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Results of Sexbierum Wind Farm; double wake measurements

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Results of Sexbierum Wind Farm; double wake measurements
– Revised –

Summary

In the framework of the JOULE-0064 'Full-scale Measurements in Wind Turbine Arrays' in the period between March-May 1992 measurements have been performed in the Sexbierum Wind Farm. The aim of the measurements is to provide data for the validation of wake and wind farm models, which are being developed simultaneously, and to provide input data for wind turbine load calculation programmes.

The campaign concerned measurement of the wind speed, turbulence and shear stress behind two wind turbines in line, which were at an inter-distance of 5 rotor diameters. The wind speed sensors were mounted on three masts at a position of 4 rotor diameters behind the second machine. Besides detailed measurements of the wind field, the power of the turbines was measured.

A database has been compiled containing 1-minute averaged values of the measured quantities. The database was analysed using a two-dimensional bin analysis with respect to the undisturbed wind direction and wind speed.

The analysis contains horizontal and vertical profiles of the:
- U-,V-, and W-component of the wind in the wake;
- turbulence intensities in three directions and turbulent kinetic energy in the wake;
- shear stresses u'v', u'w' and v'w' in the wake.

These quantities are presented both in dimensional as in non-dimensionalized form.

With the data base a useful set of data is created for the validation of wake and wind farm models.

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List of symbols

a_{hub}	Weibull scale factor at hub height
c_P	Power coefficient
D	Rotor diameter
H	Hub height
I	Turbulence intensity (e.g. u'/U)
k	turbulent kinetic energy per unit mass $\frac{1}{2}(u'^2+v'^2+w'^2)$
k_{hub}	Weibull shape factor
M_{72}	Meteo mast 7, height 2 (= hub height)
P	Turbine Power
T_{36}	Turbine 36
T_{37}	Turbine 37
T_{38}	Turbine 38
U	wind speed component along the undisturbed wind
u'	rms value of turbulent velocity fluctuations in U-directions
u'v'	U-V component of turbulent shear stress
u'w'	U-W component of turbulent shear stress
U_0	undisturbed wind speed
$u_{0'}$	undisturbed U-component of turbulent velocity fluctuations
V	wind speed component perpendicular to the undisturbed wind direction
v'	rms value of turbulent velocity fluctuations in V-directions
v'w'	V-W component of turbulent shear stress
W	vertical wind speed component
w'	rms value of turbulent velocity fluctuations in W-directions
z	height
z_0	roughness height
δ	wind direction
κ	Von Kármán constant
λ	tip speed ratio
ρ	air density

suffix

max	maximum value
min	minimum value
0	undisturbed conditions

1 Introduction

During 1992, a detailed measuring campaign was carried out in the Sexbierum Wind Farm in order to collect experimental data on the wind speed, turbulence intensity and shear stresses in the wakes of two wind turbines in line. This report gives the results of the measurements and of the bin analysis of the data. Further, it describes the measuring conditions and the geometry of the wind farm and the turbines. Future measuring campaigns will be described in separate reports. In a later stage the reports will be combined in a final report. This final report will also contain the results of long term power measurements and turbulence spectra in the wake. The purpose of this report is to document the results of the analysis and to pass the information to the participants in the project Wake and Wind Farm Modelling (JOUR-0087), who will use it for the development and validation of wake models.

The measuring campaign is part of the CEC JOULE project 'Full-Scale measurements in Wind Turbine Arrays' (JOUR-0064). The project aims at collecting full-scale data for the purpose of:
- validation of wake and wind farm models;
- providing input data for load calculations.

To this end long term measurements and short term campaigns are carried out in various wind farms within the CEC.

In the Sexbierum wind farm the following quantities are monitored:
- fast rate wind speed data in wakes: spectra and wake data;
- wind turbine power;
- fatigue loads: rain flow counts of load cycles in various components, such as blades, hub and shaft.

Spectral wake data, wind turbine power data and results of rain flow counts will be reported, separately.

In The Netherlands KEMA and TNO jointly carry out the measurements and the analysis of the wake data. KEMA is responsible for the measurements and pre-processing of the data; TNO is responsible for the experimental set-up and the analysis of the data.

Chapter 2 describes the experimental set-up of the measurements. It gives details on wind farm lay-out, properties of the wind turbines and measuring sensors and procedures. Chapter 3 describes the data analysis procedure, which has been applied and chapter 4 describes the results of the analysis.

2 Experimental set-up

2.1 Sexbierum wind farm

2.1.1 Lay-out

The Dutch Experimental Wind Farm at Sexbierum is located in the Northern part of The Netherlands at approximately 4 km distance of the seashore. The wind farm is located in flat homogeneous terrain, mainly grassland used by farmers for the grazing of cows. In the direct vicinity of the wind farm only a few scattered farms are found.

The wind farm has a total of 5.4 MW installed capacity consisting of 18 turbines of 300 kW rated power each. The wind turbines are placed in a semi-rectangular grid of 3×6 rows at inter-distances of 5 rotor diameters along one major grid line and at an inter-distance of 8 diameters perpendicular to this grid line (see figure 2.1). The direction of the rows is at 7° with the North.

Around the wind farm there are 7 meteorological masts, which enables the measurement of the undisturbed wind conditions for every wind direction. Further, the pressure and temperature are measured. Masts 4 and 6 are parallel to the prevailing wind direction and have wind sensors at 3 heights. The other 5 masts have sensors at hub height. Turbine T36 has been instrumented to study the wake effects on the wind turbine loads.

The prevailing wind direction in the wind farm is along the line T18 to T36. The wind climate at hub height is given by Weibull frequency distribution with scale factor a_{hub}=8.6 m/s and shape factor k_{hub}=2.1. The average wind speed is 7.6 m/s.

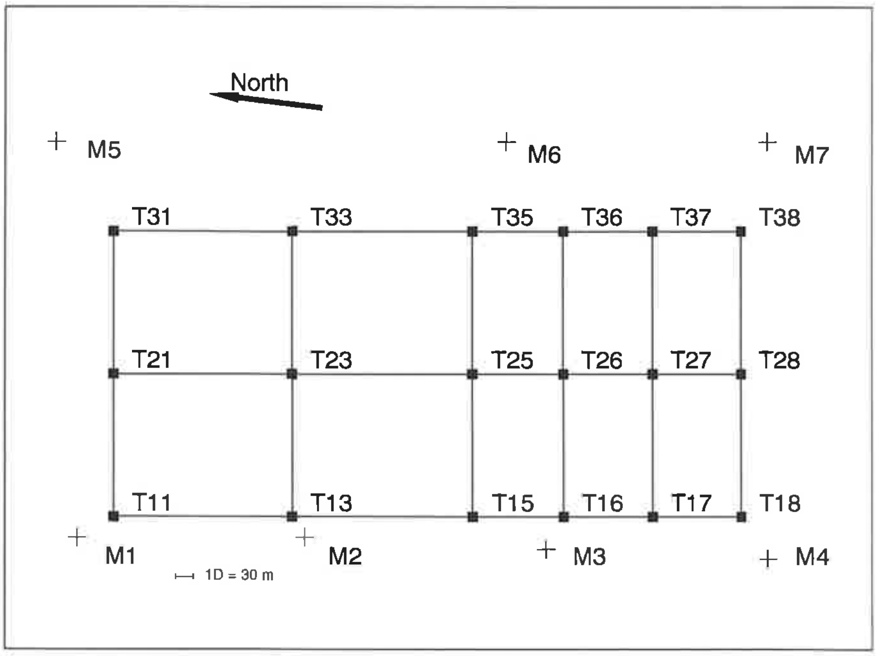

Figure 2.1 Lay-out of Sexbierum Wind Farm

2.1.2 Turbines

The wind turbines in the wind farm are HOLEC machines with three WPS 30/3 blades and with a rated power of 310 kW. The rotor diameter is 30.1 m, the hub height is 35 m. The turbines contain synchronous generators and operate at variable speed. In order to obtain maximum efficiency the tip speed ratio is kept constant up to a wind speed of 10 m/s. Above this wind speed the power is limited by means of pitch control. The machines have a cut-in wind speed of 5 m/s; a rated wind speed of 14 m/s and a cut out wind speed of 20 m/s.

The control computer of the turbine takes care of these action and also takes care of yawing. The input data for the yawing actions comes from the wind farm control computer.

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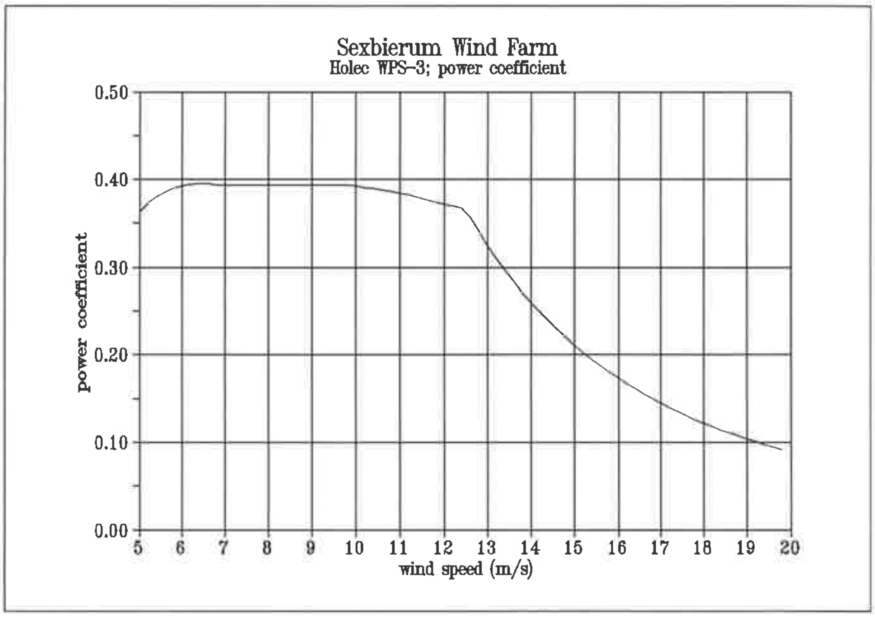

Figure 2.2 Calculated power coefficient of HOLEC WPS-30 wind turbine

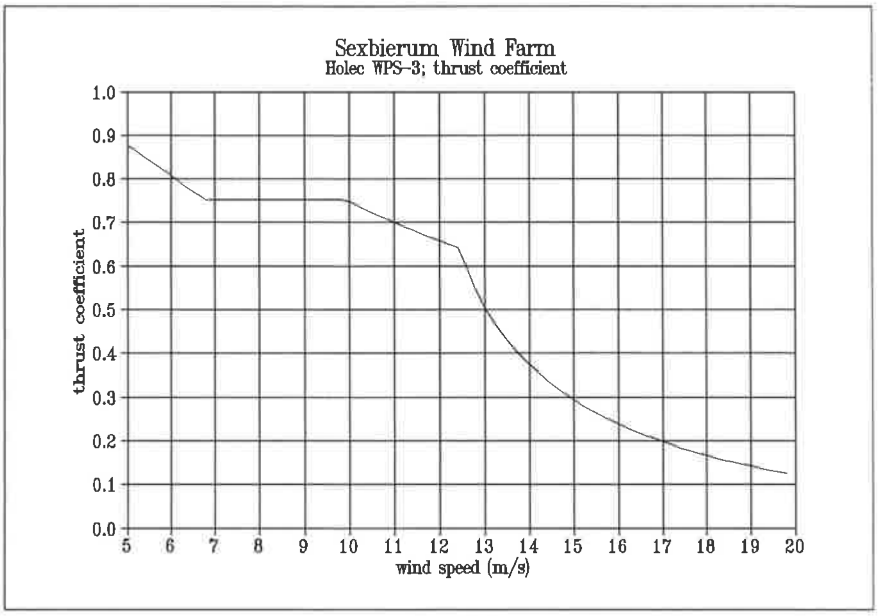

Figure 2.3 Calculated thrust coefficient of HOLEC WPS-30 wind turbine

Figure 2.2 gives the calculated power coefficient; figure 2.3 gives the calculated thrust coefficient of the wind turbine. In Annex A1 more detailed data can be found on the HOLEC wind turbine.

2.1.3 Data acquisition

The data-acquisition system and instrumentation of the wind farm serves the following purposes:
- monitoring and control of the wind farm;
- detailed measurements of the wake structure inside the farm;
- wake effects on the mechanical loads on the turbines;
- wake effects on the aggregate wind farm power;
- electrical behaviour of the wind farm.

For this purpose the wind farm has a central computer, which takes care of monitoring and control of the wind farm and a data-acquisition system consisting of measuring computers and data elaboration computers (see figure 2.4).

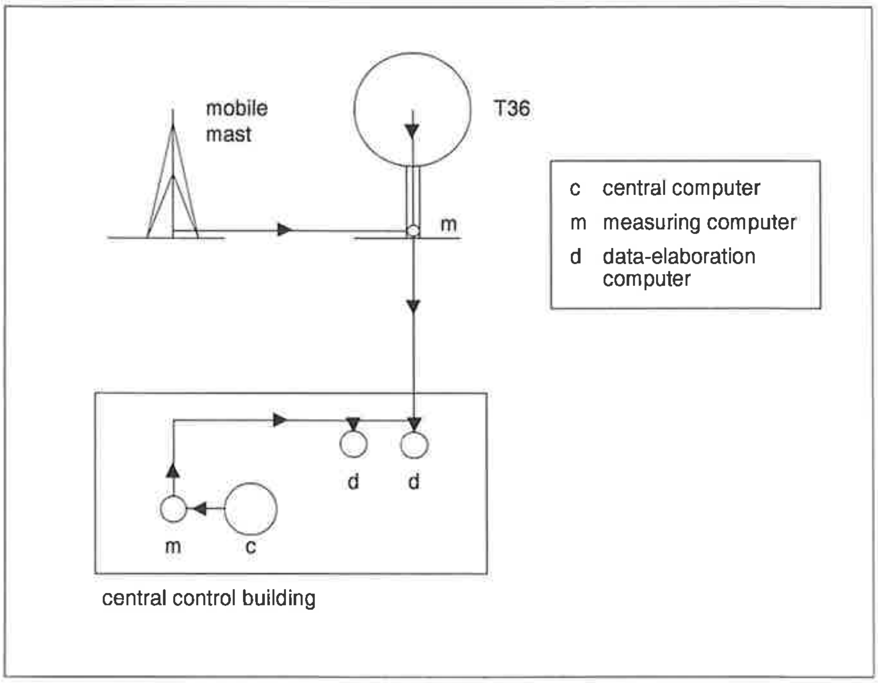

Figure 2.4 The data-acquisition system of the Sexbierum wind farm

The signals from the extra-instrumented turbine T36 are sampled at 32 Hz by a measuring computer inside the tower. The signals from the mobile measuring masts are also connected to this computer and sampled at 4 Hz.

Signals with respect to the electrical behaviour of the wind farm are sampled at 32 Hz by a measuring computer in the central control building. This computer is connected to the central computer which supplies at 1 Hz the following data:
- undisturbed wind speed and wind direction from the stationary wind masts;
- air pressure and temperature;
- status of each wind turbine.

All acquired data are passed to the two central data elaboration computers in the central control building. The data can be processed on-line using a statistical software or can be stored on tape or optical data for further processing off-line.

2.1.4 Instrumentation

Meteorological masts
The wind farm is surrounded by 7 fixed wind measurement towers. The locations of the towers are given in figure 2.1. Each tower has a wind anemometer and a wind vane at 35 m (hub height). The towers 4 and 6 have also wind sensors at 20 m and 50 m height. At mast 3 the temperature and the air pressure are measured. The signals from the meteorological tower are sampled at a rate of 1 Hz.

Instrumentation of turbines
Turbine T36 (see figure 2.1) has been extra instrumented. It contains sensors for the measurements of mechanical loads in the blades, the hub, the tower and the drive train. Sensors have been mounted for measurement of the pitch angle, blade position and nacelle direction. Further, various electrical signals are measured. The signals are sampled at a 32 Hz sampling rate. A complete list of the measured signals is given in annex A2.

Mobile wind measuring masts
There are three mobile masts in the wind farm for detailed wake measurements. It is possible to install the masts at any place inside the wind farm enabling detailed wind measurements of the wake structure.

One mast is equipped with 3-component propeller anemometers at 47 m, 35 m and 23 m, respectively. At heights of 41 m and 29 m two extra cup anemometers have been mounted. The other two masts contain 3-component propeller anemometers at 35 m. The signals from the mobile masts are sampled at a 4 Hz sampling rate.

The 3-component propeller anemometer consists of three light-weight carbon fibre propellers mounted on a pyramid-shaped rig at angles of 30° relative to each other. Combination of the three anemometer signals gives the X, Y and Z components of the wind. The sensor was calibrated in a wind tunnel and yields reliable results within a cone of approximately 30° relative to the sensor centre-line.

2.2 Measuring campaign

2.2.1 Description

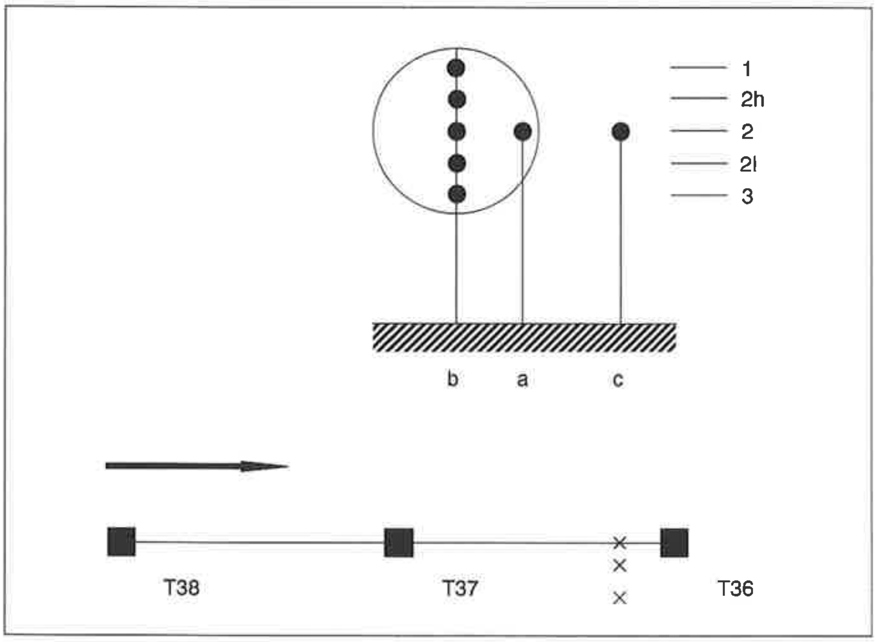

Figure 2.5 Experimental set-up during the measuring campaign

Between March and May 1992 measurements have been made in the double wake of T38 and T37, just ahead of T36 (see figure 2.5). In the indicated direction the distance between the turbines is 150 m, i.e. 5 rotor diameters.

The 3 mobile masts were installed at a distance of 120 m (4 D) behind T37. Mast **b**, which is in line with the turbines, contained the 3-component propeller anemometers at 47 m, 35 m and 23 m, denoted **b1**, **b2**, and **b3** respectively. The middle anemometer was thus mounted at hub height, the top and bottom anemometers at 0.4 rotor diameters above an below hub height. At the two intermediate heights, i.e. 41 m and 29 m, cup anemometers were mounted, denoted b2h and b2l. Next to the centre-line mast **b**, masts **a** and **c** were erected at distances of 12 m and 30 m, respectively. Both masts contained a 3-component propeller anemometer at 35 m height. The undisturbed wind conditions were measured with cup anemometer and a wind vane at 35 m height in mast M7. Since the sensors were mounted on top of the mast no wind shading of the measuring tower is to be expected. Simultaneously with the wind measurements the power of T36, T37 and T38 was measured. Table 2.1 gives an overview of the stored data.

Table 2.1 Overview of the measured and stored data

Sensor	Signal
a2..c2	U, V, W, U_{max}, U_{min}, V_{max}, V_{min}, W_{max}, W_{min}, u'^2, v'^2, w'^2, $u'v'$, $u'w'$, $v'w'$
b2l, b2h	U, u', U_{max}, U_{min}
P36..P38	P, σ_P, P_{max}, P_{min}
wvel72	U_0, u'_0, U_{0max}, U_{0min}
wdir72	δ_0, $\sigma_{\delta 0}$, δ_{0max}, δ_{0min}

The measured data were stored on hard disk and every day a back-up was made on magnetic tape. Later, the tapes were pre-processed off-line into 1-minute averaged samples.

2.2.2 Observations

During the campaign no serious problems arose. There was a problem with sensor b21, caused by hum in the measurement amplifier of the upper leg of the sensor which resulted in, among others, in an apparent average vertical wind speed. The signals have been corrected by setting the vertical component of the wind speed to zero. As a result no vertical turbulent velocities are available for this sensor.

During maintenance after the measurement campaign had finished it was noticed that sensor c2 showed an angle off-set with the main axes of 11 degrees. This has been corrected during pre-processing of the data. The results of this sensor for large angles of attack may therefore be unreliable.

The sensor data are transmitted to the central data-acquisition computer by means of fibre-optics. During the measurement campaign it showed that the fibre-optics transmissions were sometimes shortly interrupted. This occurred at irregular intervals between 15 minutes and a few hours and was due to bad connections. Since the interruptions were very short the measurements have been hardly affected. However since the acquisition computer was instructed to record only data when both the upstream machines were running, every time an interruption occurred the measurements were temporarily stopped and the results were written to a file. Immediately after the interruption the signal transmission resumed and a new recording was started. This has resulted in a large number of smaller files (time series with a length between 10 and 90 minutes). Meanwhile this problem has been solved and transmissions interruptions no longer occur.

3 Analysis

3.1 Pre-processing and resulting database

A first data-reduction and quality control of the measured data was done during pre-processing of the data. The 1 Hz and 4 Hz time series of the measured quantities were manipulated in order to obtain time series of 1-minute averages of various quantities such as the wind speed, the turbulent velocities and the shear stress. Table 2.1 gives an overview of the time series contained in the data base. The 1-minute data have served as the working data base. The chosen format makes it possible to combine the 1-minute averages into samples with multiple-minute averages. Annex A3 gives the statistical operations used for the data manipulation.

3.2 Time averaging

Before the data base was further analysed, the samples were combined to obtain 3-minutes averaged quantities. Considerations for selecting a period of 3 minutes were the following:

- **stationarity of the data**
  It is common practice to assume a spectral gap for wind velocity data between 10 minutes and 1 hour. Shorter averaging periods will result in non-stationary data;

- **coherence between undisturbed wind signal and wake signal**
  Meteorological mast 7 and the mobile masts are 350 m apart, assuming a wind speed of 8 m/s, this corresponds to a delay of 45 seconds, approximately. In order to obtain a reasonable coherence between the wake wind data and the undisturbed wind data it is necessary to use an averaging period of more than this period.

- **effect of slow wind direction variations**
  If the averaging period is chosen too long, slow variations in the wind direction will blur the details of the wake.

- **number of available records**
  Longer averaging periods result in less samples. A 3-minutes averaging period resulted in a database with 573 samples.

- **effect on wind turbines**
  Power curves for wind turbines are most often determined using averaging periods of 10 minutes; Wind fluctuations shorter than 1 minute are most important for the determination of wind turbine loads. Slower fluctuations are absorbed by the control system.

The wake deficit profiles are hardly affected by the averaging period. However, non-linear signals, such as turbulent velocities and shear stresses are indeed affected by the changing averaging period. Longer averaging periods result in higher turbulent velocities, for instance. Nevertheless, it is not easy to select an optimum averaging period. Taking into account the arguments listed above, it was decided to analyse the data on the basis of 3-minutes averaged samples.

3.3 Frame of reference

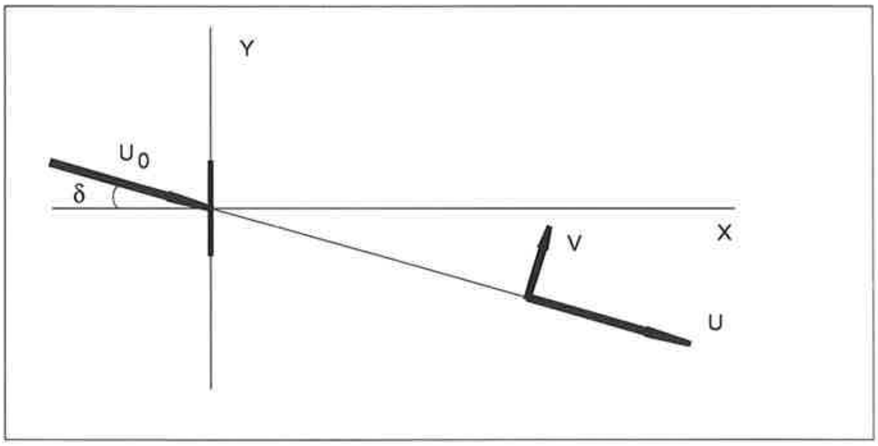

Figure 3.1 Definition of the frame of reference

Besides scalar quantities, such as the wind turbine power and the total turbulent kinetic energy k, also vector quantities (wind vector) and tensor quantities (turbulent co-variance matrix) had to be analysed. Therefore it was necessary to define a proper frame of reference for the presentation of the data. It was decided to couple the frame of reference of the wake data to the co-ordinate system of the undisturbed wind. The definition of the frame of reference is given in figure 3.1. The undisturbed wind direction is given with respect to the line connecting the turbines T38 and T36, defined as 0 degrees. The u-component is parallel to the undisturbed wind, the v-component is perpendicular to the undisturbed wind in the horizontal plane. The w-component is in the vertical direction. u,v and w define a right-handed co-ordinate system. This conforms to the normal meteorological definitions. Before the 3-minutes samples were bin-sorted, they were converted first to the above given coordinate system, using the co-ordinate transformation formulas given in Annex A3.

During the analysis of the data it showed that the sensor used to measure the undisturbed wind direction had a misalignment of 5°. Prior to the analysis, the undisturbed wind direction and the other measured quantities have been corrected for this misalignment.

3.4 Bin-sorting

The 3-minutes samples were sorted into different bands of undisturbed wind speed and wind direction. Between 5 m/s and 12 m/s a bin width of 1 m/s was used; above 12 m/s the bin width was taken equal to 2 m/s. The selected wind direction bin width was 2.5°.

For each bin the mean value, variance, minimum and maximum values of the measured quantities were determined and saved in separate files. Together with these quantities the number of samples in the bin, the average undisturbed wind speed and the average wind direction were saved.

Since the wind turbines operate at constant tip speed ratio in the interval 6-10 m/s, it was expected that the wake effects would not vary much over this speed range. A selected number of bin analyses has been made using a single wind speed bin of 5-10 m/s.

3.5 Dimensionless quantities

Except in dimensional form the results are also presented in a non-dimensionalized form.
First, the measured quantities have been non-dimensionalized with the undisturbed wind speed:
- U/U_0, V/U_0, W/U_0;
- u'/U0, v'/U0, w'/U0, k/U_0^2, u'/u'_0;
- $u'v'/U_0^2$, $u'w'/U_0^2$, $v'w'/U_0^2$.

Second the quantities have been non-dimensionalized using local parameters:
- V/U, W/U;
- u'/U, v'/U, w'/U, k/U;
- u'v'/k, u'w'/k, v'w'/k.

In the next chapter the results of the analysis are presented.

4 Results

This chapter contains the results of the analysis performed on the double wake data described in the previous chapters. First, the undisturbed wind conditions during the measuring period are described. Secondly, the power output of the turbine in the free-stream (T38) and the power output of turbine T37 (single wake) and T36 (double wake) is investigated. The next sections describe the results of the wind measurements on the mobile measuring masts. Successively, the wind speed, the turbulence levels and the shear stresses in the wake are treated for a selected number of cases. A comprehensive overview of the analysis results can be found in annex A4.

4.1 Undisturbed wind conditions

This section describes the undisturbed wind conditions at the Sexbierum wind farm during the described measuring period. Further a description of the undisturbed turbulence intensity is given and the roughness length of the upwind terrain is derived.

4.1.1 Wind speed distribution

Figure 4.1 gives the wind speed distribution during the measuring period. It shows that the majority of the data has been found between 7 and 9 m/s. The figure also shows that the wind direction distribution is non-symmetrical about the axis.

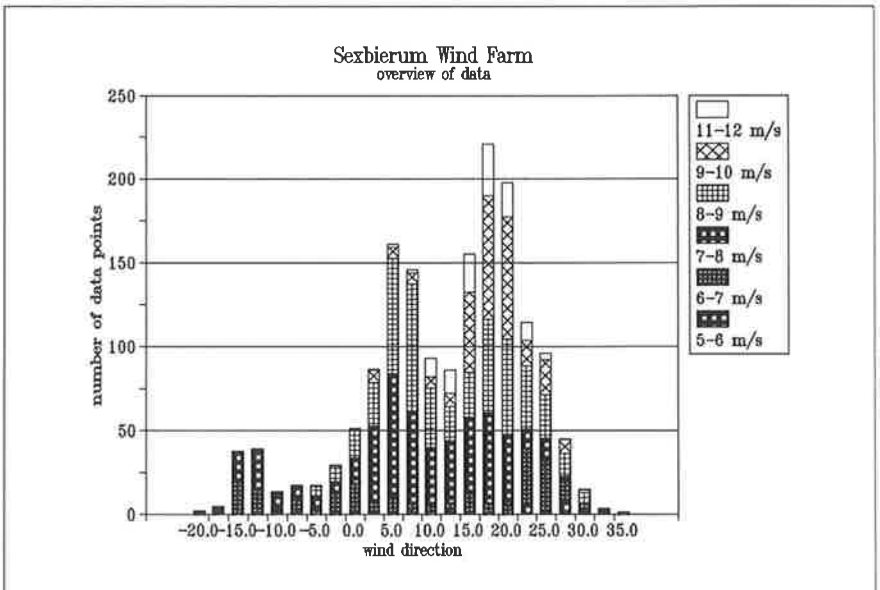

Figure 4.1 Overview of available data

4.1.2 Turbulence intensity

Table 4.1 Turbulence intensity of undisturbed flow as a function of averaging time

Averaging time (min)	Turbulence intensity	Corrected intensity	z_0	Number of samples
1	0.086	0.169		1726
3	0.095	0.136	0.046	573
10	0.107	0.132	0.038	137
60	0.131	0.138	0.051	10

The turbulence intensity has been determined by applying linear regression on pairs of undisturbed wind speed U_0 and turbulent velocity u'_0. The measured turbulent intensity is a function of the averaging time. This is shown in table 4.1.

Panofsky and Dutton [1984] give a relation between the turbulence intensity, using an averaging period of one hour, and the upstream terrain roughness. The relation is given by:

$$I = \frac{\alpha \cdot \kappa}{\ln(z/z_0)}$$

Panofsky finds values for the constant α=2.39±0.03. Beljaars has analysed turbulence data in the Dutch situation and finds the value α=2.2.

The turbulence intensity corresponding to an averaging period of 1 hour was determined in two distinct ways:

1. the data was processed using an averaging time of 60 minutes. Using this method the value I=0.131 was found. Although this is the most straightforward way, it has the disadvantage that only a few 60-minutes samples were available, since the database contains only very few continuous time series of 60 minutes length;
2. [ESDU] gives expressions for the transformation of turbulence intensities obtained using shorter averaging periods into turbulence intensities based on 1-hour averaging period. This results in the corrected turbulence intensities given in table 4.1.

Discarding the value for the 1-minute averaging period and using the corrected turbulence intensities for the roughness length upstream of the farm a value of z_0=0.045±0.07 m is found.

4.2 Wind turbine power

4.2.1 Free-stream power curve; power coefficient

Figure 4.2 gives the power curve of turbine T38 using data from all available wind directions. Further, the figure shows the power coefficient of T38 derived from the given power curve.

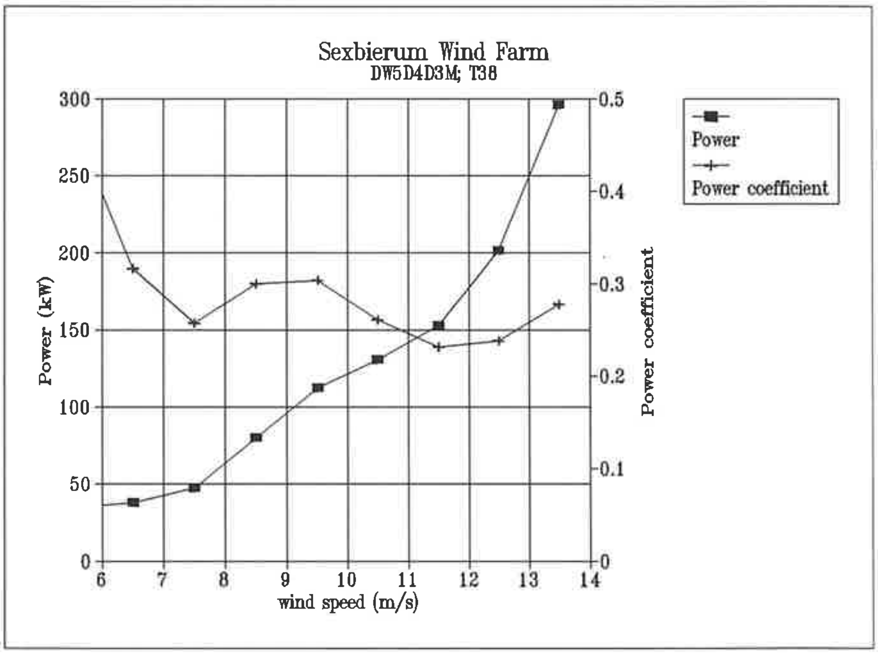

Figure 4.2 Power curve and power coefficient of wind turbine T38, based on 3-minutes averages

The figure shows that the power coefficient is more or less constant in the range between 6 and 10 m/s, which is brought about by the machine's control strategy.

4.2.2 Wake effects on wind turbine power

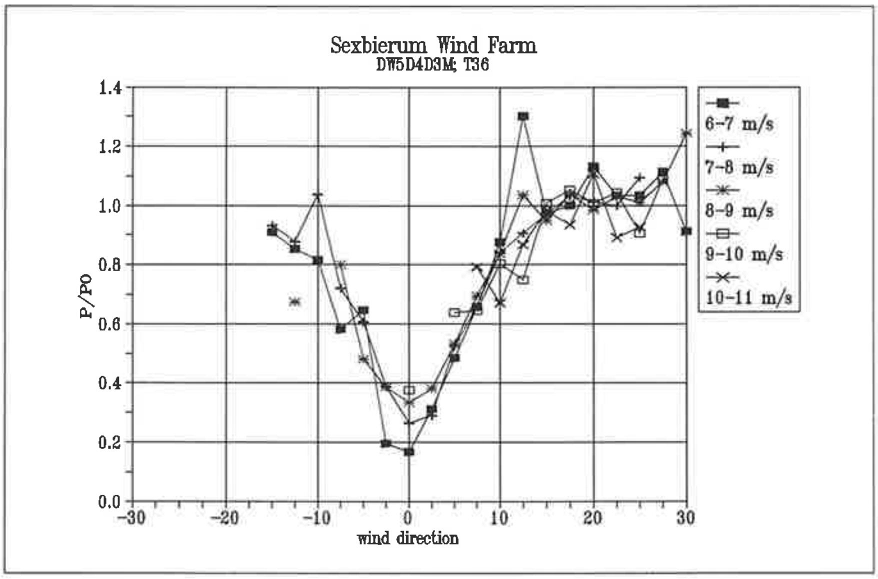

Figure 4.3 Power ratio of turbines T36 with respect to turbine T38

Figure 4.3 shows the power output of turbine T36 non-dimensionalized with the power output of T38. T36 operates in the wakes of both T38 and T37.

4.2.3 Aggregated results

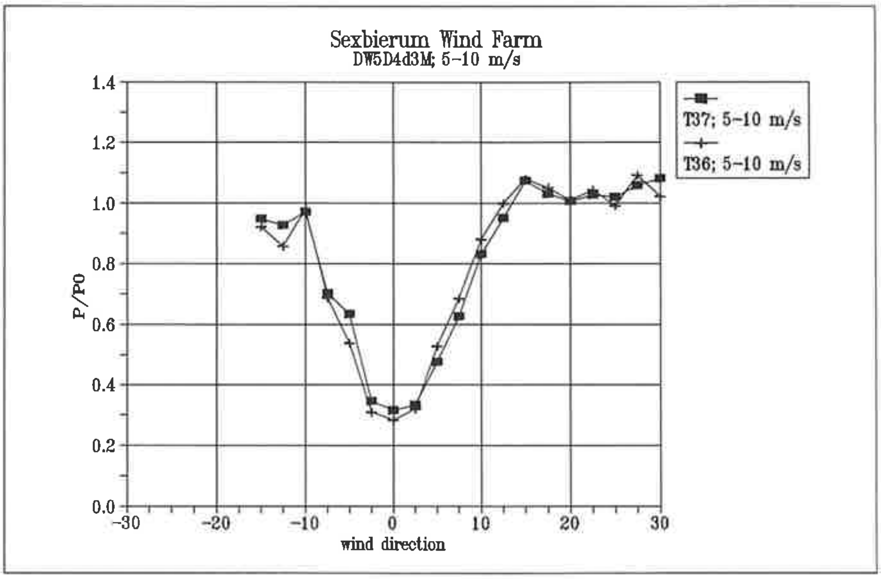

Figure 4.4 Aggregated power ratio of turbines T36 and T37 with respect to turbine T36

Figure 4.4 gives the results of the power loss due to wake effects averaged over the wind speed interval from 5-10 m/s. Remarkably, the power deficit curves of T38 and T37 almost coincide.

4.3 Wake deficit

4.3.1 Wake deficit per bin

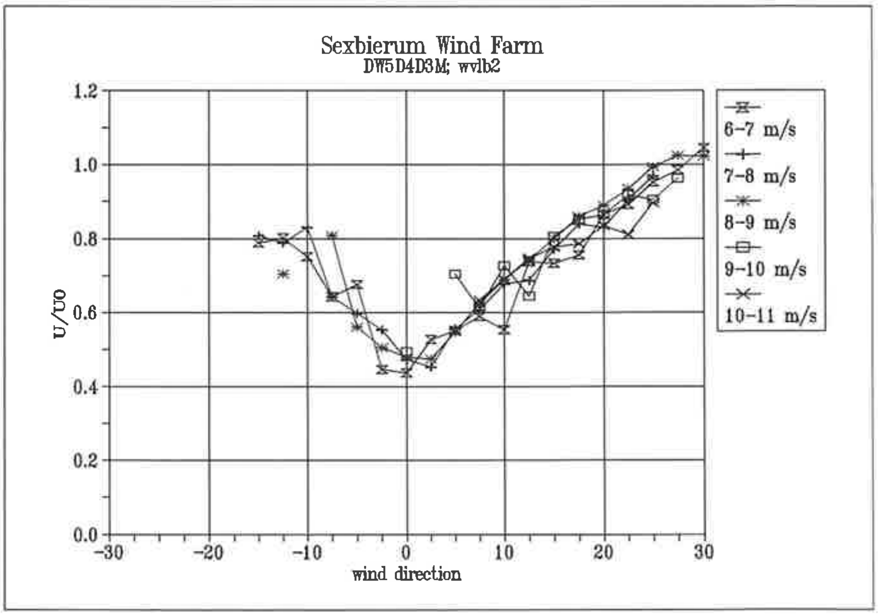

Figure 4.5 Wind speed ratio U/U_0 at sensor b2 as a function of the undisturbed wind direction

Figure 4.5 shows the wind speed ratio U/U_0 at sensor b2 as a function of the undisturbed wind direction for the wind speed classes between 6 m/s and 11 m/s. The graphs of U/U_0 of the other sensors have been gathered in annex A4.

The figure shows that the wind speed ratio U/U_0 is almost equal for the depicted wind speed classes, which can be explained by the fact that the wind turbines operate at constant tip speed ratio between 6 and 10 m/s. In this range the thrust or axial force is therefore almost constant.

At the wake centre-line U/U_0 reaches a minimum of 0.45, approximately. At an undisturbed wind direction of 30 degrees the edge of the wake is observed and U/U_0 is equal to unity. This means that the double wake is approximately 2 diameters wide. Overspeeding (U/U_0>1) which is sometimes seen at the wake edge, can not be observed in this case. If it would occur, it would be at an angles larger than 30 degrees. The figure does not show the complete wake profile. Negative wind directions were only scarcely available in the data base. The shape of the wake profile is not completely symmetrical about the origin, positive wind direction show a somewhat smaller value of U/U_0 than negative wind directions.

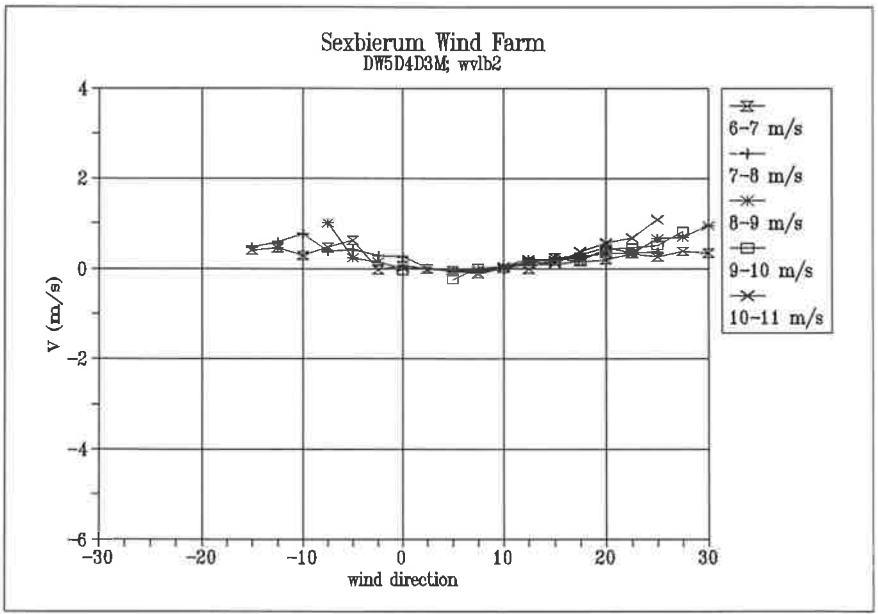

Figure 4.6 Lateral wind speed V as a function of wind direction

Figure 4.6 shows the lateral wind speed V as a function of wind direction. Clearly, the values of the lateral wind speed are small compared to those of the horizontal component. It is surprising to note that the lateral wind speed has a positive value over the whole wind direction range, with the highest values for the largest wind directions. Probably, this is an artefact caused by the sensors used. The vertical wind speed shows values nearly equal to zero, without any interesting features and is not depicted here. Since V and W are much smaller than U, the value for U is very close to the magnitude of the wind speed vector.

4.3.2 Aggregated results

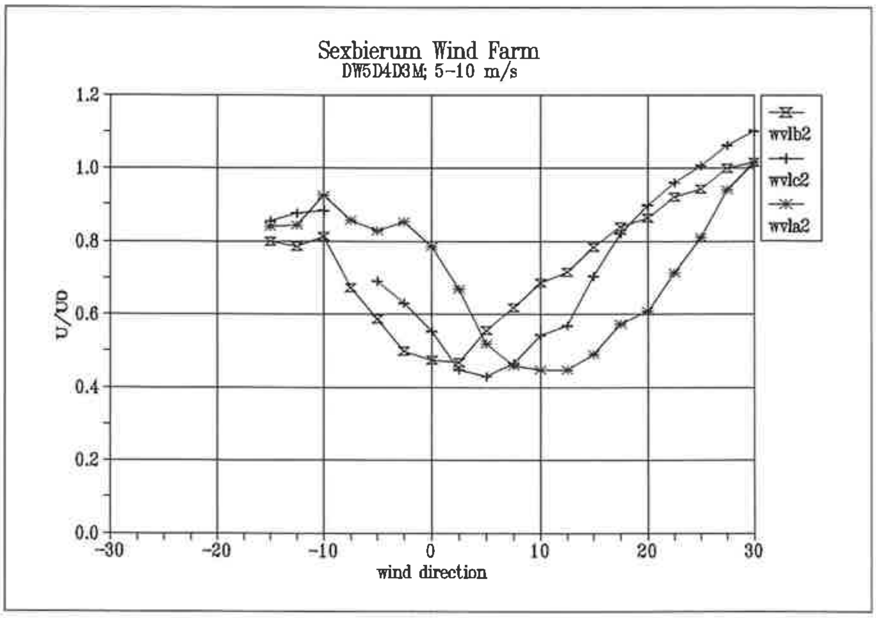

Figure 4.7 Wind speed ratio U/U_0 as a function of wind direction for sensors b2, c2 and a2

Figure 4.7 shows the aggregated results in the wind speed range of 5-10 m/s for the three sensors b2, c2, a2 in the horizontal plane at hub height. The sensors are all on one side of the line connecting turbines T38-T37-T36. b2, a2 and c2 are at a distance of 0 m, 12 m and 30 m from this line, respectively.
As is expected the minimum values of U/U_0 are shifted with respect to the 0 degree undisturbed wind direction, as is expected from the geometry of the sensor positions. Sensor c2 is at the wake centre of turbine T37 at a wind direction of 5 degrees, and sensor a2 at 14 degrees. The figure shows that the minimum of c2 is indeed found at the given value, but that the minimum of a2 is found at a smaller angle. This is due to the fact that the minimum is not found at the wake centre of T37, but is determined by the superposition of the wakes of T37 and T38. The wake centre of turbine T38 is found at 6 degrees. Further it can be noticed that the minimum ratio U/U_0 is nearly equal for the three sensors (0.45).

With the undisturbed wind direction changing, the wake configuration changes. At 0 degrees the wakes are fully immersed, but for larger angles the wakes only partially overlap. However, at one particular wind direction the three sensors give the wind speed at different positions in the wake, but for identical wake configurations.

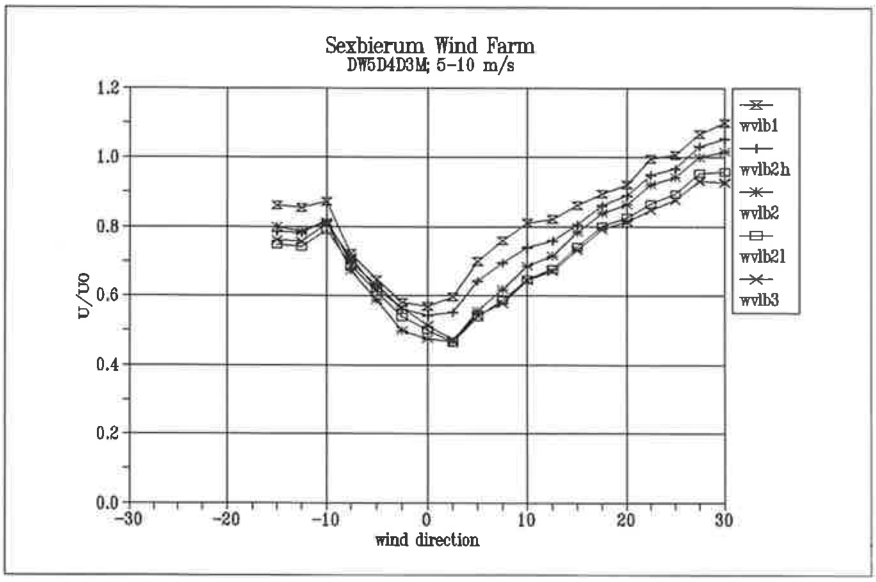

Figure 4.8 *Wind speed ratio U/U_0 as a function of wind direction for sensors b1, b2h, b2, b2l and b3*

Figure 4.8 gives the ratio U/U_0 at the 5 sensors mounted at different heights on mast b. The figure clearly reveals that the wake profiles are almost identical in shape at the given heights, with the lowest values of U/U_0 at hub height. However, the figure also shows that the profiles are asymmetrical. For negative wind directions the measured profiles coincide, while for positive wind directions they are clearly different in magnitude. Probably the effect is caused by systematic errors in the undisturbed wind measurement.

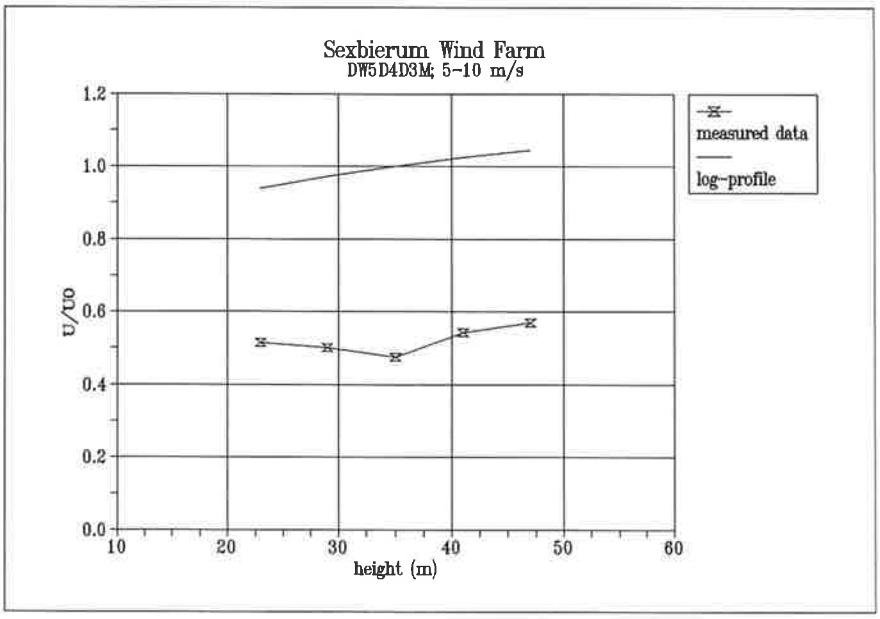

Figure 4.9 *Vertical wake profile at the wake centre-line*

In figure 4.9 the vertical profile of U/U_0 is given, together with the calculated undisturbed wind profile using z_0=0.045 m.

4.4 Turbulence intensity

4.4.1 Turbulence intensity data per bin

In this section we show the results of the analysis on the measured turbulence in non-dimensional form.

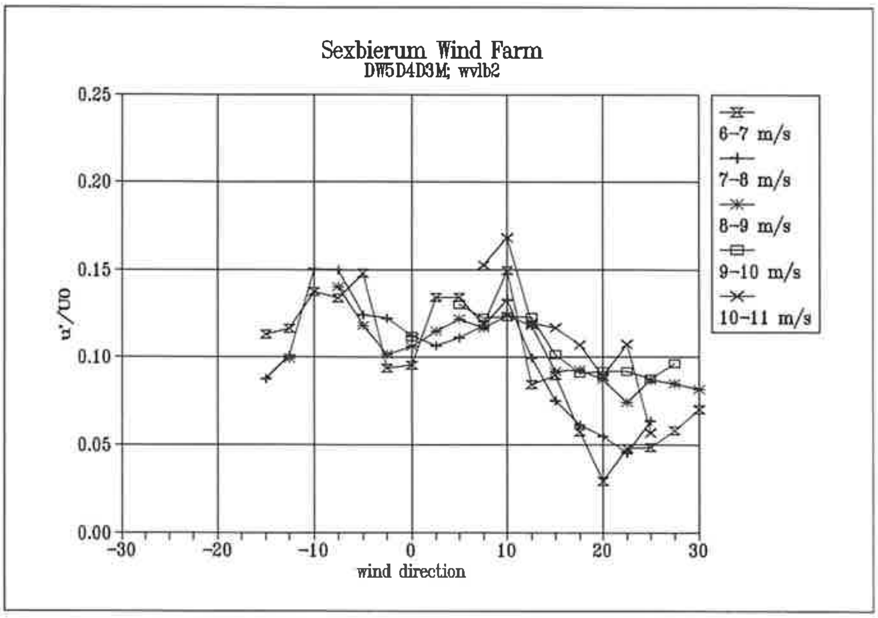

Figure 4.10 Turbulence intensity u'/U_0 as a function of wind direction at sensor b2

Figure 4.10 shows the turbulence intensity (non-dimensionalized with U_0) of the horizontal wind component for sensor b2 as a function of the wind direction. Figures 4.11 and 4.12 show the lateral and vertical turbulence intensity. The figures show that the turbulence intensity increases towards the centre of the wake. Unlike the lateral and the vertical turbulence intensity, the u-component shows peaks at a wind direction of approximately 10 degrees, which corresponds with the locus of the maximum wind speed gradient (see figure 4.5), which corresponds with maximum turbulence production. k and u' and k are more or less symmetrical about the zero wind direction, but v' and w' are higher for the negative wind direction than for the positive ones.
Although the figures show some scatter, it seems that the turbulence intensity scales with U_0 for wind directions between –10 an 10 degrees. For larger angles two branches can be observed, one for wind speeds below 8 m/s and one for the higher wind speeds.

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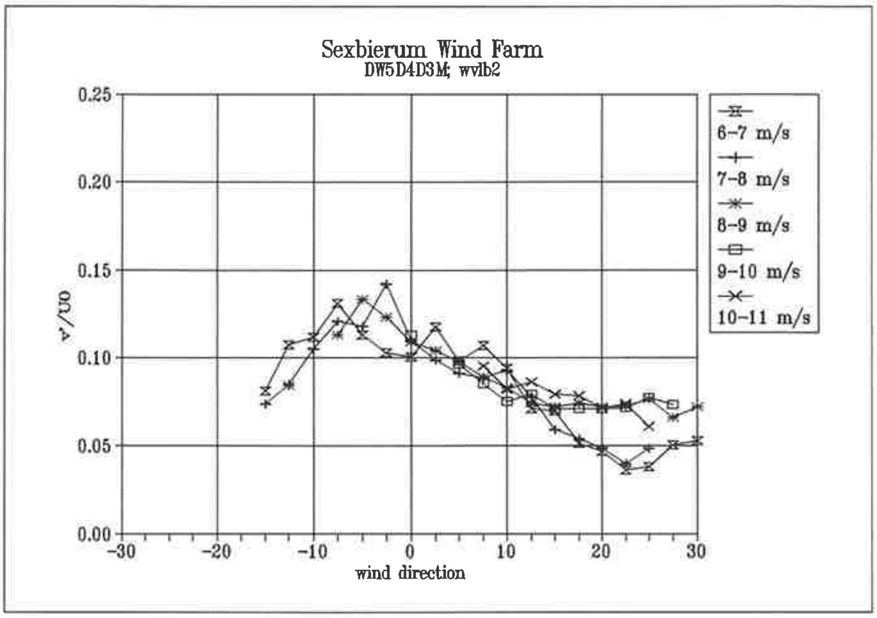

Figure 4.11 Lateral turbulence intensity v'/U_0 as a function of wind direction at sensor b2

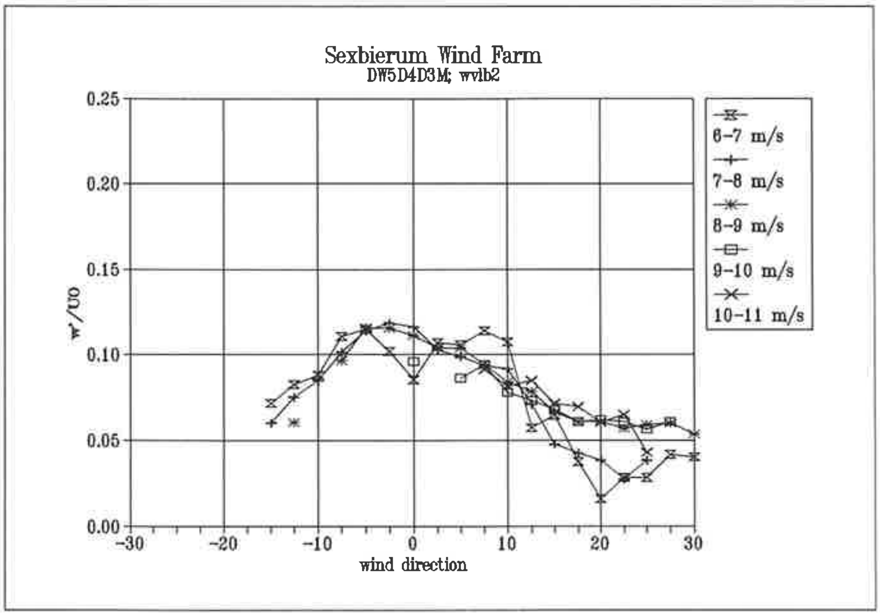

Figure 4.12 Vertical turbulence intensity w'/U_0 as a function of wind direction at sensor b2

Figure 4.13 shows the turbulent kinetic energy k (non-dimensionalized with U_0) as a function of the wind direction. The behaviour of k is roughly the same as that of the components of the turbulence. Non-dimensionalized with the local wind speed k varies much more smoothly with the wind direction.

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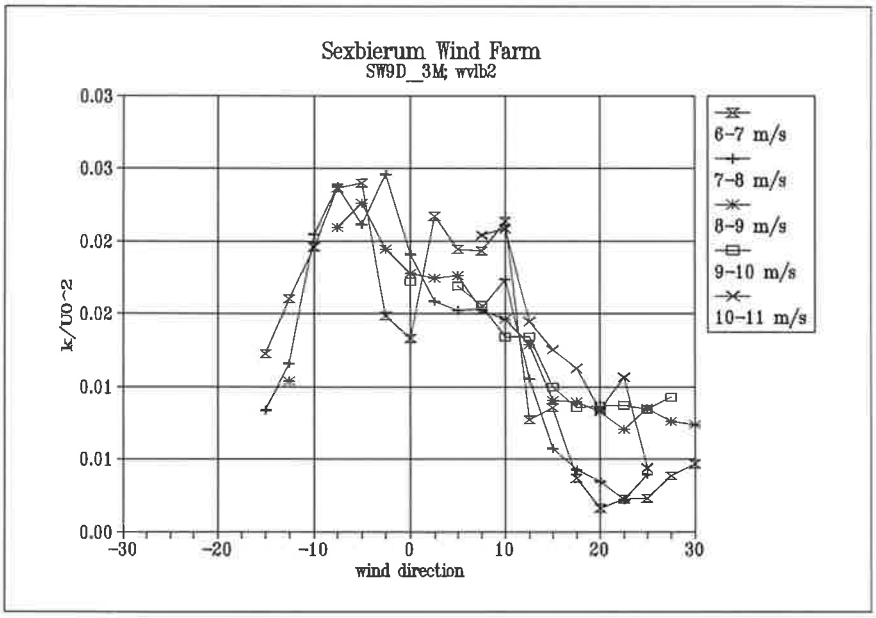

Figure 4.13 Turbulent kinetic energy k/U_0^2 as a function of wind direction at sensor b2

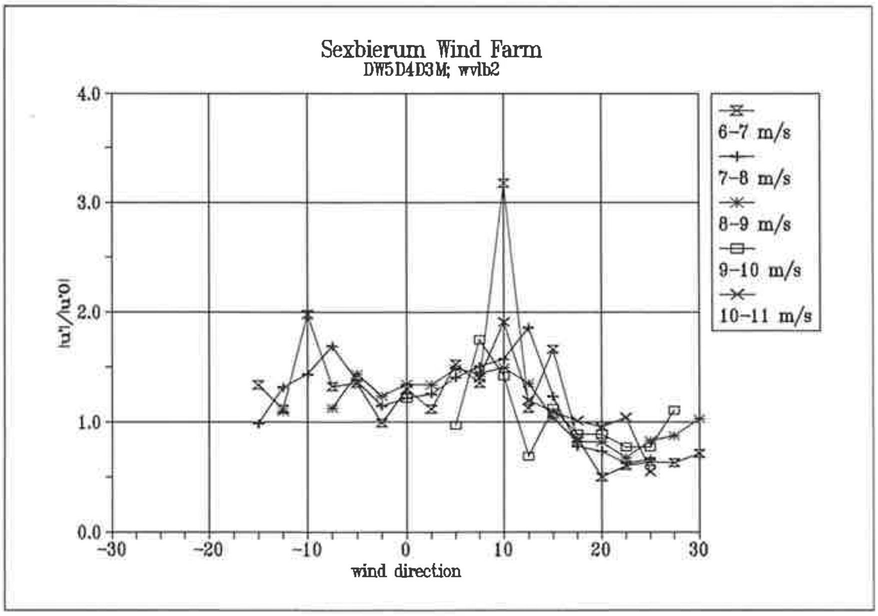

Figure 4.14 Ratio of wake turbulence and undisturbed turbulence u'/u_0' as a function of wind direction at sensor b2

In figure 4.14 the ratio u'/u'_0 is given as a function of the wind direction. The figure shows that inside the wake the turbulent velocities are higher than at the edge of the wake. Although this general behaviour is correct, it seems that there is something peculiar about these data. At the wake edge the ratio u'/u'_0 remains below unity. It is expected, however, that this ratio returns to unity at the wake edge, as for these angles the undisturbed wind conditions should be restored. It might be argued that different sensors are used for the measurement of the undisturbed wind conditions and for the wind conditions in the wake with for instance different sample rates. Nonetheless, comparison of the data of sensors b2h and b2l, which are identical to that at mast M72, shows the same results. The cause for these peculiarities are as yet unclear.

4.4.2 Aggregated results

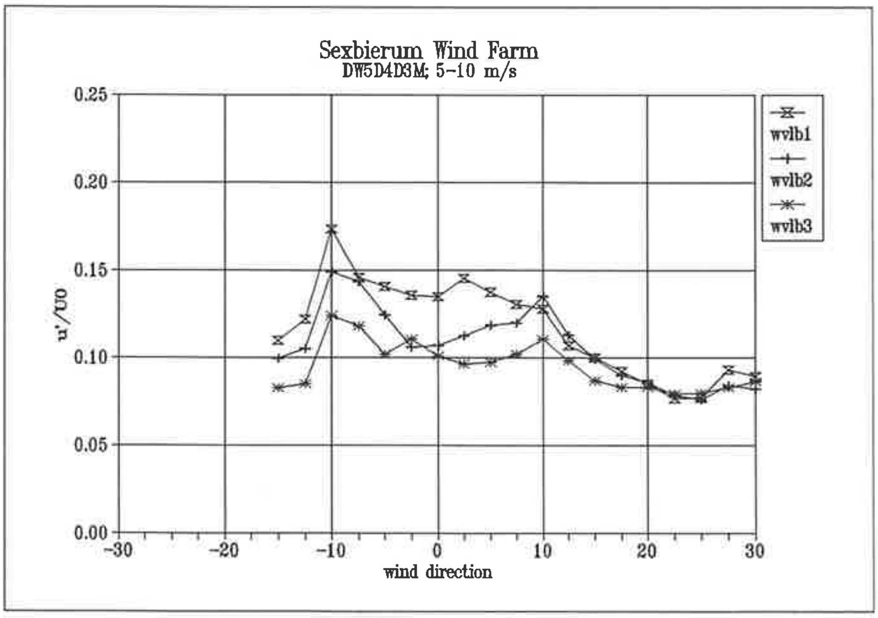

Figure 4.15 Aggregated turbulence intensity u'/U_0 as a function of wind direction at mast b

Figure 4.15 depicts the turbulence intensity u'/U_0 at mast b for the positions 1, 2 and 3. The figure shows again that there is some asymmetry in the course of the turbulence over the wind direction. Clearly, the turbulence intensity is the highest at the top-most sensor ($k/U_0^2=0.027$) and lowest at the bottom-most sensor ($k/U_0^2=0.016$). This corresponds well to what is expected. As production of turbulence is related to the wind velocity gradient, the highest turbulence is expected where the gradients are at maximum. At the highest sensor position the boundary layer wind velocity gradient is increased by the presence of the wake, while the wake decreases the gradient at the lowest sensor position (see figure 4.22).

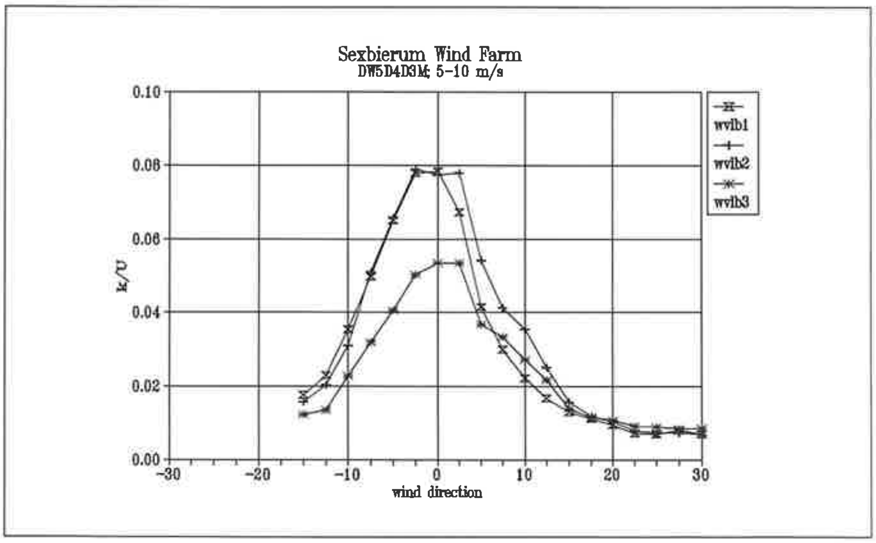

Figure 4.16 Turbulent kinetic energy non-dimensionalized with local velocity as a function of wind direction

Figure 4.16 depicts the turbulent kinetic energy non-dimensionalized with the local wind speed. Again most of the asymmetry has disappeared and the curves have a more or less Gaussian shape.

4.5 Shear stress

4.5.1 Shear stress per bin

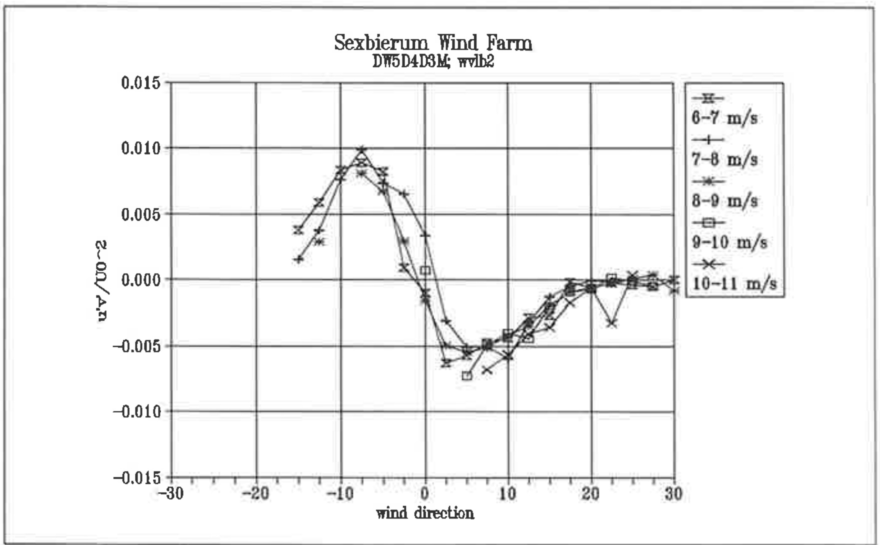

Figure 4.17 Shear stress $u'v'/U_0^2$ as a function of wind direction at sensor b2

The Reynolds-stress u'v' is the turbulent shear stress which is the driving force for the recovery of the wake deficit in horizontal direction. Figure 4.17 shows the shear stress u'v' non-dimensionalized with the undisturbed wind speed U_0 against the undisturbed wind. Starting from the right side of the figure (positive wind directions) and going to the negative wind directions it shows that at the edge of the wake $u'v'/U_0^2$ is equal to zero and then shows a minimum of -0.005. At 0° wind direction it goes through zero, it then shows a maximum of 0.01 before it relaxes again to 0 at the left edge of the wake. Generally speaking this is expected, since it is generally assumed that the shear stress is proportional to the local wind shear, i.e. the horizontal wind gradient. The fact that the curves return to zero at the edge of the wake, and that they cross the x-axis at 0° wind directions gives confidence in the quality of the data. Scaling of the data with U_0 seems to be successful.

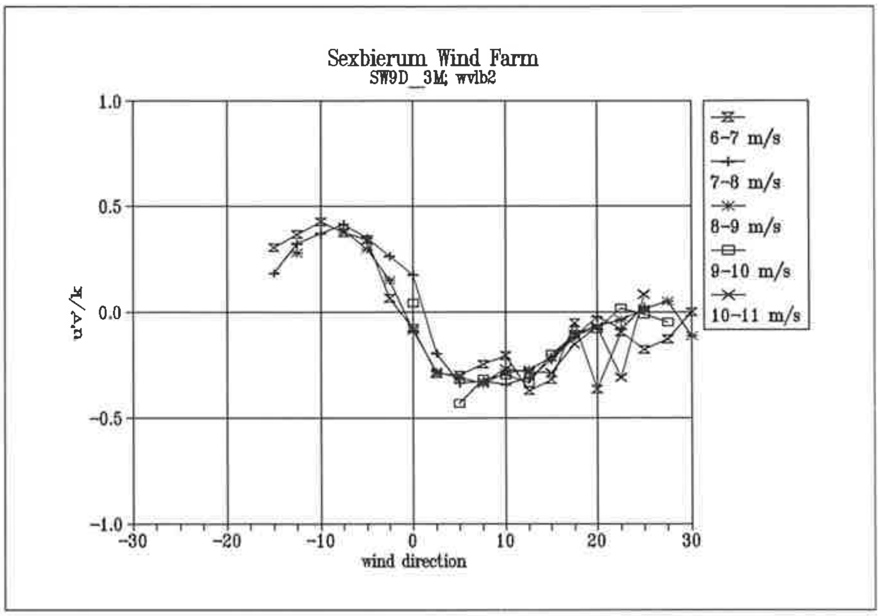

Figure 4.18 Shear stress u'v' non-dimensionalized with the local turbulent kinetic energy as a function of wind direction at sensor b2

The profile for u'v' shows to be asymmetrical. This is consistent with the measurements of the turbulence intensity and the horizontal wind profile. Figure 4.18 shows that if the shear stress is not non-dimensionalized with the undisturbed wind speed, but with a local quantity such as k, the asymmetry partly disappears.

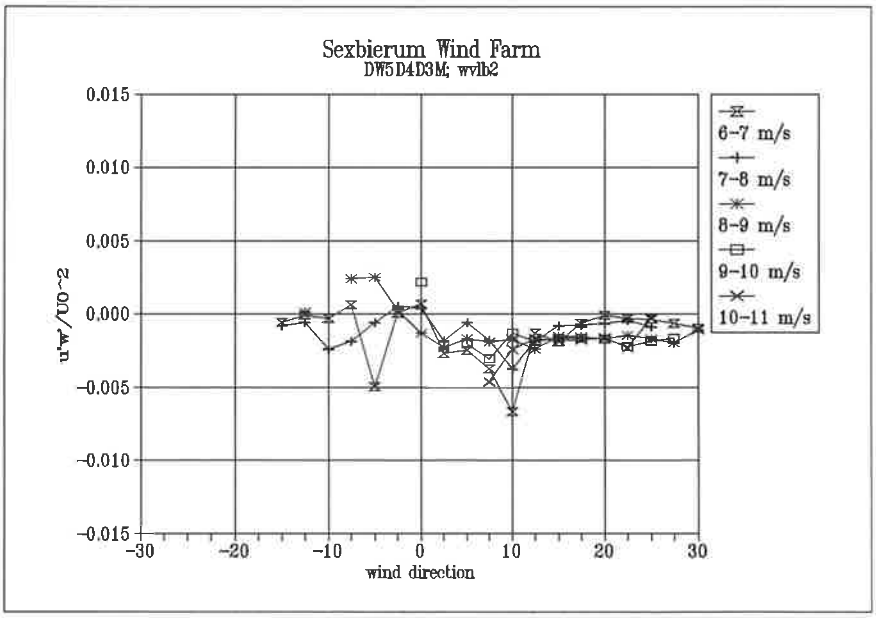

Figure 4.19 Shear stress $u'w'/U_0^2$ as a function of wind direction at sensor b2

The u'w'-component is given in figure 4.19. Apparently there is hardly a u'w'-component at sensor b2. This can be explained by the fact that sensor is at the symmetry plane of the wake. Indeed the sensors at different positions show a significant u'w'-component variation over the wind directions. This will be discussed in the next section.

The v'w'-component of the shear stress turns out to be very small at each of the sensor positions. This shear stress component is proportional to the spatial derivatives of V and W, which are both very small throughout the wake. Hence the shear stresses are also small.

4.5.2 Aggregated results

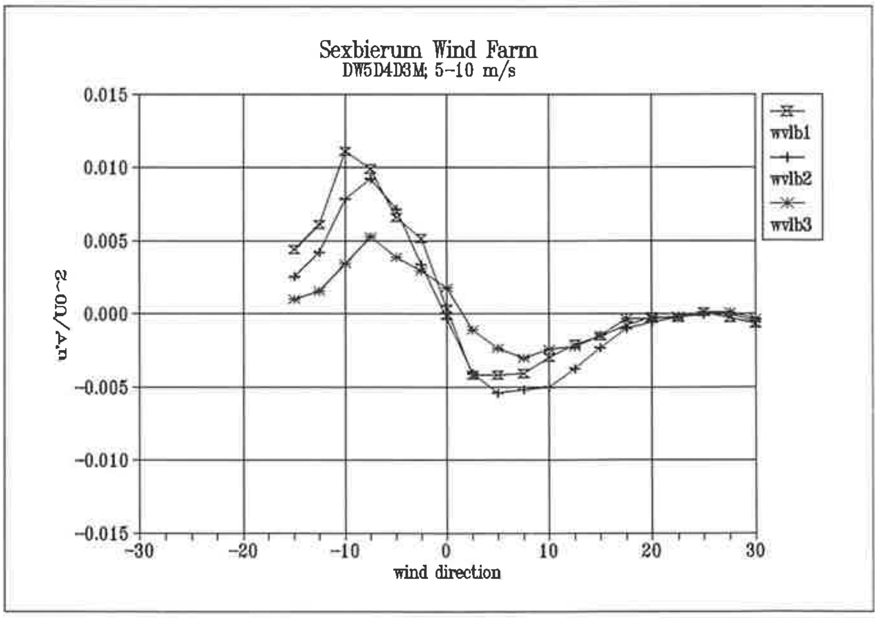

Figure 4.20 Shear stress $u'v'/U_0^2$ as a function of wind direction for sensors b1, b2 and b3

Figure 4.20 shows the non-dimensional shear-stress $u'v'/U_0^2$ for the three sensors at mast b as a function of the undisturbed wind direction. The shape of the three curves is again very similar except horizontal shift. Eddy-viscosity theory for turbulence assumes that the turbulent shear stress is proportional to the local shear. This is clearly reflected in the curves of figure 4.20. Outside the wake no horizontal wake effect is present and hence the horizontal wind gradient is zero. At the maximum gradient dU/dy shear stress reaches a maximum, after which it decreases zero, where the wind speed shows a minimum. For larger wind directions the shear shows a similar behaviour but of an opposite sign.

The shape and the magnitude of the shear stress curves compare well with results of wind tunnel tests [Smith].

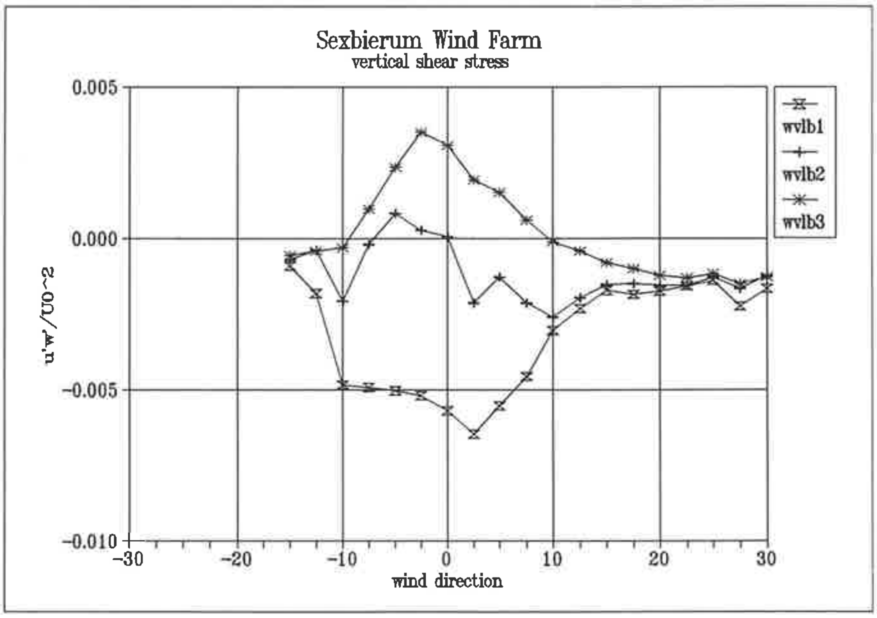

Figure 4.21 Shear stress $u'w'/U_0^2$ as a function of wind direction for sensors b1, b2 and b3

Figure 4.21 shows the non-dimensional turbulent shear stress $u'w'/U_0^2$ as a function of the wind direction at the three sensor positions b1, b2, b3. The graphs show quite a distinct behaviour from the horizontal shear.

The shear stress u'w' is proportional to the vertical wind speed gradient dU/dz. Outside the wake the u'w' is negative corresponding to the shear stress in the atmospheric boundary layer. Traversing through the wake at the top position b1, the vertical gradient increases with the increasing wake effect and so u'w' becomes more negative (figure 4.22). At the bottom sensor b3 the situation is different. When the wind direction changes the wake effect becomes stronger; the wind gradient and hence u'w' changes sign.

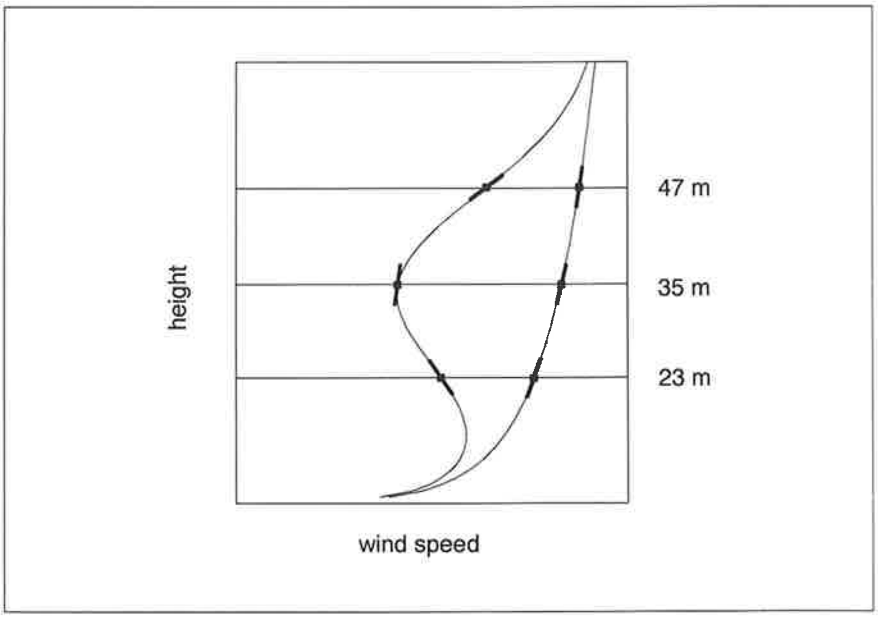

Figure 4.22 Change of the vertical wind gradient under influence of the wake deficit

5 Conclusions and recommendations

The measurement campaign in the wake of two wind turbines in line has resulted in a useful data base for the validation of wake and wind farm models and for input to wind turbine load calculation programs.

The data base is built up of 1726 1-minute samples containing data on undisturbed wind conditions, wind turbine power, wind speed components, turbulence and shear stress data. The data base has been analysed with respect to the undisturbed wind conditions, i.e. with respect to wind speed and wind direction outside the wind farm.

Initially, the measurement campaign suffered somewhat from malfunctioning and unreliable sensors. Meanwhile these problems have been resolved and the measuring system performs correctly. Software is now available to perform the tasks from pre-processing the raw data to the final analysis of the data. This means that in future measuring campaigns, data processing will be a more or less standard activity and can be carried out much faster.

The undisturbed wind conditions have been determined. The upstream roughness length was derived from the turbulence intensity.

The wake deficit at the various measuring positions has been determined. The measurements do not show the shapes of the individual wakes clearly, but give the picture of one single merged wake. For the centre-line measuring mast b, the measured wake turns out to be asymmetrical, which is surprising. This is caused by systematic errors in the undisturbed wind measurement, probably.

A similar asymmetry is found in the data of the turbulence intensities and the shear stresses. Only if the quantities are non-dimensionalized with local quantities, such as the wind speed or turbulent kinetic energy, the asymmetry seems to disappear.

The u-component of the turbulence intensity shows peaks at the maximum wind speed gradient. The other components lack such a peaked shape and have a much more smooth course. This also holds for the turbulent kinetic energy.

The shear stresses have been measured successfully. The course of the individual shear stresses can be explained qualitatively by making some simple assumptions about the wind speed gradient in the wake. Further the shape is very similar to the one measured previously in the wind tunnel.

The present measuring campaign has been carried out with 3 mobile masts across the wake in order to obtain more insight into the spatial distribution of the wake. However, it must be concluded that the extra information that is obtained in this way is rather limited. In order to measure detailed horizontal profiles, it is necessary to have more than three measuring masts. Therefore, it is advised, in a following measuring campaign, to position the masts on the wake centre-line behind one another and thus collect more information on the streamwise variations of the various quantities.

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Results of Sexbierum Wind Farm; double wake measurements
– Revised –

7 Authentication

Name and address of the principal
Commission of the European Community
contract JOUR-0064

Names and functions of the cooperators
Ir. J.W. Cleijne - research engineer

Names of establishments to which part of the research was put out to contract
-

Date upon which, or period in which, the research took place
January 1992 - November 1992

Signature	Approved by
	b.o.
Ir. J.W. Cleijne project manager	Ir. N.J. Duijm section manager wind engineering