospheric conditions

Power, edgewise and flatwise moments scale different with atmospheric conditions. The edgewise moment is dictated by gravity forces and the flatwise moment by aerodynamic force. The latter is influenced by atmosphere linearly through air density. The variation of the air density can be shown to lie between 1.18 and 1.28 kgm^{-3} for the selected samples. This is regarded as a small variation and hence the influence of atmospheric conditions is not taken into account.

3.3 Power coefficients and fatigue equivalent moments

The power coefficient for an individual turbine can be determined using

$$Cp = P/(0.5\rho U^3 A) \quad , \tag{3.1}$$

with

Cp	[-]	power coefficient
P	[Watt]	electronic power
ρ	[kgm^{-3}]	air density
U	[m/s]	wind speed
A	[m^2]	rotor area.

Here the air density ρ is calculated from the measured air pressure and temperature using the ideal gas law. To compare the power output for turbine 5 and 6 together, their values are added according to

$$Cp_{park} = Cp_{T5} + Cp_{T6} \quad , \tag{3.2}$$

with

Cp_{park}	[-]	combined power coefficient
Cp_{T5}	[-]	turbine 5 power coefficient
Cp_{T6}	[-]	turbine 6 power coefficient.

Here both Cp_{T5} and Cp_{T6} are made dimensionless using the same wind speed as measured at the meteorological mast at hub height.

In addition to the power coefficients, the fatigue equivalent flatwise and edgewise moments of turbine 6 are acquired for two different material constants (steel and glass fibre). Rain flow counting was applied to the raw signal and the equivalent loads have readily been been determined in the database according to IEC 61400-13 [1].

3.4 Pitch angle configurations

The filtered data is divided into several data sets using the operational pitch angle of turbine 5 and 6. Thereto a naming convention is adopted: 20xxx indicates a pitch angle of 5° for the first turbine in the row from west to east (turbine 5), 0° for turbine 6 and the pitch angles of the remaining turbines (7 to 9) is irrelevant for westerly winds.

3.5 Bin averaging

Bin averaging is applied to the resulting data sets both in wind speed and direction. The bin averaging settings are given in Table 3.1. The standard error of the mean within each bin is calculated using

$$S = \sigma/\sqrt{N} \quad , \tag{3.3}$$

with

S	[]	standard error of bin average mean
σ	[]	standard deviation of the bin data samples
N	[-]	number of samples per bin

Table 3.1: Bin averaging settings

	2 min average	5 min average	10 min average
Required samples per bin for valid average	12	6	2
Wind speed bins		5 to 13 m/s, Δ= 1 m/s	
Wind direction bins		200° to 300°, Δ= 5°	
	undisturbed	wake side	wake center
Wind direction sectors	200-251°	251-267°, 281-300°	267-281°

4

Results

The number of remaining samples of the resulting data sets are summarized in Table 4.1. The resulting data sets for 40xxx and 22xxx are rather small. As a result it will appear that the corresponding uncertainties for these data sets are very large.

Contour plots showing the distribution of several operational variables for configuration 00xxx are shown in appendix C (Figures C.1 to C.6). From Figure C.1 it becomes clear that the majority of the collected data points are distributed in the undisturbed south westerly direction. The turbulence intensity measured by the meteorological mast seems to increase with wind speed up to roughly 11 m/s after which a decrease sets in again. There is a clear directional dependence of roughly 5% difference which could be explained by the presence of obstructions in the vicinity such as villages and surrounding turbines. Also the turbulence intensity increases with wind speed between 5 and 11 m/s, but appears to decreases again above 12 m/s. There is little difference between the three averaging times applied, which holds for all the displayed variables in appendix C.

Table 4.1: Data set summary

Data set	2 min average samples [-]	5 min average samples [-]	10 min average samples [-]
00xxx	127857	57602	28839
20xxx	5461	2410	1285
40xxx	1789	897	442
22xxx	1617	731	402

From previous measurements [8] it was illustrated that the variation of turbulence intensity influences the performance. This can partly be explained by the increase in available kinetic energy in the air, causing a higher effective local velocity. More importantly, an increased intensity enhances the flow mixture in the wake and hence the velocity deficit in the wake recovers faster. As a consequence the power of both undisturbed (upstream) and disturbed (downstream) turbines increases for an increasing turbulence intensity.

The nacelle windspeed is an indicator for the wind experienced by the turbine. This signal is measured by a sonic anemo-meter or in case of failure of this signal by a cup anemo-meter. The top part of Figure C.2 shows the nacelle wind speed of turbine 5, which should theoretically be a flat line with wind direction. In practice a local maximum can be observed around 260° wind direction. Going back to the turbulence intensity in Figure C.1, the peaks coincide with the local maximum of the turbulence intensity. Since the nacelle wind speed measurement takes place downstream of the rotor (i.e. in the rotor wake), the increased flow mixture could explain the small peaks in the nacelle wind speed.

The bottom part of the Figure clearly shows turbine 6 to operate in the wake of turbine 5 for westerly winds. The same holds for the standard deviation of the nacelle wind speed in Figure C.3. It is noticed that the velocity standard deviation of turbine 6 decreases in the wake of turbine 5 due to the decrease in wind speed. However because of the increased turbulence in the wake of turbine 5, the standard deviation does not decrease as much as the wind speed does (relatively) and the wake affected area is less wide (direction wise).

The standard deviation of the turbine 5 nacelle wind speed does not show an entirely flat trend with wind direction. The local increase around a wind direction of 260° agrees with the direction of the maximum of the turbulence intensity from the meteorological mast.

Figure C.4 displays the tip speed ratio which is made dimensionless using the wind velocity measured by the meteorological mast. For turbine 5 again the trend with wind speed is not entirely flat and the maxima at 220°, 260° and towards 300° are in agreement with the maxima of the turbulence intensity.

As a consequence of the low velocities in the wake of turbine 5, the turbine 6 rotational speed decreases and with that also the calculated tip speed ratio. Theoretically the turbines should operate at their optimal tip speed ratio λ, since the data is filtered in the below rated region. In practice the rotational speed setting is limited by the converter, which means that the tip speed ratio (and thus the operating condition of the rotor) varies with wind speed even below rated conditions. This is clearly visible in Figure C.4. Therefore the results are presented not only as a function of direction but also of wind speed bin.

Observing the misalignment (yaw angle) in Figure C.5 it should be noted that this quantity is calculated by subtracting the wind direction as measured by the meteorological mast from the measured nacelle direction at the turbine. As such the illustrated value is not necessary a misalignment since the local wind direction might be different from the measurement at the meteorological mast, especially in the wake of the turbine.

Firstly the resulting misalignment does not vary around 0° contrary to expectations. This has been observed previously [3, 6] and is probably caused by a faulty measurement of the nacelle direction or meteorological mast wind vane since it is not likely that the turbine continuously operates in yawed flow conditions.

For turbine 5 the misalignment is not distributed randomly but changes roughly from -4° at 200° to -7° at 300° direction. As pointed out in [4] this could well be explained by a faulty indication of meteorological mast wind direction. The wind direction vane taken for this direction range is located on a boom which is aligned at 240°. It can easily be shown that the local streamlines around the mast show direction changes up to 3° at this short distance between the vane and the mast.

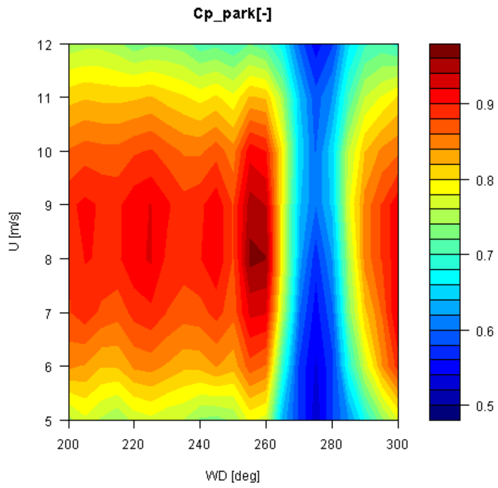
The yaw angles of turbine 6 show that the side areas of the wake (just off the wake center line) show positive and negative values with a difference of approximately 10°. This could be attributed to the fact that the turbine operates in the partial wake behind turbine 5. As was previously hypothesized in [9], this can result in an asymmetric wake expansion, causing a change in local wind direction.

4.1 Power

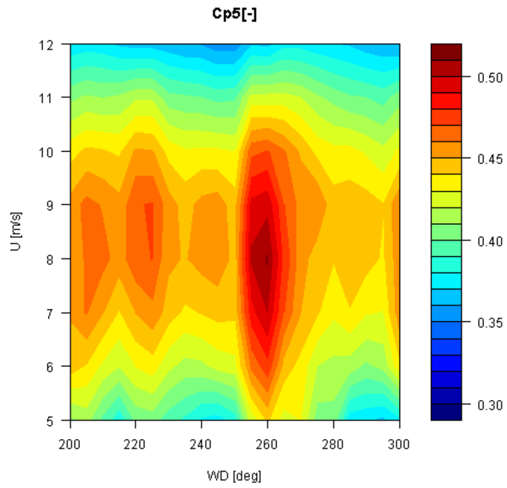
Figures 4.1 and 4.2 illustrate the variation of combined and individual power coefficients. From the contour plots, especially the one for turbine 5, it becomes clear that also here the turbulence intensity variation dictates the power coefficient variation for undisturbed wind directions. In addition to a previous hypothesis on the influence of wake rotation in partial wake [9], the peak in Cp_{park} around 260° seems to be caused by the high turbulence intensity of this direction.

From the bottom plots of Figure 4.1 it becomes clear that the heat and flux configurations are almost comparable to the undisturbed situation for the side wake sector as defined in Table 3.1. For the center wake however, a clear gain is observed around the 8 m/s bin. Figure 4.2 then illustrates the breakdown of the combined power coefficient. Theoretically the top three plots should be identical since for turbine 5 all three considered sectors are undisturbed. However an outlier is observed for the center wake sector around 8 m/s, which partly invalidates the gain in Cp_{park} at this bin. The bottom plot for the center wake clearly show the increase of turbine 6 performance due to the pitch angle settings of turbine 5.

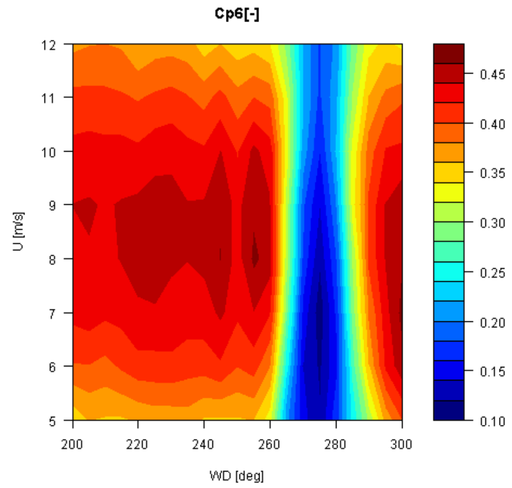
Figure 4.3 and 4.4 illustrate the variation of turbine 6 nacelle wind speed and meteorological mast turbulence intensity for the various heat and flux configurations. The increased nacelle wind speed in the center wake for the `40xxx` configuration seems not only to be caused by the pitch angle setting of turbine 5, but also by the higher turbulence intensity. Therefore the results of the `40xxx` configuration appear to overestimate the possible gain in terms of performance, since both the undisturbed as well as the downstream turbine benefit from the higher turbulence intensity. The slightly positive results of the `20xxx` configuration however indicate that in the center wake sector a true heat and flux gain is present.



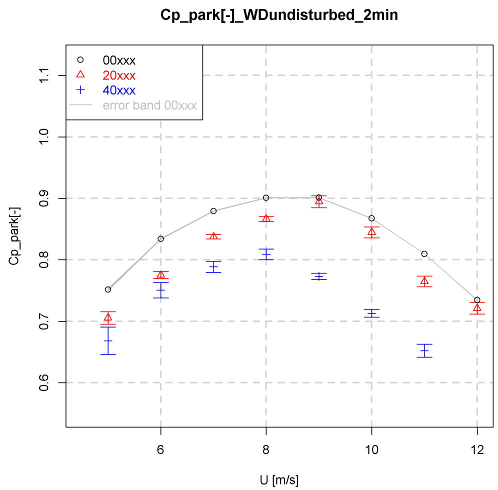
(a) Contour plot of Cp_{park} for 00xxx



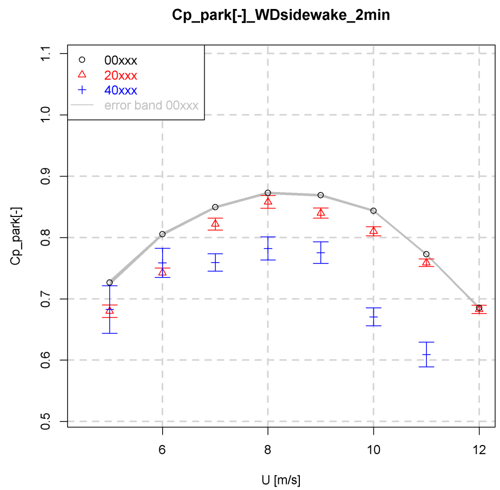
(b) Contour plot of turbine 5 Cp for 00xxx



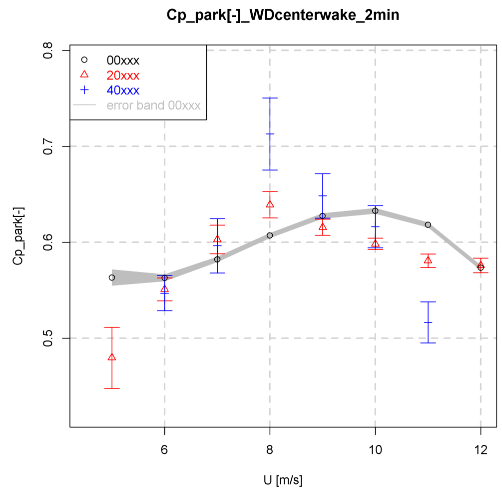
(c) Contour plot of turbine 6 Cp for 00xxx



(d) Variation of Cp_{park} with wind speed, undisturbed sector

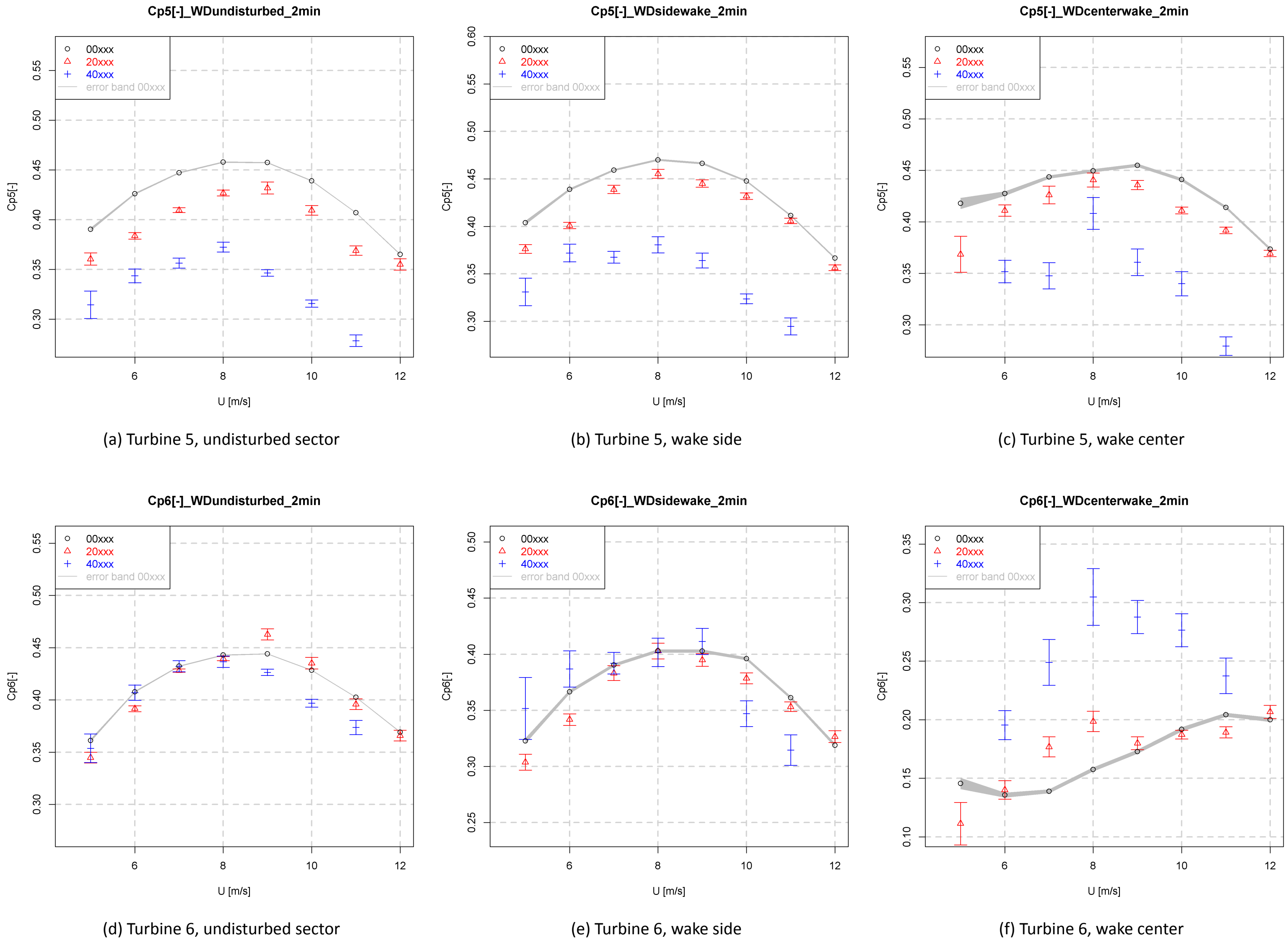


(e) Variation of Cp_{park} with wind speed, wake side



(f) Variation of Cp_{park} with wind speed, wake center

Figure 4.1: Variation of combined power coefficients for several configurations, 2 minute average



(a) Turbine 5, undisturbed sector

(b) Turbine 5, wake side

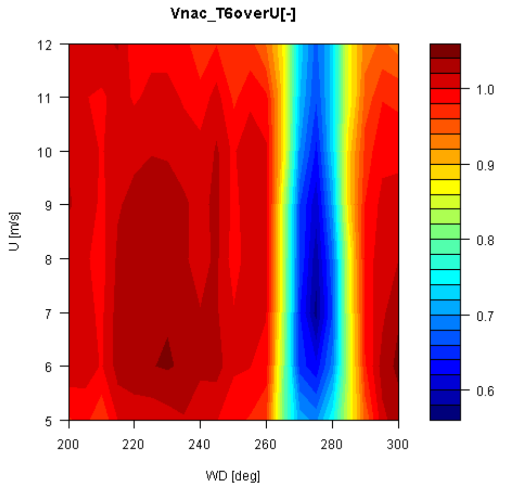
(c) Turbine 5, wake center

(d) Turbine 6, undisturbed sector

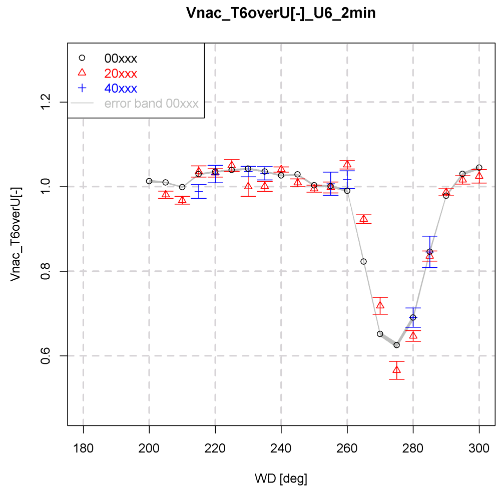
(e) Turbine 6, wake side

(f) Turbine 6, wake center

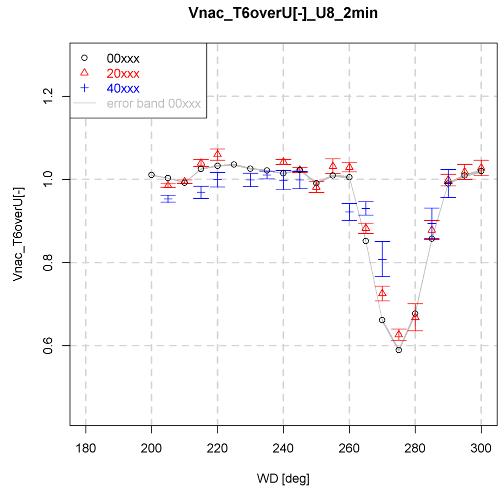
Figure 4.2: Variation of turbine 5 and turbine 6 Cp with wind speed for several configurations, 2 minute average



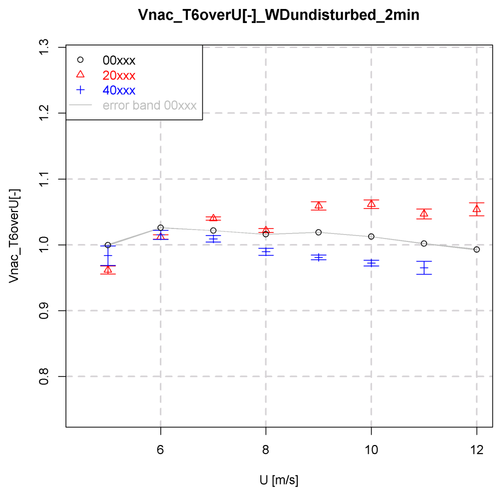
(a) Contour plot for 00xxx



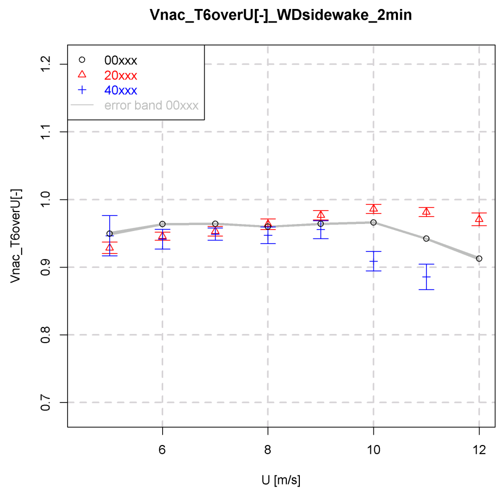
(b) Variation with wind direction, U_{bin}=6 m/s



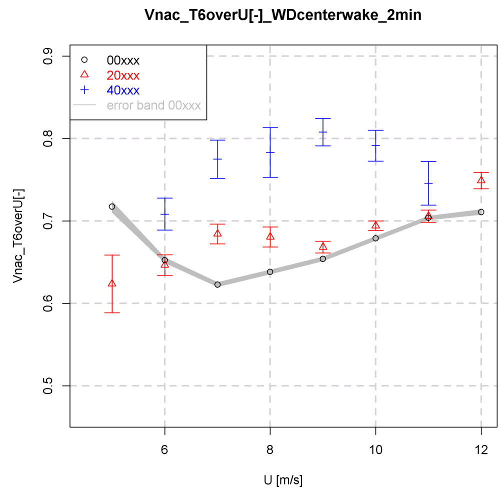
(c) Variation with wind direction, U_{bin}=8 m/s



(d) Variation with wind speed, undisturbed sector

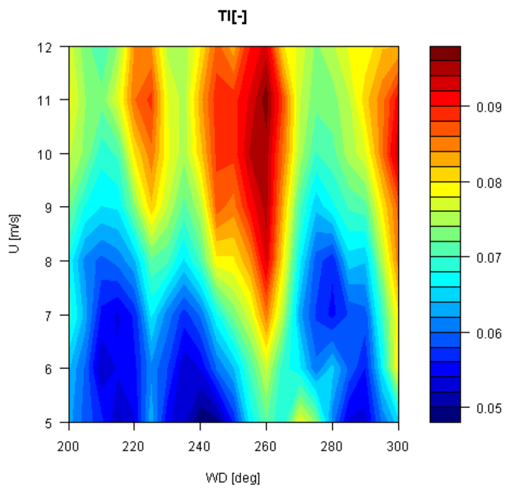


(e) Variation with wind speed, wake side

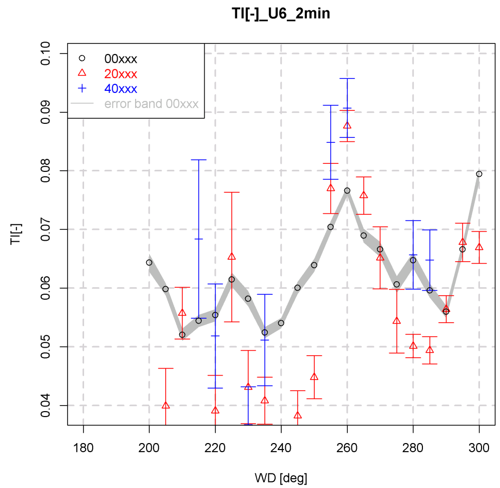


(f) Variation with wind speed, wake center

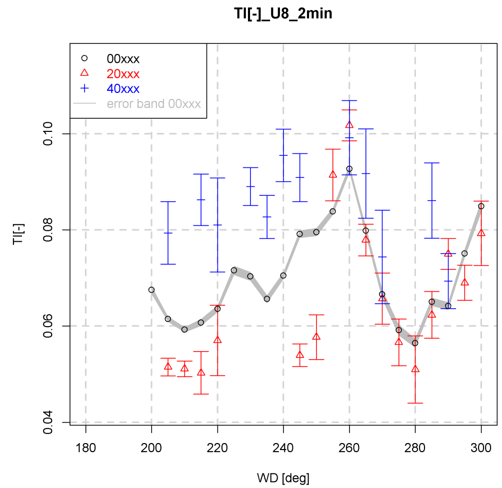
Figure 4.3: Variation of turbine 6 nacelle wind speed over meteo mast wind speed ratio for several configurations, 2 minute average



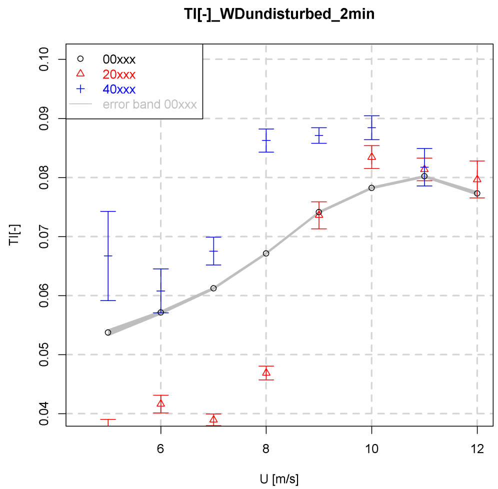
(a) Contour plot for 00xxx



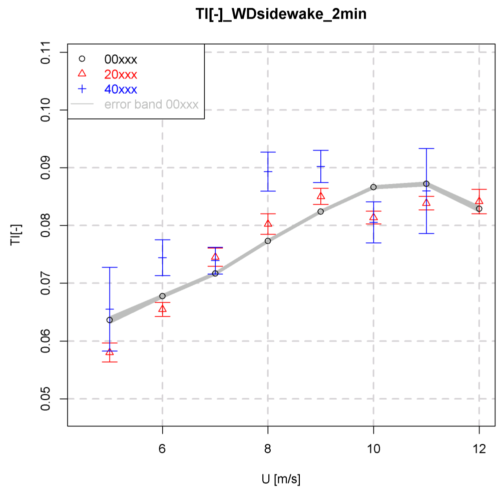
(b) Variation with wind direction, U_{bin}=6 m/s



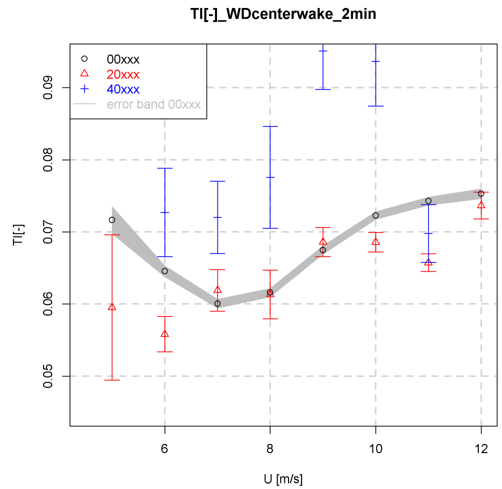
(c) Variation with wind direction, U_{bin}=8 m/s



(d) Variation with wind speed, undisturbed sector



(e) Variation with wind speed, wake side



(f) Variation with wind speed, wake center

Figure 4.4: Variation of turbulence intensity measured by the meteo mast for several configurations, 2 minute average

4.2 Loads

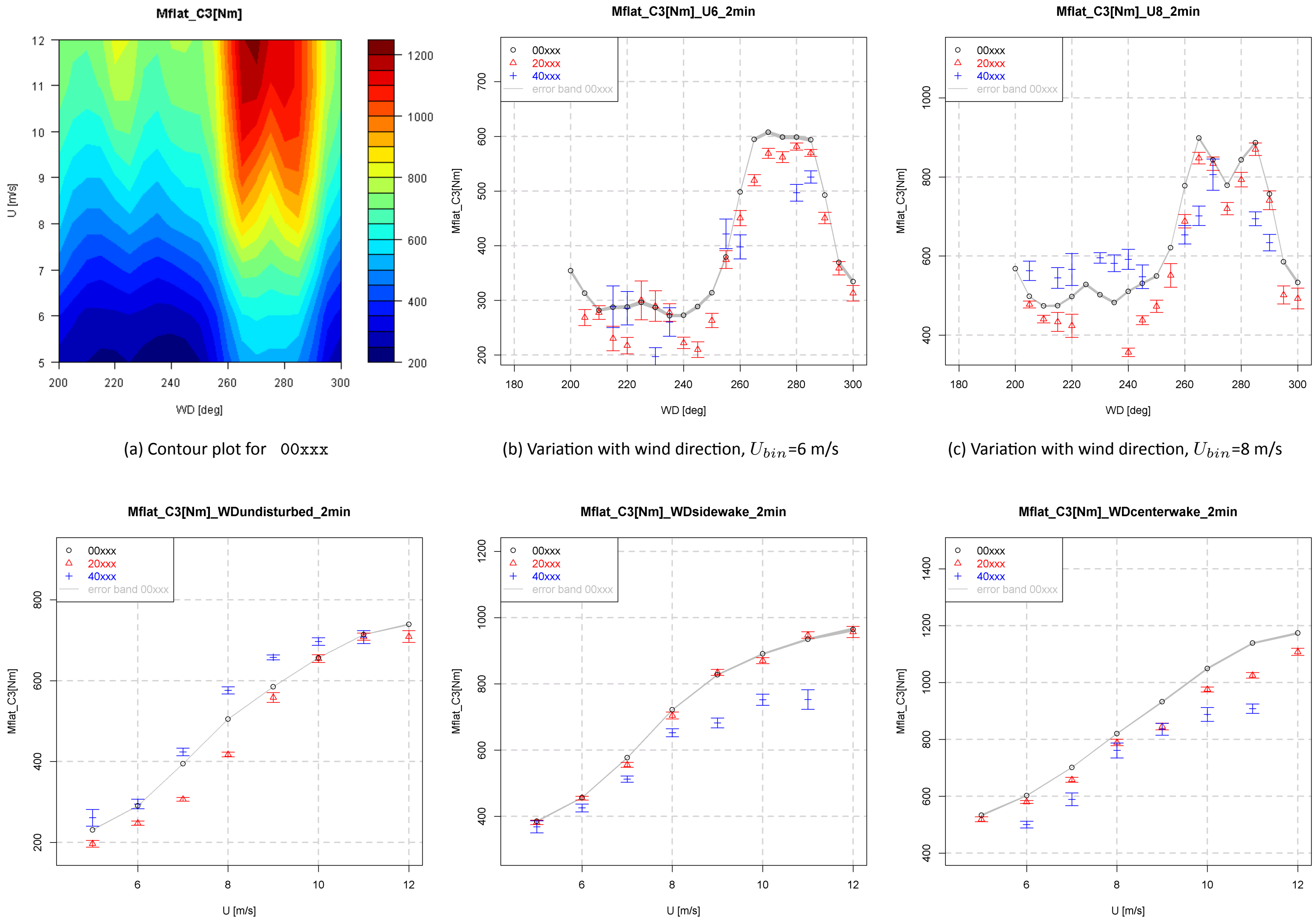
The variation of flatwise fatigue equivalent loads is illustrated in Figure 4.5. The contour plot shows a hat shape with a dent in the middle when turbine 6 is positioned directly downstream of turbine 5. This can be explained by the fact that a partial wake situation induces more unsteady loads than a turbine operating in the full wake of the upwind turbine. For a full wake situation the effective wind fluctuation as experienced by the turbine is less. In addition to that, the highly turbulent tip vortices will pass round the rotor instead of through the rotor plane. For velocities below 6 m/s the dent seems to disappear. At these low velocities and consequently high tip speed ratios (above 9), the operation enters the turbulent wake state and the wake deficit is smeared out over a wider region and hence less pronounced. Therefore the partial wake situation is less distinct, resulting in lower fatigue loads. The increased levels at 220° wind direction and the fact that the left part of the 'hat' features higher fatigue loads can be explained by the increased turbulence intensities in these directions as illustrated in Figure 4.4a.

For the undisturbed wind sector (Figure 4.5d) the different configurations should theoretically coincide. The measured discrepancies can again be explained by turbulence intensity differences as illustrated in Figure 4.4d.

For the side wake sector only the `40xxx` configuration shows a decrease, which however coincides with a higher turbulence intensity. Since an increased turbulence intensity facilitates wake mixing and a faster recovery of the wake velocity deficit, this is expected to decrease the fatigue loading in the wake of turbine 5. The question is whether changing the pitch axis of the upstream turbine or an increase in turbulence intensity is a dominant factor. The same holds for the center wake sector. For this sector however also the `20xxx` configuration shows a decrease in fatigue loading, whilst turbulence intensity levels are roughly the same. Hence it appears that these gains in fatigue loading can be attributed to a heat and flux effect. Reductions are in the order of 10% and seem to occur only for the higher wind velocities (or low tip speed ratios).

The variation of edgewise fatigue equivalent loads is illustrated in Figure 4.6. A sine shape is observed whilst traversing through the wake where the left half shows an increase and the right half a decrease. This can be explained by the contribution of the aerodynamic torque which increases the absolute value of the edgewise moment for the downstroke whilst it decreases this figure for the upstroke. As such a partial wake situation on one side of the wake increases the edgewise load difference between up- and downstroke whilst on the other side it decreases the edgewise moment difference between up- and downstroke and hence the fatigue equivalent moment.

The edgewise fatigue equivalent moment is predominantly determined by gravity contributions. A very small heat and flux effect can be observed in the order of 1%, with a light preference at higher wind speeds. However the fact that the `20xxx` configuration shows a similar decrease as for the `40xxx` configuration gives rise to speculations on the accuracy of this observation.



(a) Contour plot for 00xxx

(b) Variation with wind direction, U_{bin}=6 m/s

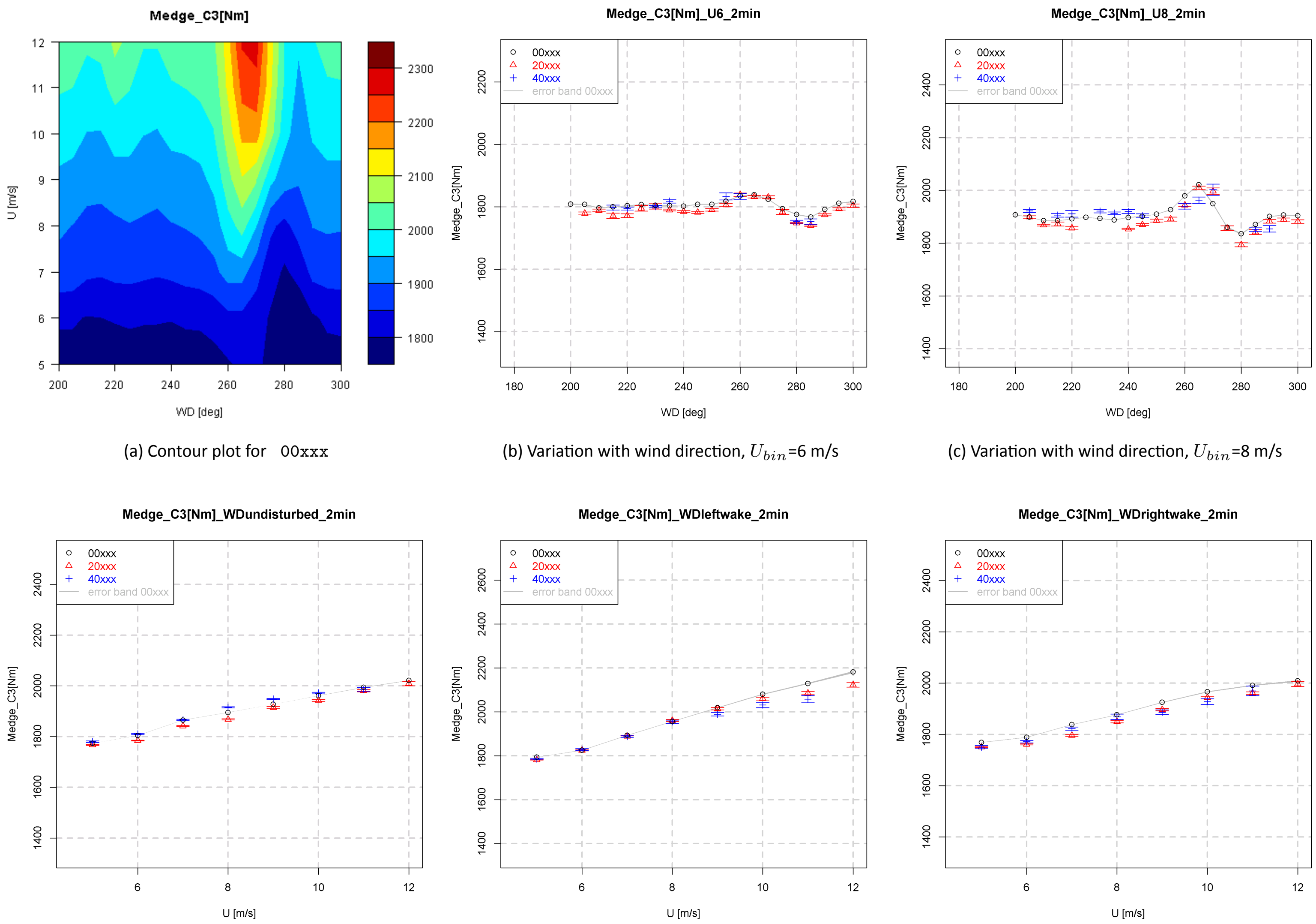
(c) Variation with wind direction, U_{bin}=8 m/s

(d) Variation with wind speed, undisturbed sector

(e) Variation with wind speed, wake side

(f) Variation with wind speed, wake center

Figure 4.5: Variation of flatwise fatigue equivalent moment for several configurations, 2 minute average



(a) Contour plot for 00xxx

(b) Variation with wind direction, U_{bin}=6 m/s

(c) Variation with wind direction, U_{bin}=8 m/s

(d) Variation with wind speed, undisturbed sector

(e) Variation with wind speed, left wake (251°-274°)

(f) Variation with wind speed, right wake (274°-297°)

Figure 4.6: Variation of edgewise fatigue equivalent moment for several configurations, 2 minute average

5

Conclusions and recommendations

The effect of turbine pitch angle variation on performance and loads of a downwind located wind turbine is investigated using field measurements. In addition to that an attempt is made to physically clarify the measured effects in terms of loads and performance of a turbine wake impinging on a downstream turbine.

An increase in combined power is observed for the center wake situation, i.e. when the downwind turbine is located exactly downstream of the upwind located turbine. This increase amounts to roughly 5% for a 2° pitch angle, and is limited to the optimum tip speed ratio regime. It should be noted that this figure holds for two turbines only and is not representative for a park configuration. A qualitative comparison of the different pitch angle settings is hampered by the fact that the turbulence intensity is not equal for the different configurations.

For the loads, presented in terms of flat- and edgewise fatigue equivalent blade root moments, the heat and flux effect is as expected mostly present in the flatwise component. Similar to the power results, the center wake situation is most promising. Reductions in the order of 10% for the downwind turbine are measured at a 2° pitch angle of the upwind turbine, which occur for the higher wind velocities (or low tip speed ratios). As for the power results, a qualitative comparison of the different pitch angle settings is hampered by variations of the turbulence intensity.

It is recommended to correct both power and loads for atmospheric turbulence intensity variations, since the trend is clearly influenced by this quantity. To reduce the standard error of the field data it is recommended to obtain more measurements. To increase the available data for heat and flux configurations, it would be beneficial if the wind turbines can be operated at a specified pitch angle for a limited time period.

Furthermore it is recommended to extend and extrapolate the results from two turbines to a representative number of turbines for a farm. To come to a conclusion on the overall benefits of the heat and flux concept, integrating the results for a representative wind rose (wind direction and speed distribution) and park configuration, whilst including an appropriate controller strategy seems to be the next step. It should also be realised that the respective distance between the turbines is only 3.8D in this case, which may not always be representative for a commercial wind farm.

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A

SQL scripts

SQL script for 2 minute average data

```
select r1."t_0",
"MM3_WS80_240_2min_avg","MM3_WS80_240_2min_std",
"MM3_WD80_240_2min_avg","MM3_WD80_240_2min_std",
"MM3_Pair80_2min_avg",
"MM3_Tair80_2min_avg",

"T6_Pwsnac_2min_avg",
"T6_PEpow_2min_avg",
"T6_Pnacdrtn_2min_avg","T6_Pnacdrtn_2min_std",
"T6_Popmode_2min_min","T6_Popmode_2min_max",
"T6_Ppitch1_2min_min","T6_Ppitch1_2min_max",
"T6_Rspd_2min_avg","T6_Rspd_2min_std",
"MM3_WS80_true_2min_avg", "MM3_WS80_true_2min_std", "MM3_WS52_true_2min_avg",

r2."t_0",
"T6_Mbe1_load_P_2min_eql_C1","T6_Mbe1_load_P_2min_eql_C3",
"T6_Mbf1_load_P_2min_eql_C1","T6_Mbf1_load_P_2min_eql_C3",

"T5_Pwsnac_2min_avg",
"T5_PEpow_2min_avg",
"T5_Pnacdrtn_2min_avg", "T5_Pnacdrtn_2min_std",
"T5_Popmode_2min_min", "T5_Popmode_2min_max",
```

```
"T5_Ppitch1_2min_min", "T5_Ppitch1_2min_max",
"T5_Rspd_2min_avg", "T5_Rspd_2min_std",

"T5_Pwsnac_2min_std",
"T6_Pwsnac_2min_std"

from ( select "t_0", "MM3_WS80_240_2min_avg","MM3_WS80_240_2min_std",
"MM3_WD80_240_2min_avg","MM3_WD80_240_2min_std",
"MM3_Pair80_2min_avg",
"MM3_Tair80_2min_avg",
"T6_Pwsnac_2min_avg",

"T6_PEpow_2min_avg",
"T6_Pnacdrtn_2min_avg","T6_Pnacdrtn_2min_std",
"T6_Popmode_2min_min","T6_Popmode_2min_max",
"T6_Ppitch1_2min_min","T6_Ppitch1_2min_max",
"T6_Rspd_2min_avg","T6_Rspd_2min_std",
"MM3_WS80_true_2min_avg", "MM3_WS80_true_2min_std",
"MM3_WS52_true_2min_avg",

"T5_Pwsnac_2min_avg",
"T5_PEpow_2min_avg",
"T5_Pnacdrtn_2min_avg", "T5_Pnacdrtn_2min_std",
"T5_Popmode_2min_min", "T5_Popmode_2min_max",
"T5_Ppitch1_2min_min", "T5_Ppitch1_2min_max",
"T5_Rspd_2min_avg", "T5_Rspd_2min_std",

"T5_Pwsnac_2min_std",
"T6_Pwsnac_2min_std"

from public."statistics_2m"
where
"MM3_WD80_240_2min_avg">200 and "MM3_WD80_240_2min_avg"<300 and
"T6_Popmode_2min_min">10.5 and "T6_Popmode_2min_max"<14.5 and
"T6_PEpow_2min_avg">25
) as "r1" join
(
select
  "t_0",
  "T6_Mbe1_load_P_2min_eql_C1","T6_Mbf1_load_P_2min_eql_C1",
  "T6_Mbe1_load_P_2min_eql_C3","T6_Mbf1_load_P_2min_eql_C3"
from public.eql_2m
```

```
) as "r2"
on (r1.t_0 = r2.t_0)
order by r1."t_0"


/*

"T6_Pwsnac_2min_std",
"T5_Pwsnac_2min_avg",

"T5_PEpow_2min_avg",
"T5_Pnacdrtn_2min_avg","T5_Pnacdrtn_2min_std",
"T5_Popmode_2min_min","T5_Popmode_2min_max",
"T5_Ppitch1_2min_min","T5_Ppitch1_2min_max",
"T5_Rspd_2min_avg","T5_Rspd_2min_std",

*/
```

B

Data reduction logs

Data reduction log for 00xxx (2 minute average)

```
"start length:595277"
"NaN in yaw_T6:4785"
"NaN in yaw_T5:34978"
"NA in Pair:6392"
"NA in Medge_C1:166145"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:29554"
"nacelle dir std T6 (<15) :1"
"nacelle dir std T5 (<15) :4"
"windspeed (5 to 15 m/s) :47348"
"v/v_nac T5 (0.85 to 1.15) :33038"
"TI (0.01 to 0.2) :1891"
"pitch_dif T6 (<0.2 deg) :33282"
"pitch_dif T5 (<0.2 deg) :8170"
"wind shear ws80/ws50 (1 to 1.2 ):43853"
"Misalignment T6 (-12.5 to 2.5 ):17930"
"Misalignment T5 (-12.5 to 2.5 ):29777"
"pitch_angle T5 / T6 (0 / 0 deg, bandwidth +/-0.2) :10272"
"final length:127857"
```

```
________ Data reduction log for 00xxx (5 minute average) ________

"start length:228179"
"NaN in yaw_T6:1913"
"NaN in yaw_T5:25755"
"NA in Pair:1998"
"NA in Medge_C1:43149"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:11632"
"nacelle dir std T6 (<15) :18"
"nacelle dir std T5 (<15) :12"
"windspeed (5 to 15 m/s) :18730"
"v/v_nac T5 (0.85 to 1.15) :7093"
"TI (0.01 to 0.2) :331"
"pitch_dif T6 (<0.2 deg) :17266"
"pitch_dif T5 (<0.2 deg) :3550"
"wind shear ws80/ws50 (1 to 1.2 ):15513"
"Misalignment T6 (-12.5 to 2.5 ):5898"
"Misalignment T5 (-12.5 to 2.5 ):11957"
"pitch_angle T5 / T6 (0 / 0 deg, bandwidth +/-0.2) :5762"
"final length:57602"
```

```
________ Data reduction log for 00xxx (10 minute average) ________

"start length:89013"
"NaN in yaw_T6:893"
"NaN in yaw_T5:1350"
"NA in Pair:986"
"NA in Medge_C1:18285"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
```

```
"power T5>25:0"
"nacelle dir std T6 (<15) :36"
"nacelle dir std T5 (<15) :11"
"windspeed (5 to 15 m/s) :8530"
"v/v_nac T5 (0.85 to 1.15) :1592"
"TI (0.01 to 0.2) :205"
"pitch_dif T6 (<0.2 deg) :9691"
"pitch_dif T5 (<0.2 deg) :1586"
"wind shear ws80/ws50 (1 to 1.2 ):7996"
"Misalignment T6 (-12.5 to 2.5 ):1871"
"Misalignment T5 (-12.5 to 2.5 ):4742"
"pitch_angle T5 / T6 (0 / 0 deg, bandwidth +/-0.2) :2400"
"final length:28839"
```

Data reduction log for 20xxx (2 minute average)

```
"start length:595277"
"NaN in yaw_T6:4785"
"NaN in yaw_T5:34978"
"NA in Pair:6392"
"NA in Medge_C1:166145"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:29554"
"nacelle dir std T6 (<15) :1"
"nacelle dir std T5 (<15) :4"
"windspeed (5 to 15 m/s) :47348"
"v/v_nac T5 (0.85 to 1.15) :33038"
"TI (0.01 to 0.2) :1891"
"pitch_dif T6 (<0.2 deg) :33282"
"pitch_dif T5 (<0.2 deg) :8170"
"wind shear ws80/ws50 (1 to 1.2 ):43853"
"Misalignment T6 (-12.5 to 2.5 ):17930"
"Misalignment T5 (-12.5 to 2.5 ):29777"
"pitch_angle T5 / T6 (2 / 0 deg, bandwidth +/-0.2) :132668"
"final length:5461"
```

Data reduction log for 20xxx (5 minute average)

```
"start length:228179"
"NaN in yaw_T6:1913"
"NaN in yaw_T5:25755"
"NA in Pair:1998"
"NA in Medge_C1:43149"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:11632"
"nacelle dir std T6 (<15) :18"
"nacelle dir std T5 (<15) :12"
"windspeed (5 to 15 m/s) :18730"
"v/v_nac T5 (0.85 to 1.15) :7093"
"TI (0.01 to 0.2) :331"
"pitch_dif T6 (<0.2 deg) :17266"
"pitch_dif T5 (<0.2 deg) :3550"
"wind shear ws80/ws50 (1 to 1.2 ):15513"
"Misalignment T6 (-12.5 to 2.5 ):5898"
"Misalignment T5 (-12.5 to 2.5 ):11957"
"pitch_angle T5 / T6 (2 / 0 deg, bandwidth +/-0.2) :60954"
"final length:2410"
```

Data reduction log for 20xxx (10 minute average)

```
"start length:89013"
"NaN in yaw_T6:893"
"NaN in yaw_T5:1350"
"NA in Pair:986"
"NA in Medge_C1:18285"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
```

```
"power T5>25:0"
"nacelle dir std T6 (<15) :36"
"nacelle dir std T5 (<15) :11"
"windspeed (5 to 15 m/s) :8530"
"v/v_nac T5 (0.85 to 1.15) :1592"
"TI (0.01 to 0.2) :205"
"pitch_dif T6 (<0.2 deg) :9691"
"pitch_dif T5 (<0.2 deg) :1586"
"wind shear ws80/ws50 (1 to 1.2 ):7996"
"Misalignment T6 (-12.5 to 2.5 ):1871"
"Misalignment T5 (-12.5 to 2.5 ):4742"
"pitch_angle T5 / T6 (2 / 0 deg, bandwidth +/-0.2) :29954"
"final length:1285"
```

Data reduction log for 40xxx (2 minute average)

```
"start length:595277"
"NaN in yaw_T6:4785"
"NaN in yaw_T5:34978"
"NA in Pair:6392"
"NA in Medge_C1:166145"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:29554"
"nacelle dir std T6 (<15) :1"
"nacelle dir std T5 (<15) :4"
"windspeed (5 to 15 m/s) :47348"
"v/v_nac T5 (0.85 to 1.15) :33038"
"TI (0.01 to 0.2) :1891"
"pitch_dif T6 (<0.2 deg) :33282"
"pitch_dif T5 (<0.2 deg) :8170"
"wind shear ws80/ws50 (1 to 1.2 ):43853"
"Misalignment T6 (-12.5 to 2.5 ):17930"
"Misalignment T5 (-12.5 to 2.5 ):29777"
"pitch_angle T5 / T6 (4 / 0 deg, bandwidth +/-0.2) :136340"
"final length:1789"
```

Data reduction log for 40xxx (5 minute average)

```
"start length:228179"
"NaN in yaw_T6:1913"
"NaN in yaw_T5:25755"
"NA in Pair:1998"
"NA in Medge_C1:43149"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:11632"
"nacelle dir std T6 (<15) :18"
"nacelle dir std T5 (<15) :12"
"windspeed (5 to 15 m/s) :18730"
"v/v_nac T5 (0.85 to 1.15) :7093"
"TI (0.01 to 0.2) :331"
"pitch_dif T6 (<0.2 deg) :17266"
"pitch_dif T5 (<0.2 deg) :3550"
"wind shear ws80/ws50 (1 to 1.2 ):15513"
"Misalignment T6 (-12.5 to 2.5 ):5898"
"Misalignment T5 (-12.5 to 2.5 ):11957"
"pitch_angle T5 / T6 (4 / 0 deg, bandwidth +/-0.2) :62467"
"final length:897"
```

Data reduction log for 40xxx (10 minute average)

```
"start length:89013"
"NaN in yaw_T6:893"
"NaN in yaw_T5:1350"
"NA in Pair:986"
"NA in Medge_C1:18285"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
```

```
"power T5>25:0"
"nacelle dir std T6 (<15) :36"
"nacelle dir std T5 (<15) :11"
"windspeed (5 to 15 m/s) :8530"
"v/v_nac T5 (0.85 to 1.15) :1592"
"TI (0.01 to 0.2) :205"
"pitch_dif T6 (<0.2 deg) :9691"
"pitch_dif T5 (<0.2 deg) :1586"
"wind shear ws80/ws50 (1 to 1.2 ):7996"
"Misalignment T6 (-12.5 to 2.5 ):1871"
"Misalignment T5 (-12.5 to 2.5 ):4742"
"pitch_angle T5 / T6 (4 / 0 deg, bandwidth +/-0.2) :30797"
"final length:442"
```

Data reduction log for 22xxx (2 minute average)

```
"start length:595277"
"NaN in yaw_T6:4785"
"NaN in yaw_T5:34978"
"NA in Pair:6392"
"NA in Medge_C1:166145"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:29554"
"nacelle dir std T6 (<15) :1"
"nacelle dir std T5 (<15) :4"
"windspeed (5 to 15 m/s) :47348"
"v/v_nac T5 (0.85 to 1.15) :33038"
"TI (0.01 to 0.2) :1891"
"pitch_dif T6 (<0.2 deg) :33282"
"pitch_dif T5 (<0.2 deg) :8170"
"wind shear ws80/ws50 (1 to 1.2 ):43853"
"Misalignment T6 (-12.5 to 2.5 ):17930"
"Misalignment T5 (-12.5 to 2.5 ):29777"
"pitch_angle T5 / T6 (2 / 2 deg, bandwidth +/-0.2) :136512"
"final length:1617"
```

Data reduction log for 22xxx (5 minute average)

```
"start length:228179"
"NaN in yaw_T6:1913"
"NaN in yaw_T5:25755"
"NA in Pair:1998"
"NA in Medge_C1:43149"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
"power T5>25:11632"
"nacelle dir std T6 (<15) :18"
"nacelle dir std T5 (<15) :12"
"windspeed (5 to 15 m/s) :18730"
"v/v_nac T5 (0.85 to 1.15) :7093"
"TI (0.01 to 0.2) :331"
"pitch_dif T6 (<0.2 deg) :17266"
"pitch_dif T5 (<0.2 deg) :3550"
"wind shear ws80/ws50 (1 to 1.2 ):15513"
"Misalignment T6 (-12.5 to 2.5 ):5898"
"Misalignment T5 (-12.5 to 2.5 ):11957"
"pitch_angle T5 / T6 (2 / 2 deg, bandwidth +/-0.2) :62633"
"final length:731"
```

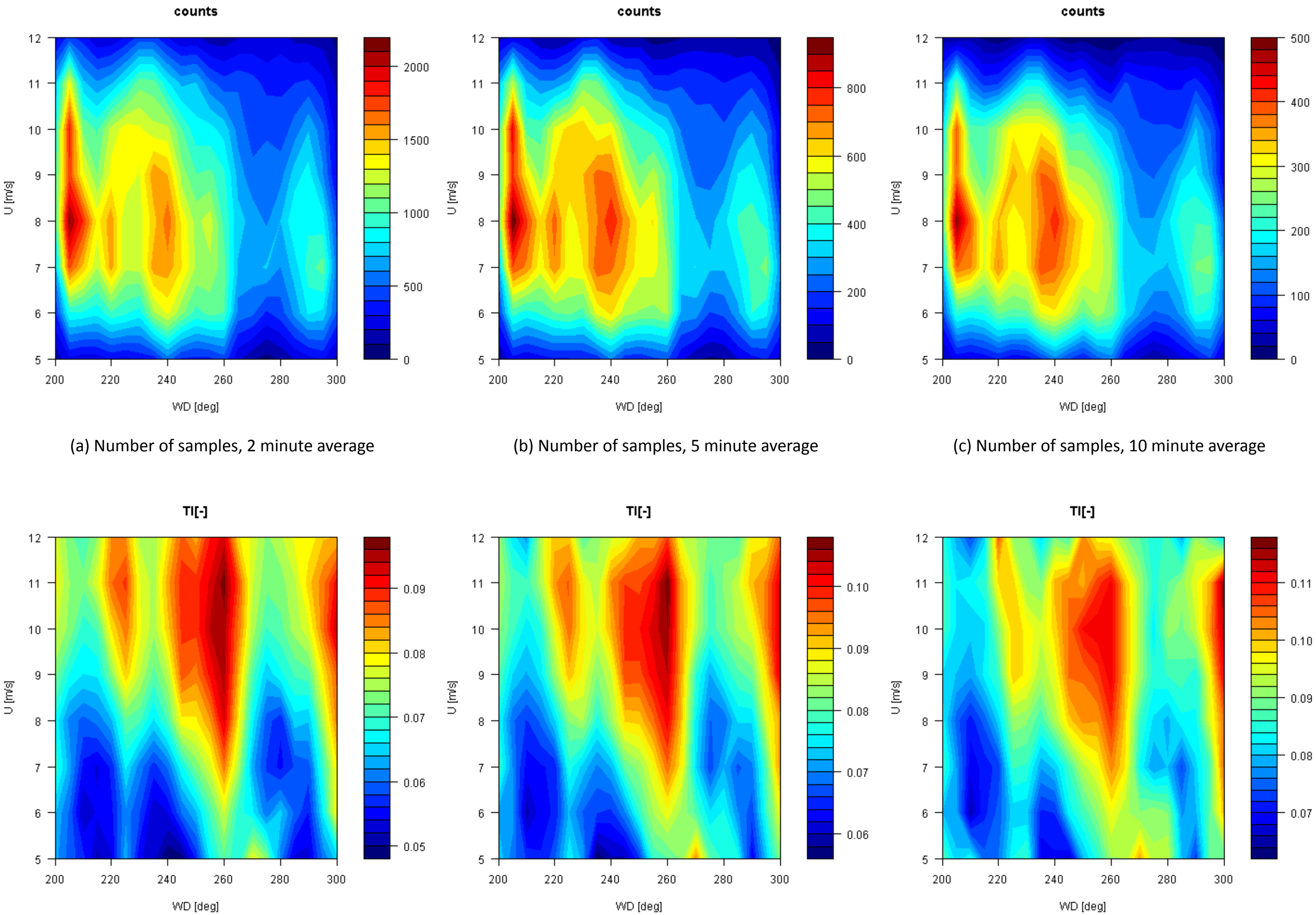
Data reduction log for 22xxx (10 minute average)

```
"start length:89013"
"NaN in yaw_T6:893"
"NaN in yaw_T5:1350"
"NA in Pair:986"
"NA in Medge_C1:18285"
"NA in Mflat_C1:0"
"NA in Medge_C2:0"
"NA in Mflat_C2:0"
"power T6>25:0"
```

```
"power T5>25:0"
"nacelle dir std T6 (<15) :36"
"nacelle dir std T5 (<15) :11"
"windspeed (5 to 15 m/s) :8530"
"v/v_nac T5 (0.85 to 1.15) :1592"
"TI (0.01 to 0.2) :205"
"pitch_dif T6 (<0.2 deg) :9691"
"pitch_dif T5 (<0.2 deg) :1586"
"wind shear ws80/ws50 (1 to 1.2 ):7996"
"Misalignment T6 (-12.5 to 2.5 ):1871"
"Misalignment T5 (-12.5 to 2.5 ):4742"
"pitch_angle T5 / T6 (2 / 2 deg, bandwidth +/-0.2) :30837"
"final length:402"
```

C

Data reduction figures



(a) Number of samples, 2 minute average

(b) Number of samples, 5 minute average

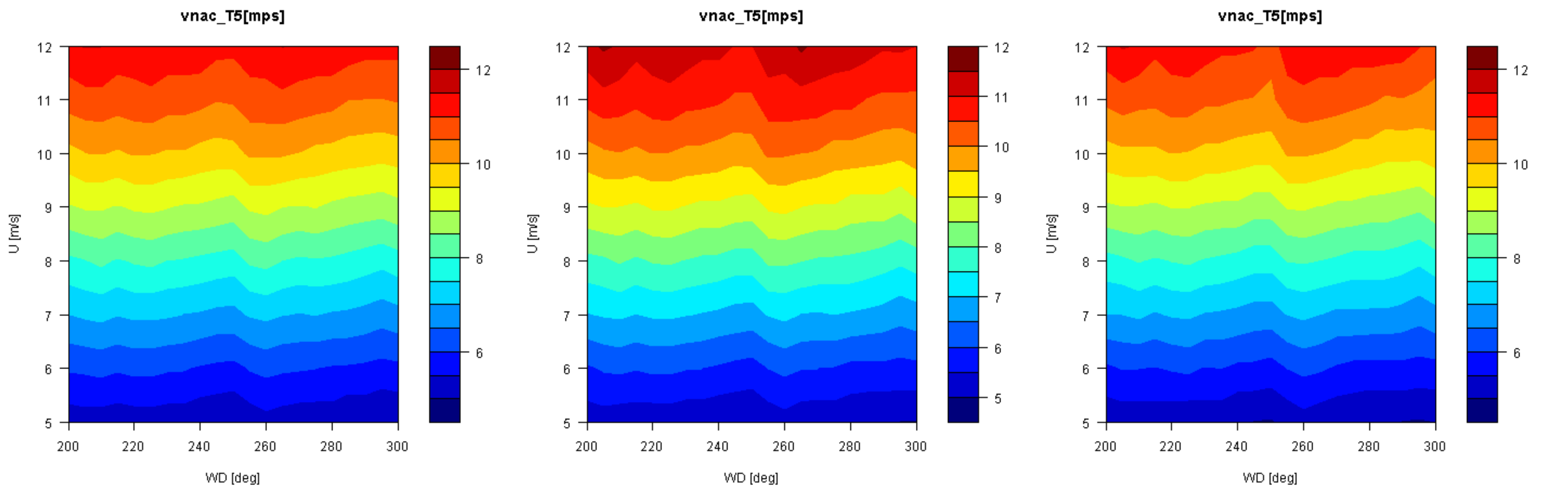
(c) Number of samples, 10 minute average

(d) Turbulence intensity, 2 minute average

(e) Turbulence intensity, 5 minute average

(f) Turbulence intensity, 10 minute average

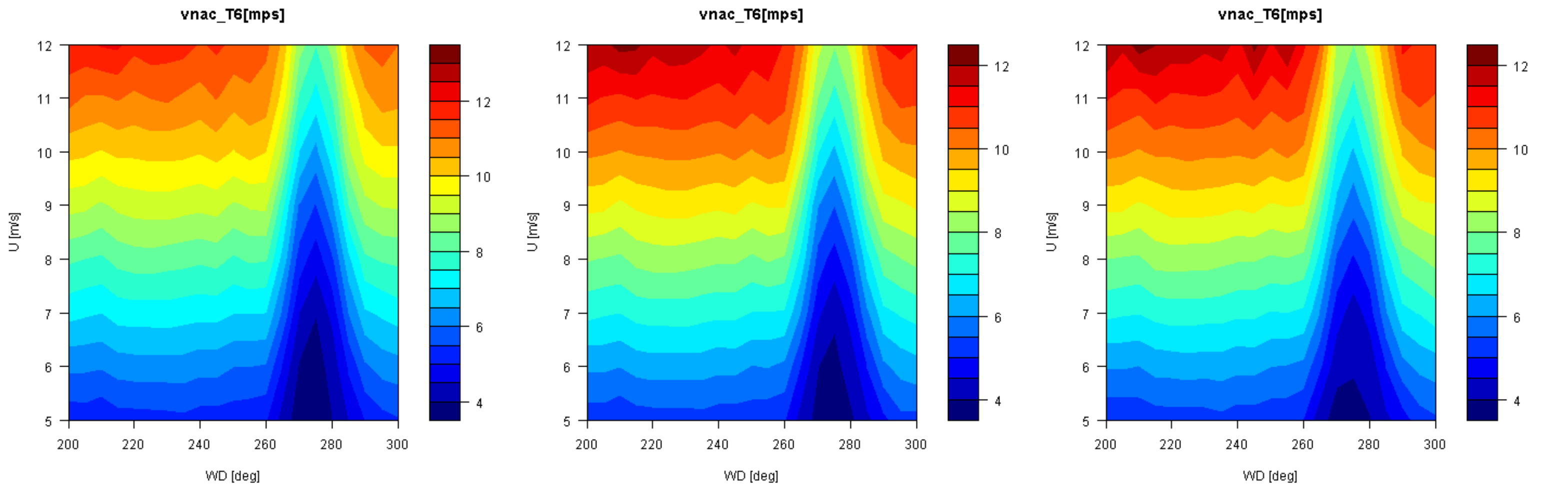
Figure C.1: Number of samples (above) and turbulence intensity (below) for configuration `00xxx`



(a) Nacelle wind speed of turbine 5, 2 minute average

(b) Nacelle wind speed of turbine 5, 5 minute average

(c) Nacelle wind speed of turbine 5, 10 minute average

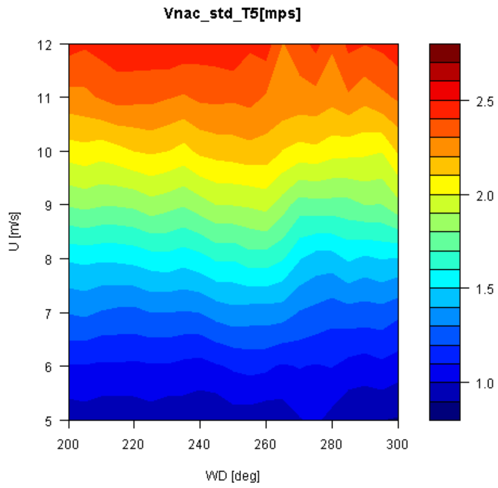


(d) Nacelle wind speed of turbine 6, 2 minute average

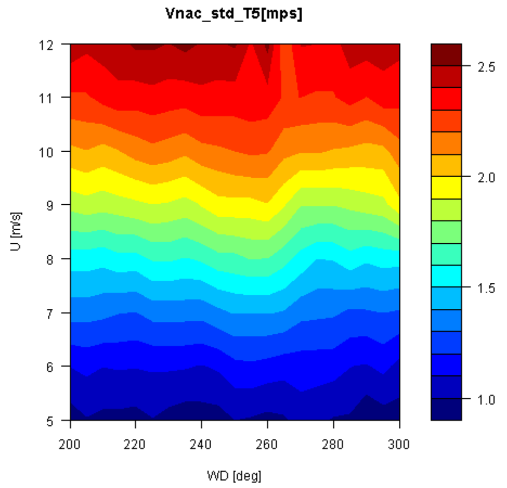
(e) Nacelle wind speed of turbine 6, 5 minute average

(f) Nacelle wind speed of turbine 6, 10 minute average

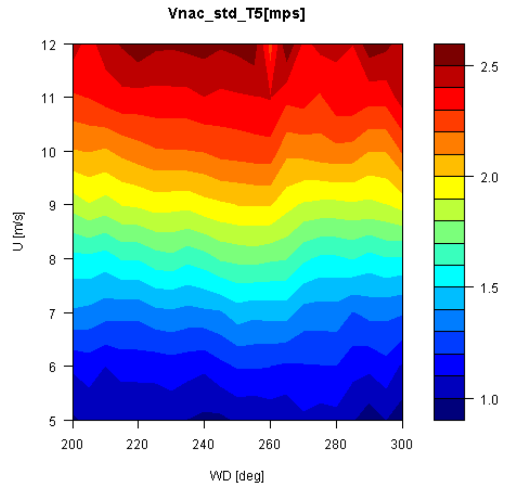
Figure C.2: Nacelle wind speed of turbine 5 (above) and turbine 6 (below) for configuration `00xxx`



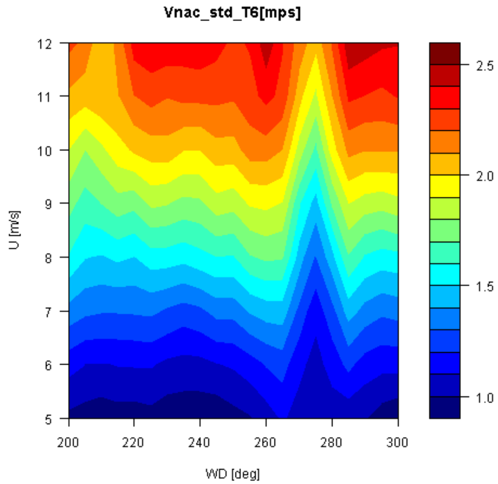
(a) Nacelle wind speed stdev of turbine 5, 2 minute avg



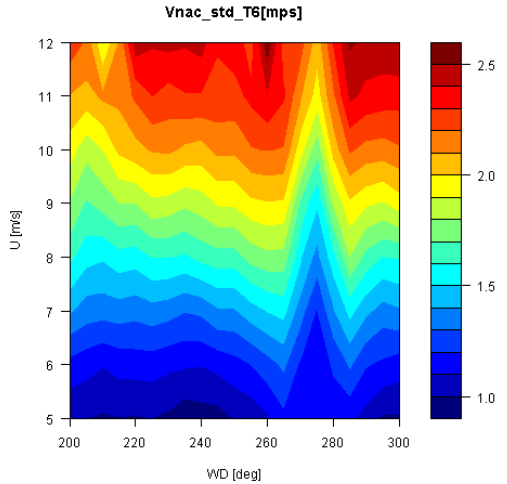
(b) Nacelle wind speed stdev of turbine 5, 5 minute avg



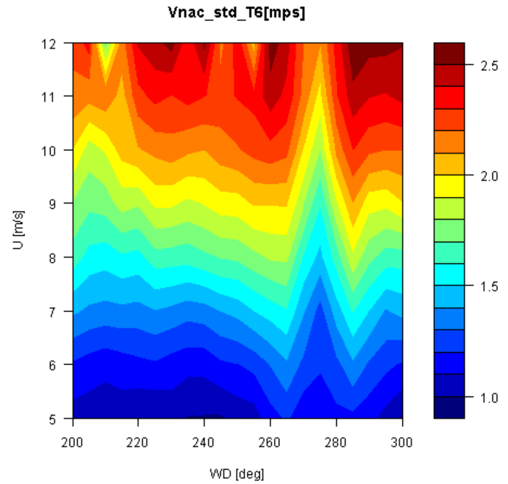
(c) Nacelle wind speed stdev of turbine 5, 10 minute avg



(d) Nacelle wind speed stdev of turbine 6, 2 minute avg

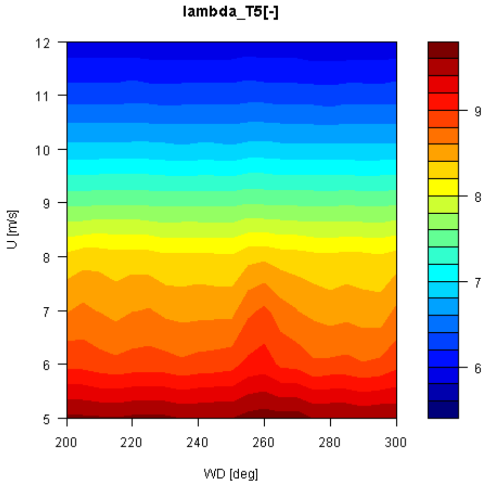


(e) Nacelle wind speed stdev of turbine 6, 5 minute avg

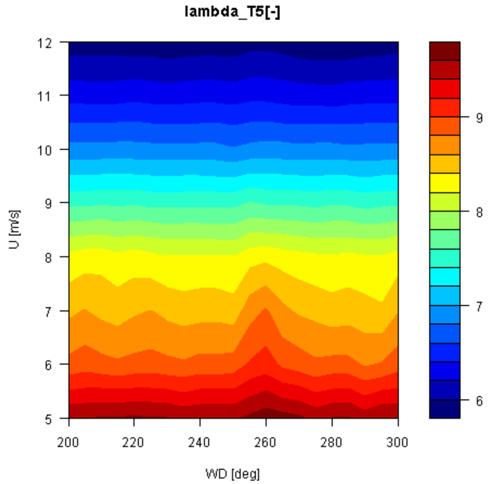


(f) Nacelle wind speed stdev of turbine 6, 10 minute avg

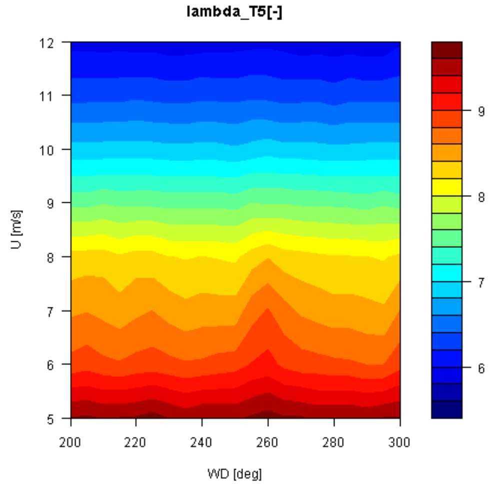
Figure C.3: Nacelle wind speed standard deviation of turbine 5 (above) and turbine 6 (below) for configuration `00xxx`



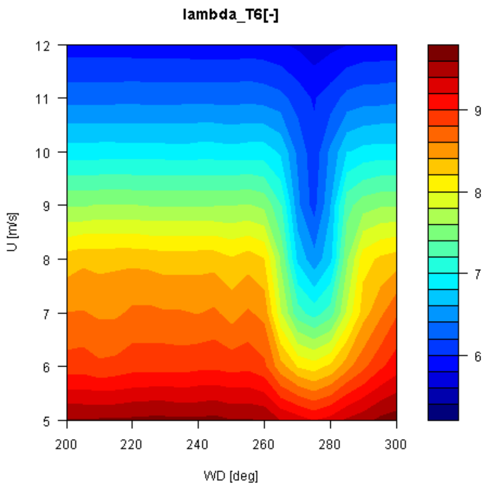
(a) Tip speed ratio of turbine 5, 2 minute average



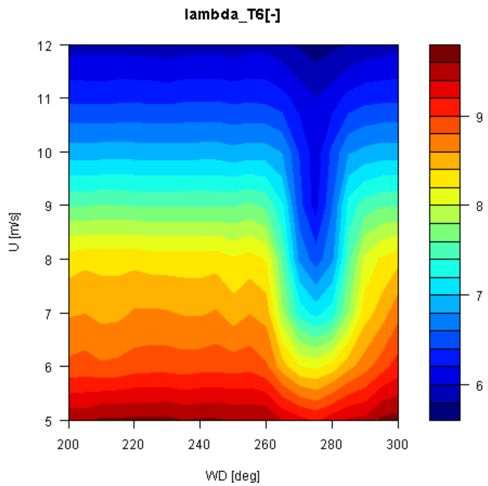
(b) Tip speed ratio of turbine 5, 5 minute average



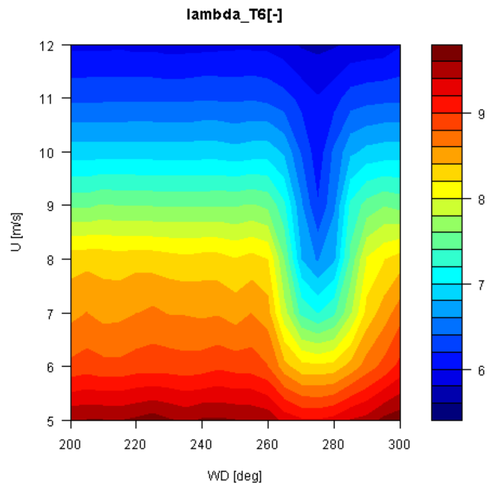
(c) Tip speed ratio of turbine 5, 10 minute average



(d) Tip speed ratio of turbine 6, 2 minute average

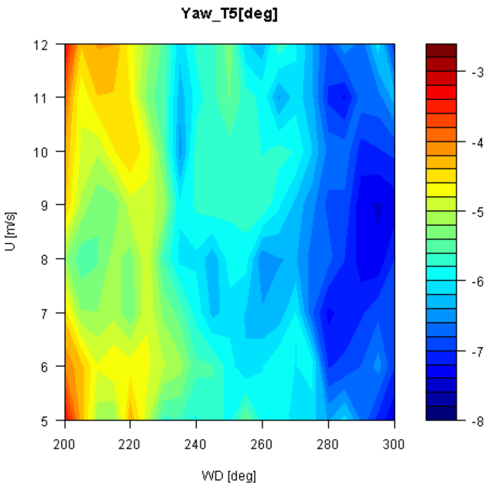


(e) Tip speed ratio of turbine 6, 5 minute average

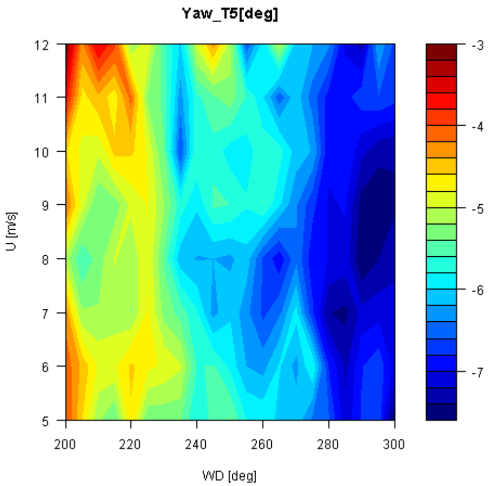


(f) Tip speed ratio of turbine 6, 10 minute average

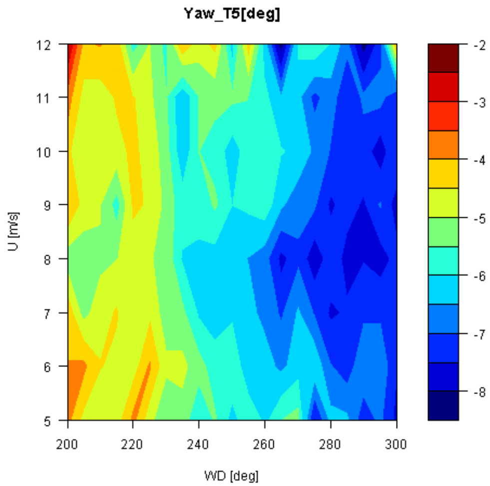
Figure C.4: Tip speed ratio of turbine 5 (above) and turbine 6 (below) for configuration 00xxx



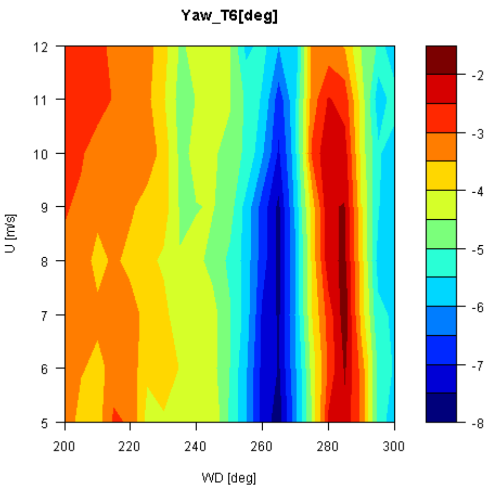
(a) Yaw angle of turbine 5, 2 minute average



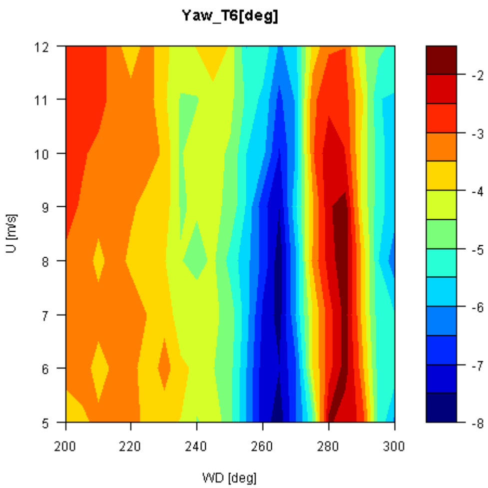
(b) Yaw angle of turbine 5, 5 minute average



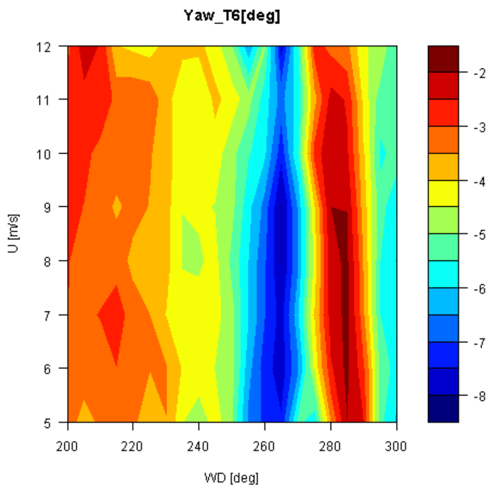
(c) Yaw angle of turbine 5, 10 minute average



(d) Yaw angle of turbine 6, 2 minute average

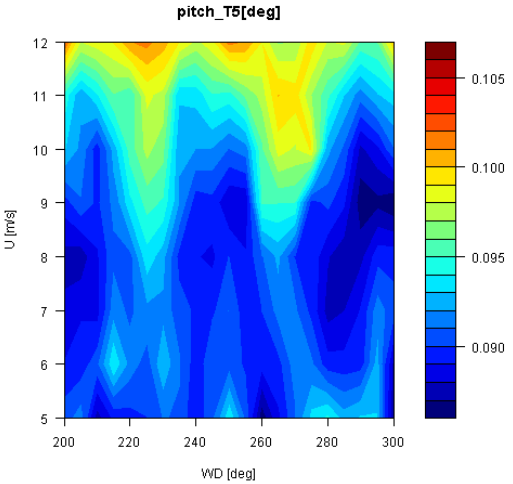


(e) Yaw angle of turbine 6, 5 minute average

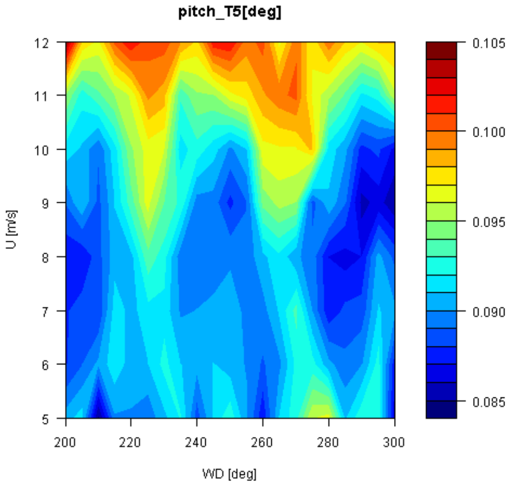


(f) Yaw angle of turbine 6, 10 minute average

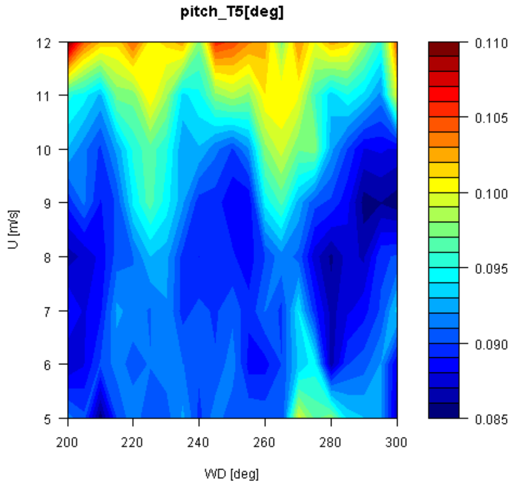
Figure C.5: Yaw angle of turbine 5 (above) and turbine 6 (below) for configuration 00xxx



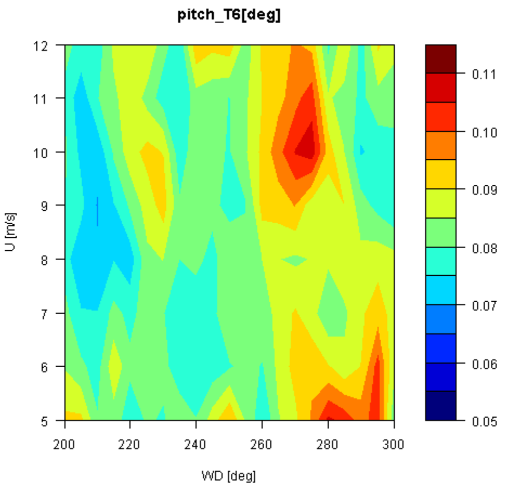
(a) Pitch angle of turbine 5, 2 minute average



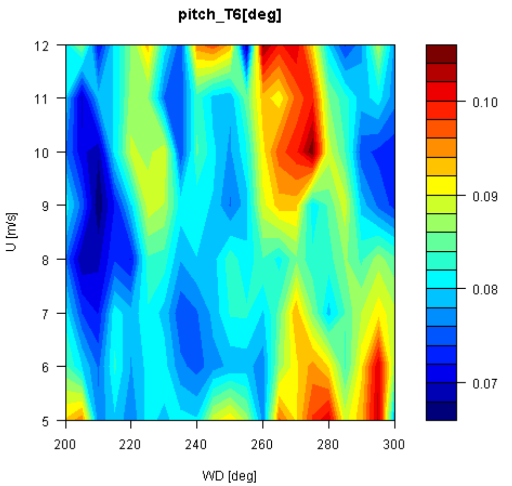
(b) Pitch angle of turbine 5, 5 minute average



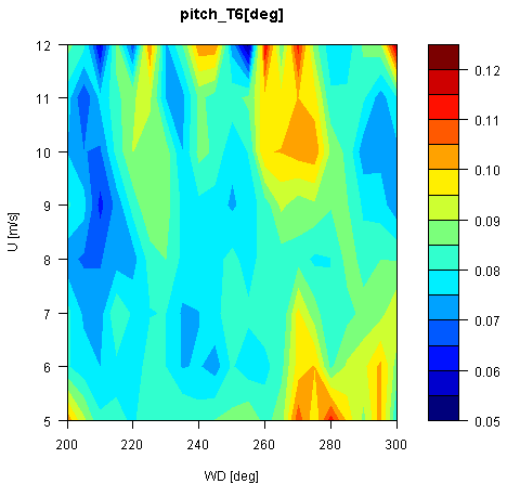
(c) Pitch angle of turbine 5, 10 minute average



(d) Pitch angle of turbine 6, 2 minute average



(e) Pitch angle of turbine 6, 5 minute average



(f) Pitch angle of turbine 6, 10 minute average

Figure C.6: Pitch angle of turbine 5 (above) and turbine 6 (below) for configuration `00xxx`

ECN

Westerduinweg 3
1755 LE Petten
The Netherlands

P.O. Box 1
1755 ZG Petten
The Netherlands

T +31 88 515 4949
F +31 88 515 8338
info@ecn.nl
www.ecn.nl