

TNO-rapport

**Dynamic loads in wind farms.
Analysis of wind spectra, coherence functions
and integral length scales of the turbulence of
the Sexbierum Wind Farm**

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Summary

The Department of Fluid Dynamics of TNO Environmental and Energy Research has contributed to the CEC JOULE project Dynamic Loads in Wind Farms. The Dutch Electricity Generating Board SEP has cosponsored the TNO contribution to this project. The main aim of this project was to quantify the level of increase in the loads which wind turbines experience when operating in wind farms. Especially the variation in loads as a function of spacing and position has been studied.

TNO has calculated the variation of wind farm power with wind speed and wind direction with their model FARMS. The results have been compared with the power variations measured in the Dutch Experimental Wind Farm at Sexbierum. One can conclude that FARMS predict the variation of power within wind farms over a wide range of ambient conditions with a reasonable degree of accuracy.

The largest part of the TNO contribution consisted of the analysis of wind speed data in order to provide input data for the calculation of wind turbine loads. The wind speed data have been derived from the Sexbierum Wind Farm and concern both mean and fluctuating values of wind speed and wind direction for the following situations:

- undisturbed flow;
- at 7D in a single wake;
- at 4D in a single wake.

The resulting power spectral density functions, coherence functions and integral length scales of the latter two situations have been compared with corresponding theoretical functions and with the results of the first situation mentioned.

The wake shape can hardly be distinguished for the 7D single wake situation but is very clear for the 4D case. The wind speed ratio (wake/undisturbed) is about 0.85 over a wide range of wind directions. On the average the turbulence intensities measured with the mobile masts are about 20% higher than the one measured with the fixed mast.

The shape of the measured power spectral density functions, expressed in non-dimensional terms, show good agreement if compared to the existing theoretical von Karman functions. This seems independent of the lateral or vertical position in the wake.

The integral length scale of the turbulence therefore can be derived easily by fitting the measured power spectra on the theoretical ones. A significant reduction in the turbulent length scale is seen in the wake. There is large similarity between the reductions of the length scales and the wind speeds: the reduction is larger for the 4D single wake situation than for the 7D case and the reduction reaches the largest value at the centerline of the wake.

If a coherence function could be determined from the data the agreement with theory is small. This holds both for vertical and lateral direction.

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In general it is concluded that large data sets are required to give reliable results on power spectral density functions, integral length scale of the turbulence and especially on coherence functions.

The CEC has approved the project proposal Dynamic Loads in Wind Farms - II. In that project wind farms operating in undulating and complex terrain will be investigated in more detail.

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Nomenclature

a	Weibull scale factor	m/s
a	'constant' in coherence function	—
C1,C2	constants	—
C_p	power coefficient	—
C_T	thrust coefficient	—
D	rotor diameter	m
D_0	expanded rotor diameter	m
H	hub height	m
I_i	turbulence intensity (also σ_i/U)	—
k	Weibull shape factor	—
xLi	integral turbulence length scale in x-direction, $i=u$ or $i=v$	m
yLi	integral turbulence length scale in y-direction, $i=u$ or $i=v$	m
zLi	integral turbulence length scale in z-direction, $i=u$ or $i=v$	m
m	thrust parameter	—
n	frequency	1/s
n'	non-dimensional frequency, $n'=n \cdot xLi/U$	—
R	half-wake width	m
r	axial distance to the centre line	m
$(dr/dx)^\alpha$	turbulent exchange of momentum due to ambient turbulence	—
$(dr/dx)^\lambda$	turbulent exchange of momentum due to rotor induced turb.	—
$(dr/dx)^m$	turbulent exchange of momentum due to shear induced turb.	—
S_{ii}	(single point) power spectral density, $i=u$ or $i=v$	m^2/s
$S_{ii}(\Delta r, n)$	cross-power spectral density function, $i=u$ or $i=v$	m^2/s
U	mean wind speed	m/s
ΔU	wind speed deficit, $\Delta U_{wake} = U_0 - U_{wake}$	m/s
u	longitudinal component of the wind speed	m/s
V	rotor averaged velocity	m/s
v	lateral component of the wind speed	m/s
X	distance in longitudinal direction	m
X_N	near wake length	m
Y	distance in lateral direction	m
z	height	m
z_0	roughness length	m
α	ambient turbulence level	—
$\gamma(\Delta r, n)^2$	coherence function	—
Δ	spatial separation	m
κ	von Karman constant, $\kappa=0.4$	—
λ	tip speed ratio of rotor blades	—
λ	correction function for "constant" a	—
σ_i	rms value of wind speed fluctuations	m/s
ω	rotational speed	rad/s

subscripts:

0	in the undisturbed atmospheric flow
add	added (due to wake effects)
cl	centre line
H	hub height
i	wind speed component, $i=u$ or $i=v$

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wake in the flow of a wake:

- 1: in the potential core section
- 2: in the near wake section
- 3: in the far wake section
- H: at the end of the potential core section
- N: at the end of the near wake section
- F: at the end of the far wake section

1 Introduction

The application of wind energy has grown strongly over the last few years and is expected to continue its growth at least for the next decade. A large and still increasing part of the wind turbines are used in wind farms. The turbines thus are operating part of their lives in the wake of upstream turbines.

A wind turbine changes the wind speeds in the atmospheric boundary layer. The mean wind speed behind a turbine or within a cluster of turbines will be reduced. In addition, turbulence levels will be increased above the ambient level due to increased velocity shear and the mechanical turbulence generated by the upstream rotor(s). Compared with an isolated wind turbine, a machine located within the array will thus not only generate less energy but may also be expected to experience greater fluctuating loads. This is of importance for manufacturers, designers and owners of wind turbines.

The energy yields of a wind turbine and the fluctuating loads it experiences during its life time depend on the wind regime of the location and the design of the machine. If the surrounding terrain is inhomogeneous also the distribution of the wind speeds over the wind rose is of importance.

In addition the level of energy losses and increasing fluctuating loads of turbines located in a cluster also depends on the wind farm layout. The spacing between the machines and the position of the machines towards the prevailing wind direction, are largely responsible for these effects.

The JOULE project Dynamic Loads in Wind Farms concentrated on the expected increased loads on wind turbines operating in clusters. The following institutes participated in this project: Garrad Hassan and Partners (UK, main contractor), ECN (NL), KEMA (NL) and TNO (NL).

The contribution of the Department of Fluid Dynamics of TNO Environmental and Energy Research mainly consisted of the analysis of wind speed data in order to provide input data for the calculation of wind turbine loads. The TNO contribution has been financed by the CEC and the Dutch Electricity Generating Board SEP.

This report is especially written for SEP and NOVEM, the Netherlands Company for Energy and Environment. SEP has co-sponsored the TNO contribution to this project. NOVEM has co-sponsored two other CEC JOULE projects which are closely related to this one, i.e. Wake and Wind Farm Modelling and Full-scale Measurements in Wind Farm Arrays. The main parts of this report are also to be found in sections 3.1, 5.1 and 6.1 of the final report of the total project Dynamic Loads in Wind Farms (Tindal et al. '93).

The wind speed data have been gathered by KEMA in the Dutch Experimental Wind Farm at Sexbierum and by TNO in one of their wind tunnels. The full scale data concern both mean and fluctuating values of wind speed and wind direction. The experimental set-up is described in chapter 2. The measurements have been performed for the following situations:

- undisturbed flow;
- at 7D in a single wake;
- at 4D in a single wake.

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The latter two measurements series contain data from positions between the wake centre and the wake edge and from mean wind speeds between 7 and 14 m/s.

The data measured in the TNO wind tunnel have been send to Garrad Hassan and Partners for further analysis. This work has been reported separately (Leene '92).

TNO has calculated the variation of wind farm power with wind speed and wind direction with their model FARMS. In chapter 3 a brief description of FARMS is given as well as a comparison between measured and calculated power.

The analyses of the data from the full scale measurements have been concentrated on power spectral density functions, coherence functions and integral length scales of the turbulence. The results are presented in chapter 4.

The conclusions are drawn in chapter 5.

2 Experimental set-up

2.1 Sexbierum wind farm

The Sexbierum wind farm is located in the Northern part of The Netherlands at approximately 4 km distance of the shore and is surrounded by flat homogeneous terrain, mainly grassland used by farmers for the grazing of cows. According to the Wieringa terrain classification (Wieringa & Rijkoort '83), which is close to the Davenport terrain classification (ESDU '82), the Sexbierum terrain can be parametrized with roughness length z_0 is about 0.03 to 0.10 m. From the long term data of KEMA, it seems that $z_0 = 0.05$ m give good results for wind shear and turbulence level at hub height $H = 35$ m.

The wind farm has a total of 5.4 MW installed capacity, consisting of 18 turbines of 310 kW rated power each. The wind turbines are placed in a rectangular grid with inter distances of 5, 8 and 10 rotor diameters. More detailed information on the Sexbierum wind farm and the wind turbines are to be found in (Cleijne & Hutting '93) and (Bulder & Schepers '91) respectively.

2.2 Sexbierum wind regime

The prevailing wind direction is South West. 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 at hub height is 7.6 m/s.

The wind shear is calculated according to the logarithmic wall law. The wind speed at height z can be calculated if the wind speed at hub height U_H is known:

$$U(z) = U_H \ln(z/z_0) / \ln(H/z_0)$$

The turbulence intensity at height z , $I(z)$ or $\sigma_u/U(z)$, is calculated according to Beljaars '87:

$$I(z) = 2.2 \kappa / \ln(z/z_0)$$

in which $\kappa = 0.4$. For the V-component of the wind the constant is 1.8. Panofsky & Dutton use the same formula, but with the constants 2.4 and 1.9 for the U- and V-component respectively. For the surface roughness $z_0 = 0.05$ m the turbulence intensity at hub height becomes $I_H = 0.134$.

2.3 Instrumentation

Measurement campaigns have been carried out for three different situations, i.e. 'undisturbed flow', '7D single wake' and '4D single wake'.

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The wind measurements have been performed with cup anemometers placed at hub height on fixed masts just outside the park and with 3-component propeller anemometers on the mobile masts A, B and C inside the park. In a later stage two additional cup anemometers have been placed on mast B. The sampling rate of the cup anemometers is 1 Hz, for the propeller anemometers this is 4 Hz. Details are given in (Cleijne '92) and (Tindal et al. '93).

During a measuring campaign the data of the undisturbed wind condition have been collected with the fixed mast most close to the upstream wind turbine. For the 7D campaign this is mast 3, for the 4D campaign this is mast 7. The letter U before the number of the fixed mast denotes wind speed as the letter D denotes wind direction. The number 2 behind the number of the fixed masts and the numbers 1, 2 and 3 behind the letter of the mobile masts denotes the height: 47, 35 (hub height) and 23 m respectively.

2.4 Data storage and time averaging

In general wind measurements are stored in 10 or 60 minutes series. During these periods the wind is expected to be stationary in most cases. It also provides good statistical information of the wind. In wake situations the wind conditions strongly depend on the position in the wake, in this case the height and the wind direction. For our purpose the latter is not stationary enough over 10 minutes. Series of one minutes periods would give much better results.

A large part of the energy in the wind however, is to be found between 1 and 10 minutes. In order to analyse spectral density functions the project team therefore decided to use series of about 3 to 4 minutes lengths. Besides this should give a reasonable correlation between the mean wind speed measured in the upstream undisturbed situation and the one in the wake. For calculation purposes TNO decided to divide the measurement series into blocks of 256 s.

Due to the energy loss in the low frequency part of the wind signal, the turbulence intensity averaged over a large number of 256 s blocks is about 20% lower compared to 60 minute values (calculated according to Wood, ESDU '83). The restriction of the sampling rate causes an additional loss of 2% (4 Hz sampling rate) to 5% (1 Hz sampling rate). Instead of $I_{35} = 0.134$ according to Beljaars '87 with $z_0 = 0.05$ m, we should find $I_{35} \approx 0.10$ for the undisturbed wind condition.

The blocks has been binned into mean wind speed (intervals of 2 m/s) and mean wind direction (intervals of 2.5 degrees). The ensemble average values of all blocks within one bin have been used for further analysis. An increasing number of blocks means an increasing accuracy and reliability of the result (for detailed information see Bendat & Piersol '86).

3 Power production of the sexbierum wind farm

3.1 Description of FARMS

FARMS is semi-empirical kinematic numerical model that calculates the velocity deficits and the increase of the turbulence intensities in an arbitrary position in a wind farm. Also the power loss in a wind farm can be calculated. FARMS is developed by TNO and is based on the former computer program MILLY (refs. Vermeulen & Builtjes, Vermeulen & Vijge, Luken). FARMS has been adjusted several times in the last few years. The main formulas written in the most recent version (1992) are given in Appendix A.

Only the longitudinal component of the wind is parametrized. The wake of an individual machine is calculated as a function of local parameters, i.e. mean velocity, tip speed ratio and thrust coefficient. The calculations are made according a sort/march routine starting with the most upstream wind turbine. In case of multiple or overlapping wakes the velocity deficits are added linearly. The rotor swept area is divided into 44 sections. The wind speed and the turbulence intensity are calculated in all sections. The average of the 44 values gives the final result per turbine.

The following data are needed as input:

- the undisturbed mean wind speed at a given height (preferably hub height) U_z or U_H ;
- the turbulence intensity at the same height, I_z or I_H , or the terrain roughness length, z_0 ;
- operational conditions of the wind turbines, i.e. λ and/or ω , C_T and C_p , all as functions of U (the latter two eventually as functions of λ);
- the hub height and the rotor diameter of the wind turbines;
- the number and the positions of the turbines in the wind farm;
- the first and the last value for the wind direction and the step value.

The output per turbine consist of:

- number of the turbine;
- coordinates expressed in X/D and Y/D compared to the original coordinate system;
- the rotor averaged wind speed and the turbulence intensity;
- the power coefficient C_p and the power output;
- the thrust coefficient C_T .

The power output for the total wind farm can be given in both absolute values and relative values, i.e. the ratio of the absolute value compared to the summation of the power output of all turbines in an undisturbed situation.

3.2 Calculations with FARMS

The final FARMS calculations have been carried out for the power output of the Sexbierum wind farm as a function of the wind direction (step

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size 2.5 degrees) and the wind speeds 5.5 to 12.5 m/s (step size 1 m/s), 14.0 and 17.5 m/s.

During a significant part of the measurement programme turbines 11 and 31 were non-operational. The calculations therefore have been performed for only 15 machines (turbines 11, 21 and 31 excluded). The measured data have been adjusted for this purpose. More detailed information is given in (Tindal et al. '93) and (Cleijne & Hutting '93).

Part of the results are presented in figure 3.1. The calculated reduction in power due to wake operation show a small under-prediction compared to the measured one. The amount of scatter at different wind speeds and different wind directions are related to the frequency of occurrence. The most data are found at low wind speeds and south westerly wind directions. The comparison between model predictions and measured results therefore should concentrate on these bins.

4 Changes to properties of the wind within wind farms

In section 4.1 the results of the measurements of the mean wind speed and the rms-values of the wind speed fluctuations are discussed. The latter are expressed as wake turbulence intensity, $\sigma_{u,wake}/U_{wake}$. The second section describes the results of the wind power spectra including those of the turbulent integral length scales. The information on the coherence functions is scarce. The results are given in § 4.3. In all paragraphs a distinction has been made according to the measurement campaigns, i.e. 'Undisturbed flow', '7D single wake' and '4D single wake'.

4.1 Variation in mean wind speed and turbulence intensity

Undisturbed flow

In order to get information on the influence of a wake flow on a wind turbine, the influence of the undisturbed flow on this turbine has to be known. To this end three measurement campaigns has been performed, i.e. series 13, 14 and 23. The series 13 and 14 has been measured with one of the fixed masts (signals 61, 62 and 63), the series 23 has been measured with the mobile masts (signals A2, B1, B3 and C2) and the fixed mast (signal U72). For series 23 no data were available of signal B2.

The series are short and contain only 14, 3 and 5 blocks of 256 seconds respectively. The values of the blocks has been averaged per series. The average values of the mean wind speed and of the turbulence intensity of the series are given in table 4.UF.MEAN.

The values of the turbulence intensities and especially the length scales (see section 4.2) of series 23 are low. Also the differences between the mean wind speeds of anemometer U72 on the one hand and those of A2 and C2 on the other hand are relatively large (about 15%).

Due to the number of blocks the data from series 13 are the most reliable. The measured turbulence intensities are in good agreement with the theoretical values.

7D single wake

One measurement campaign was aimed to investigate the 7D single wake situation. The results of the mean wind speed and the turbulence intensity of the various signals are presented in the tables and figures 4.7D.MEAN and 4.7D.TURB-U. The results of the undisturbed flow are to be found in columns U32 and D32. The results of the wake flow are to be found in columns A2, B1, B2, B3 and C2.

For wind direction 263 degrees the concerning wind turbines are in line with mast B. If the wind direction is 3.3 degrees higher or lower, mast A or C respectively stands in the centerline of the wake. In order to show more clear results in the figures, the measured values of signals A2 and C2 have been shifted so that the centerlines of masts A, B and C coincide.

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In figure 4.7D.MEAN the wind speed ratio U_{wake}/U_0 is given as a function of the wind direction. No distinction has been made between the several wind speed bins. The shape of the wake is not very clear. This is probably due to the fluctuations in wind direction in combination with the distance (7D, which corresponds with about 20 seconds if $U_0 = 10$ m/s) behind the upstream wind turbine. The wind speed ratio is about 0.85 over a wide range of wind directions.

Also from figure 4.7D.TURB-U no clear wake sheap can be distinguished. On the average the turbulence intensities measured with the mobile masts are about 20% higher than the one measured with the fixed mast. Taken the lower mean wind speeds into account, there is hardly any difference in the variance (and thus the energy) of the various signals.

The turbulence intensity of the undisturbed wind condition is close to the one calculated by theory as discussed in section 2.4.

4D single wake

One measurement campaign was aimed to investigate the 4D single wake situation. Except for the fixed mast (anemometer U72 has been used for this campaign) the set up equals the one of the 7D campaign. During this campaign two additional cup anemometers have been put on mast B, i.e. B2H and B1L. The positions are 6 m above and below B2 respectively. The analysis of the wind data measured with the propeller anemometers also concerned the V-component of the wind. Anemometer B2 was not operating during this campaign. The results of the mean wind speed and the turbulence intensity are given in the tables and figures 4.4D.MEAN, 4.4D.TURB-U and 4.4D.TURB-V.

For wind direction 173 degrees the concerning wind turbines are in line with mast B. If the wind direction is 5.7 degrees higher or lower, mast A or C respectively stands in the centerline of the wake. In order to show more clear results in the figures, the measured values of signals A2 and C2 have been shifted so that the centerlines of masts A, B and C coincide.

In spite of the relatively small number of blocks the wake shape in 4.4D.MEAN is very clear. The difference between the various signals is negligible. The half-wake width is about 20 to 25 degrees which corresponds with about 1.2D to 1.7D.

The same holds for the wake turbulence intensities of both the U- and V-component of the wind. The values for signals B2H and B2L are significantly lower than those of the others. As can be seen in the following section, the response of both cup anemometers is very bad. Therefore the results have not been presented in figure 4.4D.TURB-U. The average value of signal U72 is 0.108 which is a few percent higher than the value calculated by theory as discussed in section 2.4.

Some of the series of the V-component show very high values (see Table 4.4D.TURB-V). KEMA could not give any plausible reason to explain these values. These values have not been presented in figure 4.4D.TURB-V.

4.2 Variation in wind energy spectra

The measured wind speed series have been delivered by KEMA in files of several minutes to about 3 hours length, dependant on the stationarity of the upstream wind condition and the operational condition of the concerned wind turbines. The files have been processed by TNO. The process is described in Appendix B.

For the processing of data TNO used the computer software package DaDisp in case of the 'undisturbed flow' and the '7D single wake'. The number of files turned out to be much larger (and the average length much shorter) as expected. The file handling therefore became too time consuming. In order to avoid this problem TNO has written a computer program to process the data of the 4D single wake campaign. The transformation from the processed data into power spectral density functions (PSD) and coherence functions (COH, see section 4.3) has been based on known FFT-routines. For the final analysis TNO has used the software package Lotus-123.

Theory

The measured PSD's have been compared with the theory. To this end the ESDU spectrum, based on the von Karman spectral equations (ESDU '85), have been used. In neutral atmospheric wind conditions, which appears among others during periods of wind speeds higher than about 6 to 8 m/s, PSD's can be described with one single expression for each wind speed component:

$$n \cdot S_{uu}(n) / \sigma_{uu}^2 = 4 \cdot n' / (1 + 70.8 \cdot n'^2)^{5/6}$$

$$n \cdot S_{vv}(n) / \sigma_{vv}^2 = 4 \cdot n' \cdot (1 + 755.2 \cdot n'^2) / (1 + 283.2 \cdot n'^2)^{11/6}$$

in which $n' = n \cdot xLi / U$, n being the frequency, U the mean wind speed and xLi the integral turbulence length scale in x -direction for $i=u$ and $i=v$ respectively.

According to ESDU '75 the integral turbulence length scale for the U- and the V-component are:

$$xLu = 25 \cdot z^{0.35} / z_0^{0.063}$$

$$xLv = 5.1 \cdot z^{0.48} / z_0^{0.086}$$

For $z = 35$ m (hub height) and $z_0 = 0.05$ m the results are 105 and 36 m respectively. For $z = 20$ and $z = 50$ m the results are 86 and 119 m for the U-component and 28 and 43 m for the V-component.

Panofsky & Dutton '84 (p.176) state that the derivation of the length scales from atmospheric data can not be well defined. Besides the methods to derive the length scales differ very much. At last TNO would like to remark that the number of blocks is very low and thus the results, as far as the length scales are involved, are not very reliable from a statistical point of view.

The method that TNO has used to derive the length scales is to fit the resulting data on the high frequency part of the theoretical PSD. High here means: frequencies

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above the frequency where PSD has its maximum value. Due to the small number of blocks (in most bins) and the relatively short length of the blocks it is difficult to detect the maximum value of the measured PSD. Apart from the reliability of the method and the number of data a deviation of 10 to 20% in the individual results are possible.

Undisturbed flow

The shape of the PSD is in very good agreement with the one of ESDU. For the data measured with the propeller anemometers this holds until about 0.5 Hz. These anemometers seem to filter the higher frequencies. An example is shown in figure 4.UF.PSD.

The results of the length scales (see table 4.UF.LENGTH) of series 13 and 14 are surprisingly close to the ones mentioned in the former section 'theory'. As already stated in section 4.1 the length scales of series 23 are extremely low.

7D single wake

As mentioned in section 4.1 no difference can be seen from the results between the various wind directions. This also holds for the PSD's. In order to improve the statistics TNO made an ensemble average of all PSD's between directions 255 and 270 degrees per signal. The final results have been compared with theory.

Except for the frequencies above 0.5 Hz (see 'undisturbed flow') no differences have been found between the shape of the PSD's according to ESDU (solid line in the figures 4.7D.PSD-A2, -C2 and -U72) and the PSD's from the measured data in the 7D single wake case (symbols in the figures).

The length scale (see table 4.7D.LENGTH) of the undisturbed wind (signal U32) is about 0.60 times the one calculated by theory. The length scales of the 7D single wake data are about 0.75 times the length scale of U32. This value is close to the average wind speed ratio.

4D single wake

Compared to the 7D single wake data both mean wind speed and the turbulence intensity vary strongly over the various wind direction bins. Adding the PSD's in order to gain statistical reliability was not possible in this case.

In spite of the small number of blocks still no difference could be found between the shape of the PSD's of the single wake data and those of ESDU. This does not hold for signals B2H and B2L. Above about 0.1 Hz hardly any energy has been measured. The results of both signals therefore have not been used for further analysis. Some examples of the PSD's are given in figures 4.4D.PSD-A2, -C2 and -U72 (line=ESDU, symbols=measured).

The determination of the length scales only have been carried out in case the number of blocks in a bin is at least 2. For the undisturbed wind (signal U72) we found values between 50 and 140 m. This endorses the option of Panofsky & Dutton. However, if the length scales of the 4D single wake data are divided by the corresponding length scales of U72, the wake shape is pretty clear. This length scale ratio is shown in figure

4.4D.LENGTH as a function of the wind direction. At the centerline this ratio is about 0.25, what is twice as small as the wind speed ratio at that point.

4.3 Variation in coherence functions

The transformation from the processed data into coherence functions (COH or γ^2) have been carried out parallel to the transformation into power spectral density functions (PSD or S_{ii} , see former section). The procedure is described in Appendix B.

Theory

The measured COH's, if available, have been compared with the theory. The right definition of the coherence function is:

$$\text{COH} = \gamma(\Delta r, n)^2 = |S_{ii}(\Delta r, n)|^2 / \{S_{ii}(n) * S_{ii}'(n)\}$$

in which $S_{ii}(n)$ and $S_{ii}'(n)$ are the single point power spectral density functions at the two points r and r' , measured in the same time with equal frequency rate. $S_{ii}(\Delta r, n)$ is the cross-power spectral density functions.

In the theory a large number of formulas are available. The most of them have the following format:

$$\gamma(\Delta r, n) = \exp(-a * n * \Delta r / U)$$

in which n is the frequency, Δ is the spatial separation and U is the average wind speed. The spatial separation Δr can be Δy , Δz or $(\Delta y^2 + \Delta z^2)^{0.5}$. The 'constant' a varies over the number of formulas and sometimes is a function of Δ , z , U and/or the integral length scale of the turbulence.

For our comparisons the formulas of Panofsky & Dutton ('84) and ESDU ('75) have been used. ESDU, and many others, define γ instead of γ^2 to be the coherence. In the tables and the figures given in this section we also will use the square root of the coherence function, γ . In these cases the 'constant' a should be halved.

According to Panofsky & Dutton the constant a holds for separations in both y - and z -direction (for the U -component of the wind):

$$a = (12 + 11 * \Delta r / z) * 0.5$$

in which z is the average height: $z = \{z(i) + z(j)\} / 2$.

ESDU uses:

$$a = (3 + 135 * \Delta r^{1/3} / r L_u) * \lambda$$

in which r can either be y or z and λ is a correction function:

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$$yLu = 10 * z^{0.38} / z_0^{0.068}$$

$$zLu = 6.3 * z^{0.45} / z_0^{0.081}$$

$$\lambda = 1.91*(U/15)^{0.5} - 0.49*(U/15) - 0.42$$

Both Panofsky & Dutton ('84) and ESDU ('75) state that a large number of data should be available before comparisons with their formulas could be made. Unfortunately the number of data in our measuring campaigns is relatively scarce.

Undisturbed flow

An overview of the constant a for the various combinations of signals in the undisturbed flow situation is given below. Note that only the situation of series 13 have been used.

	Signal	U612	U623	U613
Coherence constant a:				
P&D	a	7.9	9.0	10.7
ESDU	a	10.5	11.8	13.2
measured	a	4.0	4.5	5.4

In figure 4.UF.COH of series 13 are shown. For the theoretical lines however, the value a is about 0.5 times the ones according to Panofsky & Dutton and even smaller if compared with the ones from ESDU. This endorses the statement of Panofsky & Dutton and ESDU.

The coherence functions of the other series are very inaccurate due to the very small number of blocks.

7D single wake

An overview of the constant a for the various combinations of signals in the 7D single wake situation is given below.

Signal	AB2	BC2	AC2	B12	B23	B13
Coherence constant a:						
P&D	7.9	7.9	9.8	7.6	8.3	9.8
ESDU	7.2	7.1	8.4	7.8	8.5	9.7
measured	3.2	3.2	3.9	3.0	3.3	3.9

An ensemble average coherence function have been made similar to the method for the 7D single wake PSD's. The results are shown in figures 4.7D.COH-ABC2 and

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4.7D.COH-B123. The values for a in the theoretical lines now are about 0.4 times the above mentioned values from both Panofsky & Dutton and ESDU.

4D single wake

An overview of the constant a for the various combinations of signals in the 4D single wake situation is given below only for Panofsky and Dutton. Note that signal B2 was not operating during this campaign and that two additional cup anemometers have been used.

Signal	AC2	B13	B2HL
Coherence constant a :			
P&D	9.8	9.8	7.9

Compared to the 7D single wake data both mean wind speed and the turbulence intensity vary strongly over the various wind direction bins. As for the PSD's adding the coherence functions in order to gain statistical reliability was not possible in this case. As there is no mean wind speed, the ESDU theoretical data can not be given.

In contradistinction to the PSD's the coherence functions could hardly be recognized, except for a small number of bins for the B2HL signal combination. Unfortunately no results therefore can be given.

As we could not find a relation between the number of blocks within a bin and the clearness of the coherence function of the latter signal, the reason for the poor results should be found elsewhere.

One aspect which probably play an important role is the structure of the wind in and at the edge of a wake. In the undisturbed wind and for spatial separations of 10 to 30 meters, the coherence function is larger than 0.5 for wind structures lasting at least several seconds or longer periods. One therefore require long time series to recognize a clear coherence function. From the results of our campaign we might conclude that for 'long period' structures (between say 10 and 100 seconds) and separations close to the rotor diameter coherence at 4D distance in a wake hardly exists.

The results are not considered to be meaningful but the coherence function from one direction bin is, however, included in figure 4.4D.COH for completeness.

5 Conclusions

Power output

With the TNO model FARMS it is possible to predict the variation of power within wind farms over a wide range of ambient conditions with a reasonable degree of accuracy.

Undisturbed flow

The number of data is small. The analysis has been concentrated on series 13. The measured turbulence intensities, the integral length scales of the turbulence, the PSD's show good agreement with the theoretical ones. The coherence functions show little agreement with theory if the value a is about 0.5 times the value which is proposed by Panofsky & Dutton.

In general and within the limits of statistical reliability, this also holds for measurements of the undisturbed flow on the fixed masts during the 7D and the 4D single wake campaigns.

7D single wake

No wake shape can be distinguished. The wind speed ratio (wake/undisturbed) is about 0.85 over a wide range of wind directions. On the average the turbulence intensities measured with the mobile masts are about 20% higher than the one measured with the fixed mast.

The shape of the measured PSD's, expressed in non-dimensional terms, show good agreement if compared to the ESDU spectral density function. Thanks to this the integral length scale of the turbulence can easily be derived by fitting the measured data on the ESDU function. The length scales of the 7D single wake data are about 0.75 times the length scale of the undisturbed wind. This value is close to the average wind speed ratio.

The coherence function show little agreement with theory if the value a is about 0.4 times the value which is proposed by Panofsky & Dutton. This holds both for vertical and lateral direction.

4D single wake

The profiles of U_{wake}/U_0 , $\sigma_{u,\text{wake}}/U_{\text{wake}}$ and $\sigma_{v,\text{wake}}/U_{\text{wake}}$ are very clear.

The shape of the measured PSD's, expressed in non-dimensional terms, here too show good agreement if compared to the ESDU spectral density function. This seems independent of the lateral or vertical position in the wake.

A length scale ratio has been defined, i.e. the length scale derived from measured data in the wake divided by the length scale simultaneously derived from measured data in the undisturbed wind. The shape of this length scale ratio is similar to the one from the wind speed ratio. The 'deficit' however is larger. The smallest value (at the

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centerline of the wake) is about 0.25 which is about 0.50 times the smallest value of the wind speed ratio.

Hardly any coherence function could be determined from this data set. From the results of our campaign we might conclude that for 'long period' structures (between say 10 and 100 seconds) and separations close to the rotor diameter coherence at 4D distance in a wake hardly exists.

Overall

Large data sets are required to give reliable results, especially for the PSD's, the integral length scale of the turbulence and most of all the coherence functions.

The shape of the PSD, expressed in non-dimensional terms, does not change in wake situations. The integral length scale of the turbulence can easily be derived by fitting measured PSD's on a theoretical function of the PSD.

The length scale ratio equals one at the edge of the wake and reaches its smallest value at the centerline. This ratio decreases moving from the upstream wind turbine in the wind speed direction.

6 References

- [1] Beljaars, A.C.M.;
The measurements of gustiness at routine wind stations - A review;
WMO instruments and observing methods, report no. 31, Geneva, 1987.
- [2] Bendat, J.S. and Piersol, A.G.;
Random data - Analysis and Measurement procedures; 2nd edition;
J. Wiley & Sons, New York, 1986.
- [3] Bulder, B.H. and Schepers, J.G.;
Calculation data base of the WPS-30 wind turbine;
ECN report ECN-CX--91-053, Petten, September 1991.
- [4] Cleijne, J.W.;
Results of Sexbierum Wind Farm - double wake measurements;
TNO Environmental and Energy Research, 92-388, Apeldoorn,
November 1992.
- [5] Cleijne, J.W. and Hutting, H.K.;
Full-scale measurements at the Dutch experimental wind farm at Sexbierum;
TNO Environmental and Energy Research, 93-174, Apeldoorn, June 1993.
- [6] ESDU;
Characteristics of atmospheric turbulence near the ground. Part III: variations
in space and time for strong winds (neutral atmosphere);
Engineering Sciences Data Item 75001, July 1975.
- [7] ESDU;
Strong winds in the atmospheric boundary layer. Part 1: mean-hourly wind
speeds;
Engineering Sciences Data Item 82026, September 1982.
- [8] ESDU;
Strong winds in the atmospheric boundary layer. Part 2: discrete gust speeds;
Engineering Sciences Data Item 83045, November 1983.
- [9] ESDU;
Characteristics of atmospheric turbulence near the ground. Part II: single point
data for strong winds (neutral atmosphere);
Engineering Sciences Data Item 85020, October 1985.
- [10] Leene, J.A.;
The wake of 3 wind turbines in a row;
TNO Environmental and Energy Research, 92-382, Apeldoorn,
November 1992.

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

- [11] Luken, E.;
NIBE wake measurements - Data analysis and model validation;
TNO Environmental and Energy Research, 88-301, Apeldoorn, December 1988.
- [12] Panofsky, H.A. and Dutton, J.A.;
Atmospheric Turbulence - Models and Methods for Engineering Applications;
J. Wiley & Sons, New York, 1984.
- [13] Vermeulen, P.E.J. and Builtjes, P.J.H.;
Mathematical modelling of wake interaction in wind turbine arrays - Part I:
Description and evaluation of the mathematical model;
TNO Environmental and Energy Research, 81-01473, Apeldoorn, February 1981.
- [14] Vermeulen, P.E.J. and Vijge, J.B.A.;
Mathematical modelling of wake interaction in wind turbine arrays - Part II:
Description of the MILLY computer program;
TNO Environmental and Energy Research, 81-02834, Apeldoorn, 1981.
- [15] Wieringa, J. and Rijkoort, P.J.;
Wind Climate of The Netherlands (in Dutch);
Staatsuitgeverij, Den Haag, 1983.

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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

September, 1990 - June, 1993

Signature



F.J. Verheij
project leader

Approved by



ir. N.J. Duijm
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Appendix A Main formulae of FARMS

In FARMS the wake is divided into four sections (see figure A1):

- I. The 'potential core' section;
- II. The near wake section;
- III. The far wake section;
- IV. The final section.

The size of a section is described in terms of the wake width and the distance to the turbine. Both width and distance are related to the expanded rotor diameter D_0 :

$$D_0 = D \{(m+1)/2\}^{0.5}$$

in which D is the rotor diameter and m is a thrust parameter

$$m = (1 - C_T)^{-0.5}$$

In FARMS the half-wake widths are calculated. Per definition:

$$R_0 = 0.5 D_0$$

The local velocity is calculated by adding all velocity defects linearly, thus $V = U_0 - \sum \Delta U_{w,i}$. U_0 is the undisturbed wind speed, $U_{w,i}$ is the wind speed in the wake of turbine i .

The power output is calculated based on rotor the averaged velocity V .

I. 'Potential core' section.

In the first section a uniform velocity distribution is assumed behind the rotor disc. The centre line velocity deficit ΔU_{cl} in this section is calculated according to the actuator disc theory as:

$$(\Delta U/U_0)_{cl,1} = (m - 1)/m$$

in which U_0 is the undisturbed wind speed.

The centre line velocity deficit is taken to be constant over this section.

The section ends at X_H , the position where the potential core is fully eroded (see also figure A1). The flow inside and outside the potential core mixes due to a turbulent exchange of momentum, i.e. ambient turbulence (index α), rotor induced turbulence (index λ) and shear induced turbulence (index m).

The length of the first section X_H is calculated by:

$$X_H = R_0 / \{ (\frac{dr}{dx})_{\lambda,\alpha}^2 + (\frac{dr}{dx})_m^2 \}^{0.5}$$

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The mixing of the flow due to the ambient and the rotor induced turbulence $(dr/dx)_{\lambda,\alpha}$ is found by Luken and is related to the ambient turbulence level α and the tip speed ratio λ :

$$(dr/dx)_{\lambda,\alpha} = \{7.50 \cdot 10^{-2} \alpha^{0.21} + 4.57 \cdot 10^{-4} \lambda^{(0.71\alpha + 2.62)}\}^{0.5}$$

The mixing of the flow due to the shear is related to the thrust parameter m :

$$(dr/dx)_m = \{(1 - m)(1.49 + m)^{0.5}\} / \{9.76 (1 + m)\}$$

The half-wake width R_H at position X_H is calculated as follows:

$$R_H = R_0 (0.134 + 0.124 m)^{-0.5}$$

II. Near wake section.

The near wake section begins at X_H and ends at position X_N . In FARMS the wake is taken constant over this section. The centre line velocity deficit and the half-wake width thus equal the values of section I.

The distance X_N between the rotor and the end of the section, often called the near wake length, is:

$$X_N = \{C1 \cdot (1 - C2) / C2 \cdot (1 - C1)\} X_H$$

in which

$$C1 = (0.214 + 0.144 m)^{-0.5}$$

$$C2 = (0.134 + 0.124 m)^{-0.5}$$

III. Far wake section.

In the far wake section the velocity deficit at the centre line decreases according to:

$$(\Delta U/U_0)_{cl,3} = ((m - 1)/m) (X/X_N)^{-1.25}$$

The length of the third section X_F is 5 times the near wake length, thus:

$$X_F = 5 X_N$$

The corresponding half-wake width R_F is:

$$R_F = R_0 (2.38 \cdot 10^{-3} + 3.19 \cdot 10^{-2} m)^{-0.5}$$

IV. Final section.

In the final section the centre line velocity deficit further decreases as follows:

$$(\Delta U/U_0)_{cl,4} = 0.487 ((m^2 - 1)/m^2) (1/R_4(X))^2$$

The half-wake width R_4 increases slowly. The mixing process in this region is calculated similar to the mixing of passive contaminants e.g. stack plumes:

$$R_4(X) = R_F + \alpha/0.51 (X - X_F)$$

Wake profile.

Except for the first section FARMS uses the following profile to describe the shape of the wake:

$$(\Delta U/U_0)_j = (\Delta U/U_0)_{cl,j} (1 - \{r/R_j(X)\}^{1.5})^2$$

in which the subscript j stands for (section) 2, 3 or 4 and r is the axial distance to the centre line.

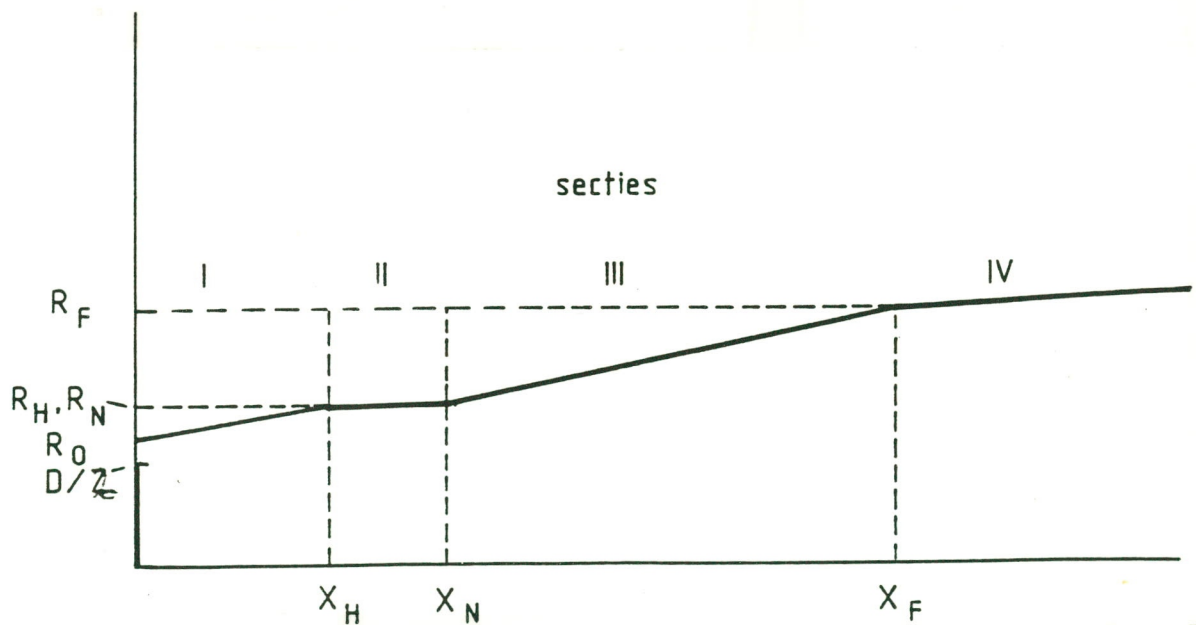


Figure A1 The four sections of a wake according to FARMS.

Appendix B Procedure of processing Sexbierum data

Transferring Sexbierum wind data into spectra

Data are available from several wind speed intervals (bin width 2 m/s) and wind direction intervals (bin width 2.5 degrees).

The data are sampled at 4 Hz with the 3D-propeller anemometers of the mobile meteorological masts and are sampled at 1 Hz with the cup anemometers at the stationary met-masts and the additional cups at the mobile masts.

To arrive at the PSD's the following analysis has been performed:

1. Each supplied file has been divided into blocks of 256 seconds and eventually a remaining block if the remaining block was larger than 128 seconds.
2. The average undisturbed wind speed and the average undisturbed wind direction of each of the blocks are calculated and stored on disk.
3. Using the average wind directions of step 2, the X- and Y-values from the signals measured with the propeller anemometers are translated into U- and V-values. (During the campaigns there turned out to be a misalignment of the undisturbed wind direction of 10 degrees. The data processing has been repeated with a 10 degrees correction on the wind direction signal. The latter results have been described in this report).
4. The average wind speed and the variance of the wind speed fluctuations of each of the blocks are calculated and stored on disk.
5. From the blocks the trend and the mean is removed by subtracting a linear function found by linear regression.
6. The short block of 128 s is padded with zeros to obtain a consistent block length of 256 s.
7. The blocks are sorted on the undisturbed wind speed and wind direction.
8. Using an FFT-routine the time series are translated (per block) into frequency series and stored on disk.
9. The power spectral density functions (PSD's) are calculated per block and temporary stored on disk.
10. Per bin ensemble averages are made of all the average wind speeds and directions, the variances and the PSD's. These final results are stored on disk.
11. The PSD's are fitted on the PSD according to ESDU in order to determine the shape and to define the integral length scale of the turbulence.

Transferring Sexbierum wind data into coherence functions

To arrive at the coherence functions the following analysis has been performed:

12. The results of step 7 are used to calculate (per block, only U-component) the cross power spectral density functions (CSD's) of two signals (combinations: AB2, BC2, AC2, B12, B23, B13 and B2HL) and temporary stored on disk. (Note: the CSD's are complex functions).
13. Per bin ensemble averages are made of all the CSD's on stored on disk. (Note: this is carried out for the real and the imaginary values separately).
14. Per bin the ensemble averaged coherence functions are calculated with the results of steps 9 and 11. (Note: the square root of the so-called co-coherence function is calculated. The co-coherence is based on the real values of the CSD's.).

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Tables

Table 4. UF.MEAN

The values for the mean wind speeds and the turbulence intensities, averaged over the blocks in series 13, 14 and 23. For series 23 also the turbulence intensity for the V-component of the wind has been measured.

The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m. Masts 6 and 7 are fixed masts, the masts A, B and C are mobile masts.

Series 13	U61	U62	U63
U (m/s)	14.9	14.0	13.3
σ_U/U (-)	0.082	0.094	0.104

Series 14	U61	U62	U63
U (m/s)	10.4	10.3	9.8
σ_U/U (-)	0.070	0.084	0.091

Series 23	A2	B1	B3	C2	U72
U (m/s)	6.1	7.3	5.5	6.4	7.4
σ_U/U (-)	0.063	0.051	0.073	0.064	0.062
σ_V/U (-)	0.051	0.044	0.054	0.047	---

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Table 4.7D.MEAN

The values for the mean wind speeds, averaged over the number of blocks (column No) per bin. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m.

The results of the undisturbed mean wind speed and mean wind direction are given in columns U32 and D32.

In the last row the total average of the wind speed ratio U_{wake}/U_0 (averaged over all rows) has been written.

No	A2	B1	B2	B3	C2	U32	D32
2	12.2	12.4	12.2	11.5	12.5	13.0	238
2	13.4	13.4	13.5	12.9	13.8	14.3	240
8	10.3	10.6	10.4	9.7	10.4	11.1	243
10	9.3	10.4	10.2	9.9	10.7	11.6	245
2	7.2	8.2	7.8	7.2	8.0	8.5	245
7	10.2	10.9	10.6	10.2	11.0	12.1	248
4	10.3	11.2	10.8	10.7	11.4	13.6	248
8	10.7	11.1	10.9	10.4	11.0	13.4	250
12	9.5	10.5	9.9	9.7	10.5	11.8	250
13	6.9	7.7	7.4	7.3	8.0	8.3	250
8	8.1	9.2	8.5	8.5	9.1	10.5	251
18	10.2	10.8	10.6	10.3	10.9	12.0	252
10	10.9	11.8	11.1	10.8	11.5	13.6	252
8	7.4	8.4	7.8	7.8	8.7	10.1	253
14	7.9	8.3	7.8	7.7	8.1	10.0	255
14	11.4	12.0	11.5	11.2	11.5	13.4	255
5	6.8	7.0	6.7	6.6	6.9	8.9	255
2	9.9	9.7	9.7	9.4	9.4	11.5	255
2	11.5	12.1	11.9	11.2	11.1	13.6	256
6	9.8	10.0	9.9	9.8	10.1	11.6	257
8	8.2	8.2	7.8	7.6	7.6	10.0	257
2	7.8	7.6	7.1	6.9	6.7	8.8	260
2	10.2	10.6	10.1	9.5	9.7	11.3	260
16	8.7	8.7	8.4	8.2	7.9	9.9	260
14	9.5	9.7	9.2	8.9	8.7	10.3	262
5	9.9	10.0	9.5	9.2	8.9	11.5	263
15	8.7	9.3	8.8	8.4	8.5	10.4	265
5	6.7	7.0	6.8	6.5	6.6	7.9	265
19	9.8	10.1	9.8	9.6	9.5	11.7	265
2	6.3	6.7	6.3	6.3	6.1	6.9	266
3	7.9	8.8	8.3	7.9	8.3	11.1	266
11	6.5	7.0	6.7	6.6	6.7	8.1	268
27	8.5	9.0	8.6	8.3	8.5	10.1	268
4	11.1	11.9	11.3	11.3	11.4	12.2	269
2	6.5	7.0	6.5	6.2	6.6	8.9	269
24	8.1	8.4	8.1	7.9	8.0	10.0	270
2	6.2	6.6	6.3	6.0	5.8	6.8	270
9	8.4	8.8	8.5	8.4	8.5	9.8	272
5	6.1	6.6	6.3	6.0	6.3	8.1	272
6	8.3	8.7	8.2	8.1	8.0	10.1	276
6	9.0	9.4	8.9	8.4	8.5	10.7	278
3	6.9	7.3	6.9	7.1	7.2	10.0	279
3	8.3	8.9	8.4	8.3	8.3	8.9	279

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Table 4.7D.TURB-U

The values for the turbulence intensities based on the local wind speeds, averaged over the number of blocks (column No) per bin. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m.

The results of the undisturbed turbulence intensity is given in column U32. In the last column (D32) the average value for the undisturbed wind direction is given.

In the last row the total average of the turbulence intensity (averaged over all rows) has been written.

No	A2	B1	B2	B3	C2	U32	D32
2	0.094	0.092	0.097	0.106	0.096	0.086	238
2	0.063	0.050	0.061	0.059	0.049	0.046	240
8	0.111	0.079	0.099	0.126	0.106	0.085	243
10	0.109	0.099	0.101	0.116	0.097	0.082	245
2	0.091	0.068	0.072	0.080	0.070	0.059	245
7	0.095	0.099	0.100	0.095	0.095	0.099	248
4	0.130	0.121	0.128	0.124	0.118	0.065	248
8	0.117	0.122	0.122	0.121	0.133	0.088	250
12	0.111	0.106	0.125	0.113	0.127	0.092	250
13	0.115	0.114	0.117	0.105	0.103	0.097	250
8	0.093	0.090	0.088	0.079	0.091	0.089	251
18	0.099	0.110	0.112	0.106	0.112	0.086	252
10	0.113	0.103	0.105	0.108	0.110	0.072	252
8	0.114	0.126	0.134	0.115	0.142	0.095	253
14	0.130	0.143	0.121	0.118	0.123	0.091	255
14	0.107	0.107	0.106	0.104	0.107	0.080	255
5	0.144	0.141	0.144	0.121	0.138	0.096	255
2	0.109	0.141	0.139	0.140	0.154	0.108	255
2	0.117	0.118	0.118	0.126	0.122	0.104	256
6	0.128	0.143	0.129	0.139	0.143	0.095	257
8	0.122	0.130	0.120	0.106	0.114	0.090	257
2	0.070	0.113	0.135	0.115	0.142	0.097	260
2	0.089	0.100	0.108	0.108	0.130	0.111	260
16	0.113	0.124	0.116	0.120	0.115	0.092	260
14	0.093	0.109	0.108	0.110	0.123	0.097	262
5	0.112	0.124	0.124	0.122	0.128	0.101	263
15	0.110	0.104	0.109	0.117	0.114	0.101	265
5	0.126	0.116	0.120	0.134	0.117	0.095	265
19	0.108	0.114	0.114	0.118	0.121	0.101	265
2	0.094	0.104	0.106	0.090	0.106	0.106	266
3	0.067	0.075	0.080	0.079	0.100	0.074	266
11	0.119	0.108	0.110	0.106	0.107	0.123	268
27	0.108	0.109	0.106	0.108	0.112	0.112	268
4	0.090	0.082	0.087	0.092	0.094	0.070	269
2	0.074	0.075	0.081	0.079	0.074	0.063	269
24	0.105	0.108	0.113	0.114	0.119	0.110	270
2	0.116	0.125	0.122	0.111	0.138	0.131	270
9	0.106	0.095	0.100	0.104	0.092	0.097	272
5	0.111	0.094	0.109	0.102	0.098	0.087	272
6	0.126	0.115	0.118	0.125	0.123	0.091	276
6	0.107	0.105	0.101	0.116	0.109	0.110	278
3	0.087	0.099	0.096	0.103	0.097	0.081	279
3	0.113	0.096	0.111	0.124	0.112	0.131	279

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

Table 4.4D.MEAN

The values for the mean wind speeds, averaged over the number of blocks (column No) per bin. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m.

The results of the undisturbed mean wind speed and mean wind direction are given in columns U72 and D72.

No	A2	B1	B2H	B2L	B3	C2	U72	D72
2	5.0	6.2	5.8	5.8	5.8	6.5	7.5	159
2	3.9	5.2	5.0	4.9	5.0	5.7	7.2	162
1	6.0	7.5	7.1	7.1	7.1	8.2	10.0	162
1	3.7	4.4	4.6	4.8	4.7	5.6	7.3	163
3	5.7	6.9	6.7	6.7	6.9	7.8	10.1	164
2	3.7	4.7	4.6	4.6	4.7	5.4	7.2	166
4	3.7	4.3	4.2	4.1	4.1	4.7	7.3	169
5	4.2	4.2	4.2	4.1	4.1	4.3	7.7	171
5	5.2	4.9	4.9	4.7	4.7	4.6	8.1	173
1	6.0	5.5	5.6	5.8	5.9	5.5	9.1	174
8	5.0	4.5	4.5	4.4	4.3	3.8	7.7	176
1	5.9	5.2	5.2	5.3	5.1	4.7	9.3	177
11	5.5	5.0	4.9	4.7	4.8	4.2	7.7	179
3	6.6	6.1	6.1	6.0	6.0	5.4	10.2	179
5	5.7	5.5	5.4	5.2	5.3	4.7	8.0	181
1	7.0	6.4	6.6	7.0	6.9	6.3	10.1	180
4	6.7	6.7	6.6	6.4	6.4	5.9	8.0	184
3	6.9	6.6	6.5	6.4	6.4	5.5	9.3	183
6	6.9	6.7	6.6	6.5	6.4	6.1	8.1	186
7	7.7	7.5	7.5	7.3	7.1	6.8	9.7	187
2	6.8	6.8	6.8	6.5	6.3	6.2	8.3	189
4	8.0	7.8	7.8	7.7	7.6	7.2	9.5	188
7	7.8	8.0	7.8	7.5	7.3	7.7	8.2	191
1	8.1	8.1	8.1	7.8	7.7	7.4	9.3	191
3	7.3	7.5	7.4	7.2	7.1	7.5	8.3	194
2	8.4	8.7	8.6	8.3	8.0	8.4	9.5	194
7	7.1	7.3	7.1	6.9	6.7	7.1	7.6	196
3	9.8	10.2	10.1	9.7	9.3	10.1	10.2	197
9	7.8	8.1	8.0	7.6	7.4	8.0	8.3	198
2	10.1	10.4	10.2	9.7	9.3	10.1	9.9	199
1	10.9	11.4	11.3	11.1	10.7	11.4	11.8	199

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

Table 4.4D. TURB-U

The values for the turbulence intensities based on the local wind speeds, averaged over the number of blocks (column No) per bin. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m.

The results of the undisturbed turbulence intensity is given in column U72. In the last column (D72) the rms-value for the undisturbed wind direction is given.

No	A2	B1	B2H	B2L	B3	C2	U72	D72
2	0.205	0.144	0.096	0.062	0.109	0.086	0.096	5.6
2	0.247	0.218	0.144	0.118	0.148	0.147	0.105	5.9
1	0.211	0.220	0.139	0.096	0.185	0.162	0.087	5.6
1	0.240	0.225	0.153	0.103	0.183	0.111	0.096	5.6
3	0.201	0.208	0.141	0.136	0.190	0.176	0.090	5.9
2	0.213	0.196	0.126	0.118	0.182	0.197	0.130	6.2
4	0.255	0.228	0.147	0.157	0.210	0.234	0.105	6.4
5	0.252	0.243	0.159	0.151	0.216	0.223	0.089	5.7
5	0.240	0.232	0.176	0.164	0.204	0.245	0.109	6.5
1	0.254	0.229	0.135	0.110	0.168	0.222	0.120	5.6
8	0.214	0.245	0.175	0.167	0.232	0.241	0.103	6.2
1	0.150	0.204	0.129	0.135	0.203	0.223	0.115	5.1
11	0.171	0.229	0.161	0.143	0.185	0.229	0.112	6.1
3	0.188	0.245	0.193	0.157	0.194	0.236	0.088	6.1
5	0.171	0.218	0.168	0.164	0.194	0.239	0.124	6.8
1	0.248	0.273	0.221	0.140	0.191	0.236	0.109	8.1
4	0.135	0.145	0.131	0.124	0.143	0.215	0.098	7.0
3	0.147	0.179	0.134	0.131	0.161	0.233	0.105	5.9
6	0.118	0.162	0.124	0.118	0.142	0.221	0.117	6.8
7	0.120	0.157	0.103	0.098	0.146	0.204	0.112	5.6
2	0.140	0.149	0.116	0.112	0.146	0.217	0.108	6.7
4	0.110	0.128	0.098	0.096	0.128	0.188	0.112	6.2
7	0.103	0.097	0.079	0.091	0.118	0.131	0.119	7.0
1	0.106	0.139	0.095	0.099	0.141	0.227	0.130	6.6
3	0.113	0.128	0.097	0.091	0.116	0.128	0.119	6.0
2	0.102	0.091	0.074	0.081	0.106	0.129	0.100	6.0
7	0.110	0.093	0.089	0.094	0.116	0.131	0.127	5.8
3	0.099	0.085	0.064	0.069	0.095	0.090	0.113	6.1
9	0.113	0.095	0.082	0.088	0.109	0.110	0.089	5.2
2	0.107	0.096	0.086	0.089	0.115	0.108	0.103	5.6
1	0.104	0.082	0.074	0.075	0.100	0.085	0.110	5.6

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

Table 4.4D. TURB-V

The values for the turbulence intensities of the V-component of the wind based on the local wind speeds, averaged over the number of blocks (column No) per bin. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m.

No	A2	B1	B3	C2
2	0.176	0.130	0.091	0.082
2	0.228	0.182	0.148	0.104
1	0.238	0.188	0.151	0.120
1	0.251	0.213	0.145	0.099
3	0.227	0.192	0.168	0.126
2	0.256	0.220	0.203	0.154
4	0.239	0.251	0.219	0.196
5	0.211	0.244	0.212	0.214
5	0.185	0.236	0.205	0.739
1	0.200	0.213	0.212	0.252
8	0.142	0.189	0.757	0.862
1	0.556	0.196	0.642	0.228
11	0.116	0.161	0.680	0.197
3	0.120	0.161	0.543	0.188
5	0.108	0.147	0.129	0.704
1	0.126	0.157	0.168	0.224
4	0.081	0.093	0.086	0.120
3	0.105	0.142	0.114	0.602
6	0.089	0.111	0.092	0.119
7	0.095	0.107	0.099	0.130
2	0.094	0.107	0.095	0.126
4	0.092	0.104	0.091	0.115
7	0.421	0.096	0.445	0.424
1	0.120	0.113	0.111	0.117
3	0.093	0.090	0.088	0.076
2	0.081	0.072	0.092	0.071
7	0.084	0.084	0.084	0.073
3	0.080	0.077	0.080	0.071
9	0.085	0.083	0.090	0.082
2	0.083	0.081	0.085	0.074
1	0.082	0.078	0.090	0.074

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

Table 4.UF.LENGTH

The values for the integral turbulence length scales, averaged over the blocks in series 13, 14 and 23. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m. Masts 6 and 7 are fixed masts, the masts A, B and C are mobile masts.

Series 13	U61	U62	U63
xLu (m)	110	110	90

Series 14	U61	U62	U63
xLu (m)	100	120	80

series 23	A2	B1	B3	C2	U72
xLu (m)	20	15	20	15	15

Table 4.7D.LENGTH

The values for the integral turbulence length scales, averaged over all blocks. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m.

The results for the undisturbed wind speed condition is given in column U32.

A2	B1	B2	B3	C2	U32
50	55	50	45	50	65

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

Table 4.4D.LENGTH

The values for the integral turbulence length scales x_{Lu} , averaged over the number of blocks (column No) per bin. The (lateral) distance between masts A and B and between masts B and C is in both cases 12 m.

The results of the undisturbed wind condition is given in column U72. In the last column (D72) the mean value for the undisturbed wind direction is given.

In case the number of blocks equals 1, the length scale has not been determined.

No	A2	B1	B3	C2	U72	D72
2	40	40	40	40	100	159
2	20	30	20	30	60	162
1	162					
1	163					
3	20	30	40	40	70	164
2	20	20	20	30	80	166
4	25	15	30	20	70	169
5	40	20	30	30	100	171
5	40	30	25	30	80	173
1	174					
8	40	30	40	20	80	176
1	177					
11	40	40	30	25	120	179
3	50	60	60	50	90	179
5	60	60	50	40	140	181
1	180					
4	80	60	70	60	70	184
3	80	60	60	50	120	183
6	80	60	60	60	80	186
7	50	50	50	40	100	187
2	70	70	70	80	100	189
4	80	60	60	50	100	188
7	70	60	70	60	80	191
1	191					
3	80	100	80	90	100	194
2	80	80	80	90	50	194
7	120	100	100	110	100	196
3	70	70	60	60	70	197
9	50	40	40	50	50	198
2	50	50	50	60	50	199
1	199					

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

Figures

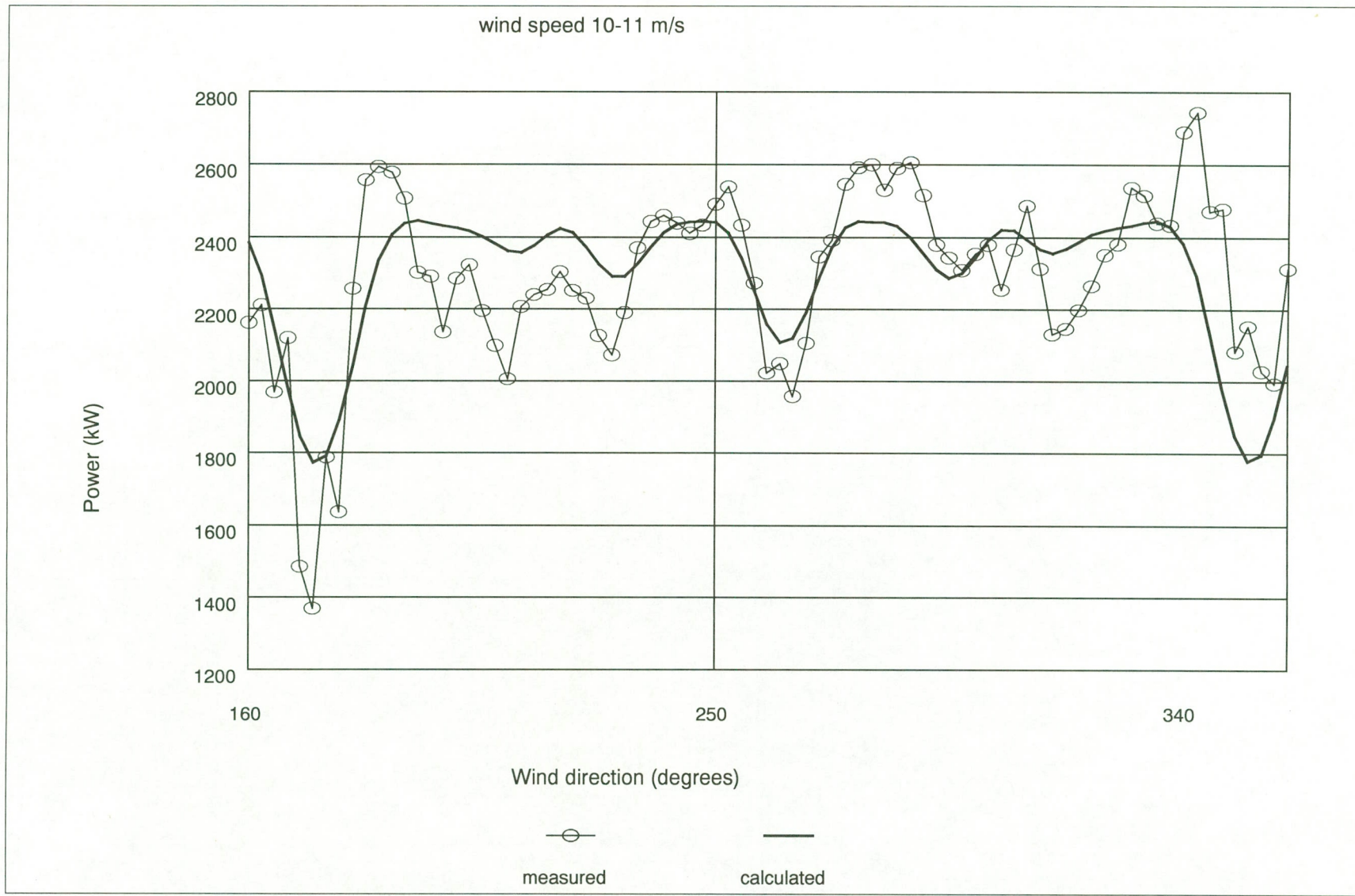


Figure 3.1 Calculated versus measured variations of wind farm power with wind direction of the Sexbierum Wind farm (turbines 11, 21 and 31 excluded). The wind speed is between 10 and 11 m/s

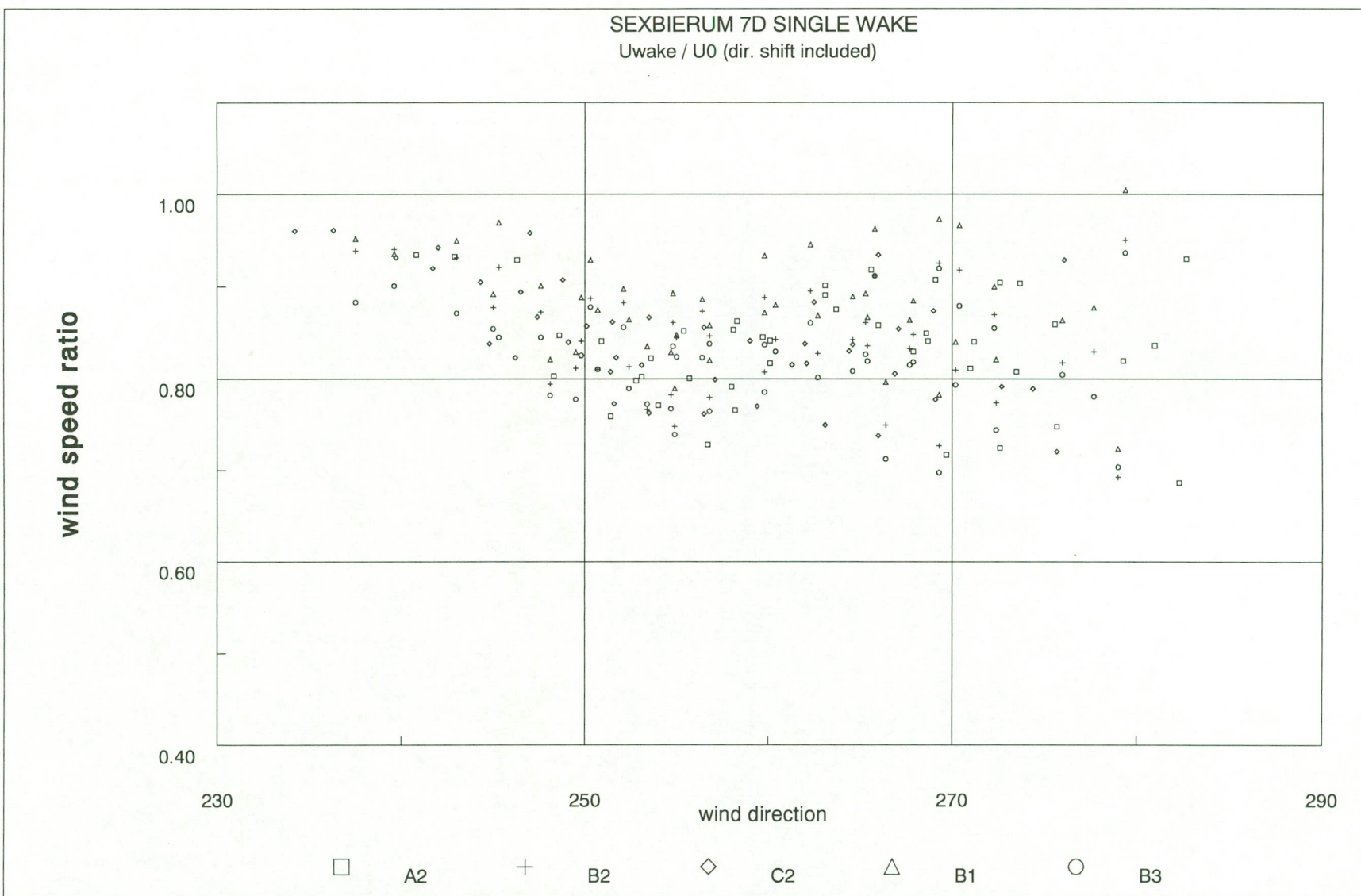


Figure 4.7D.MEAN Average wind speed ratio U_{wake}/U_0 in the wake at 7D behind turbine 26 as a function of the wind direction

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

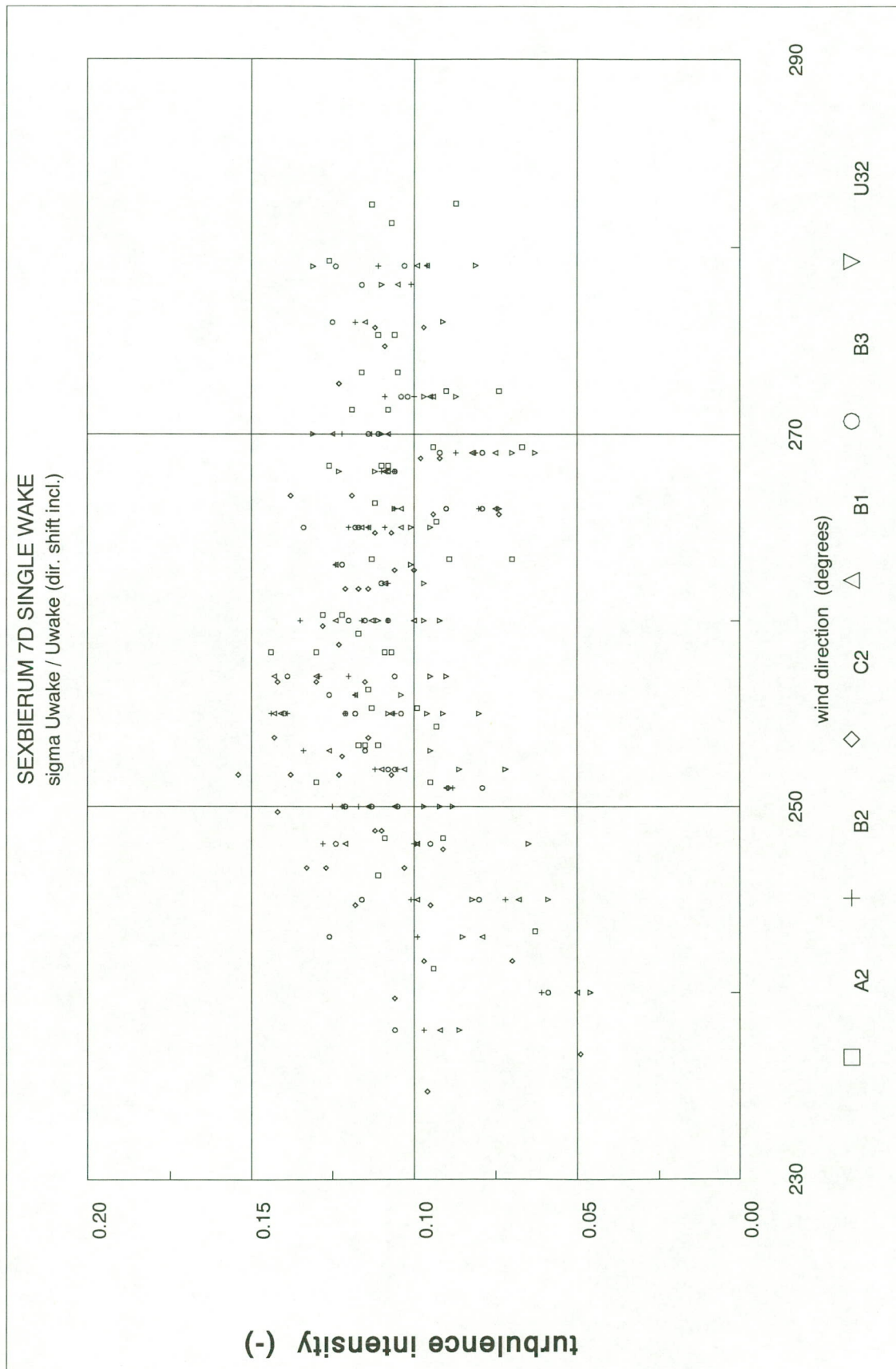


Figure 4.7D. TURB-U Turbulence intensity $\sigma_{u,wake}/U_{wake}$ in the wake at 7D behind turbine 26 as a function of the wind direction

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

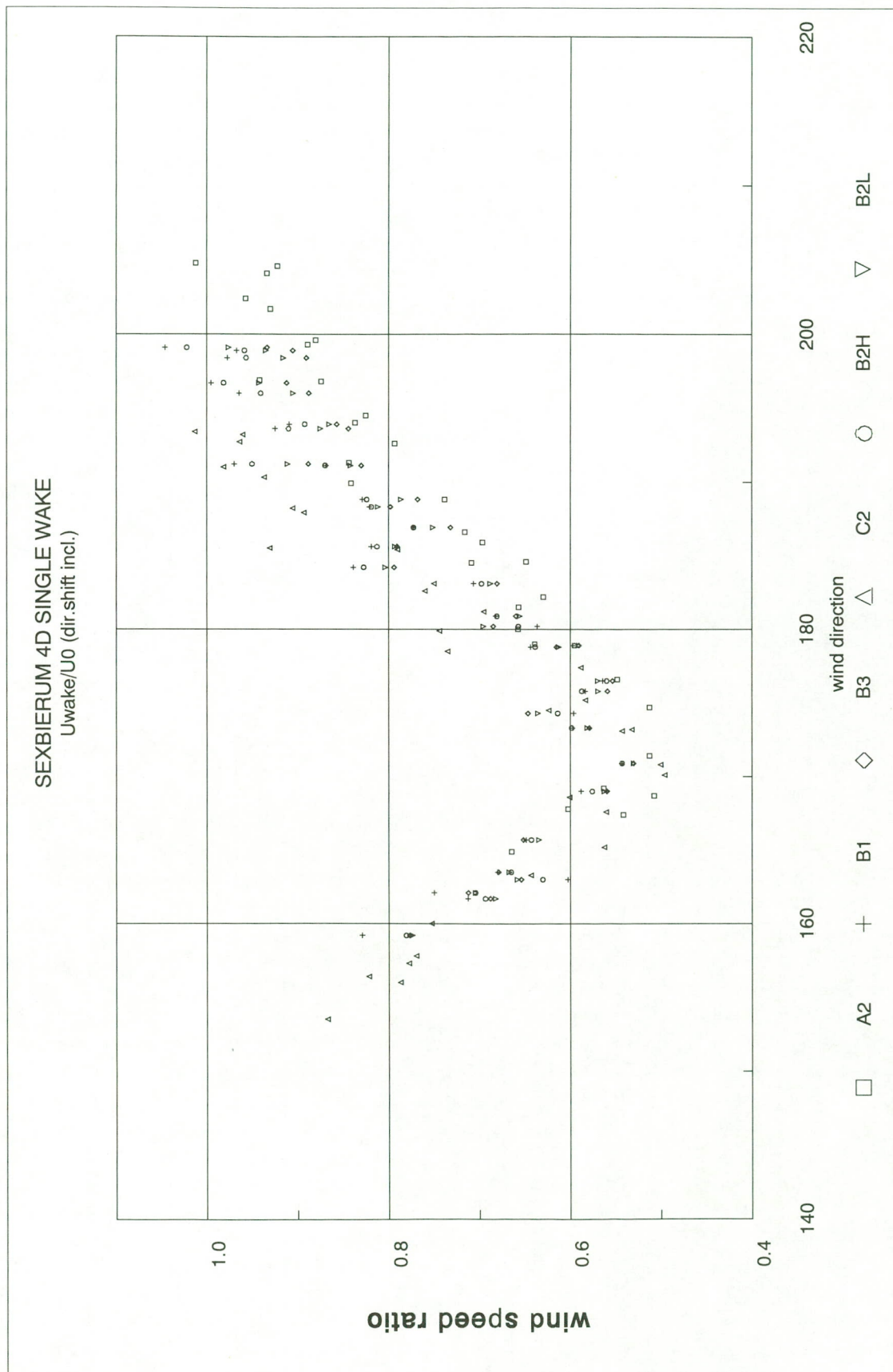


Figure 4.4D. MEAN Average wind speed ratio U_{wake}/U_0 in the wake at 4D behind turbine 37 as a function of the wind direction

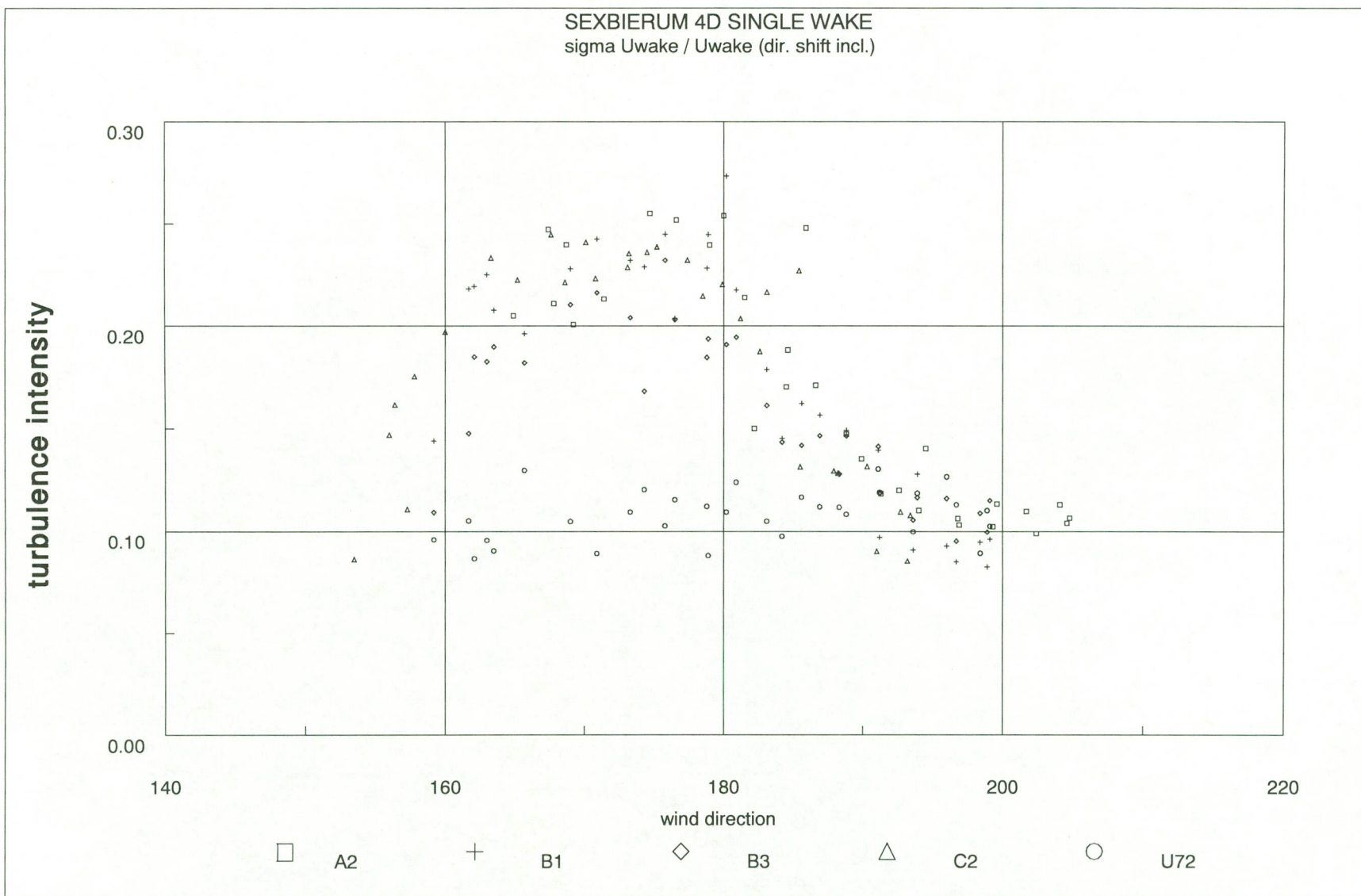


Figure 4.4D.TURB-U Turbulence intensity $\sigma_{u,wake}/U_{wake}$ in the wake at 4D behind turbine 37 as a function of the wind direction

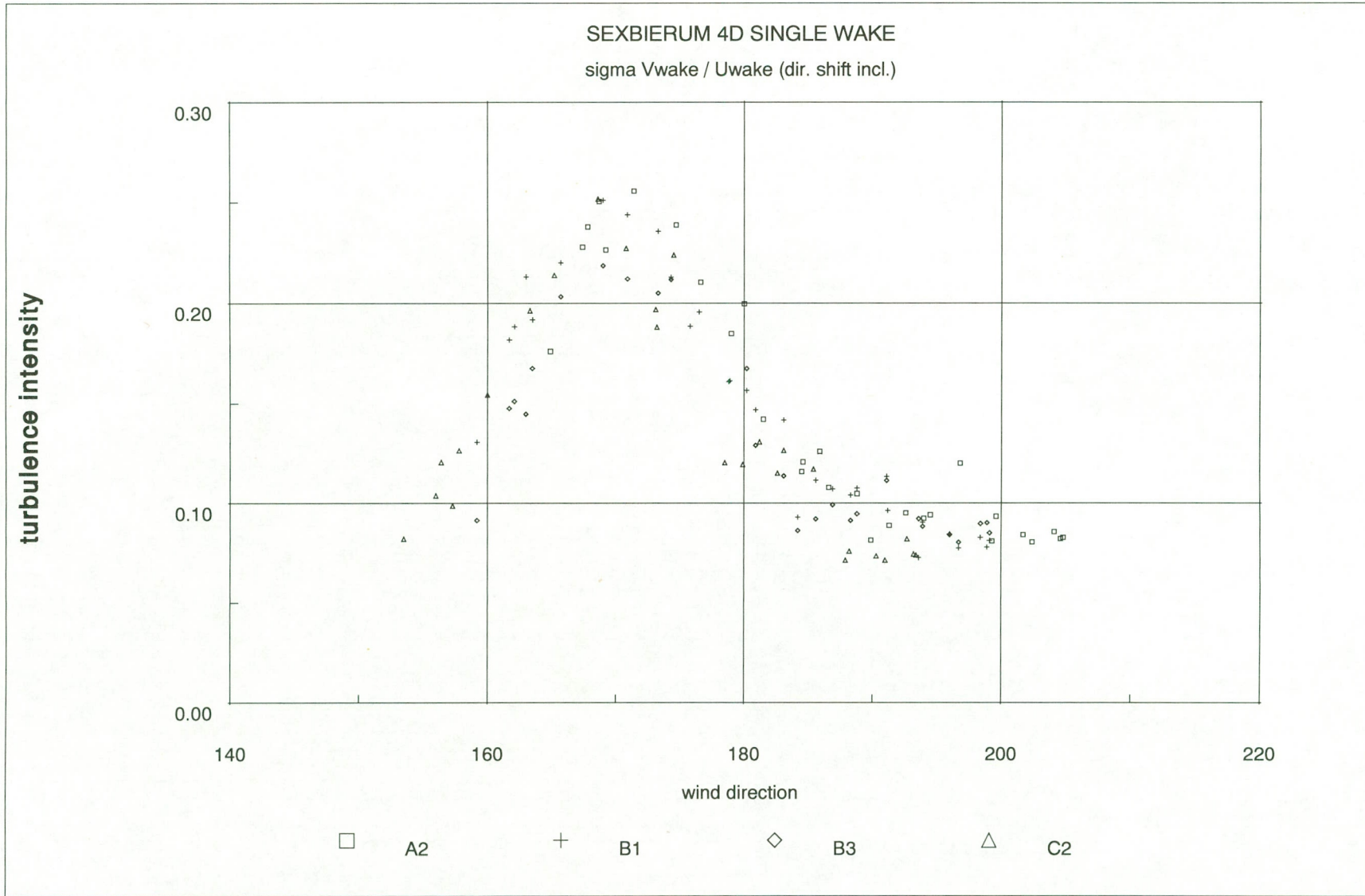


Figure 4.4D.TURB-V Turbulence intensity $\sigma_{v,wake}/U_{wake}$ in the wake at 4D behind turbine 37 as a function of the wind direction

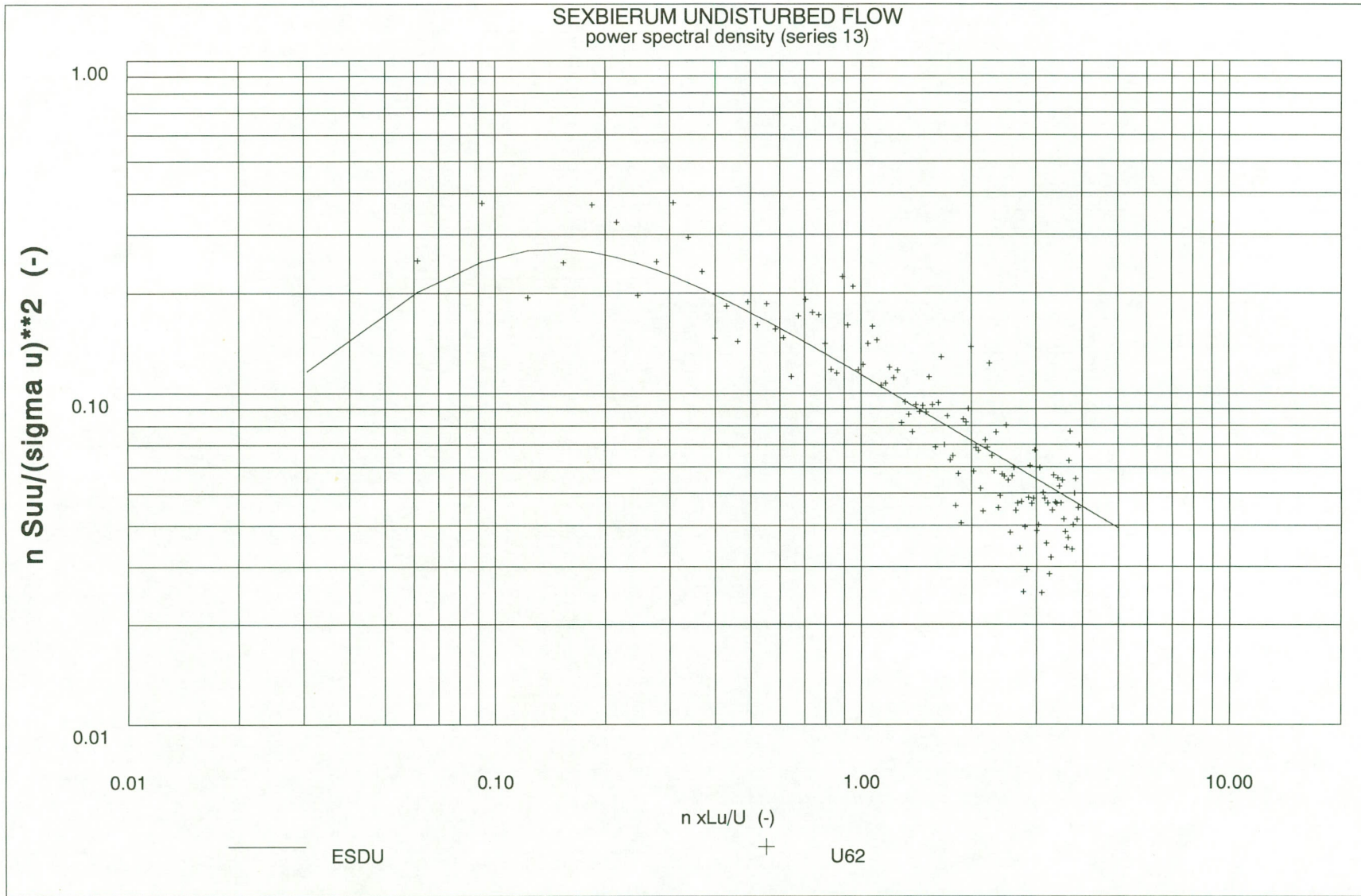


Figure 4. UF.PSD The power spectral densities measured (anemometer U62) in the undisturbed atmospheric flow compared with the theoretical spectral densities according to ESDU. The spectra have been presented in non-dimensional parameters

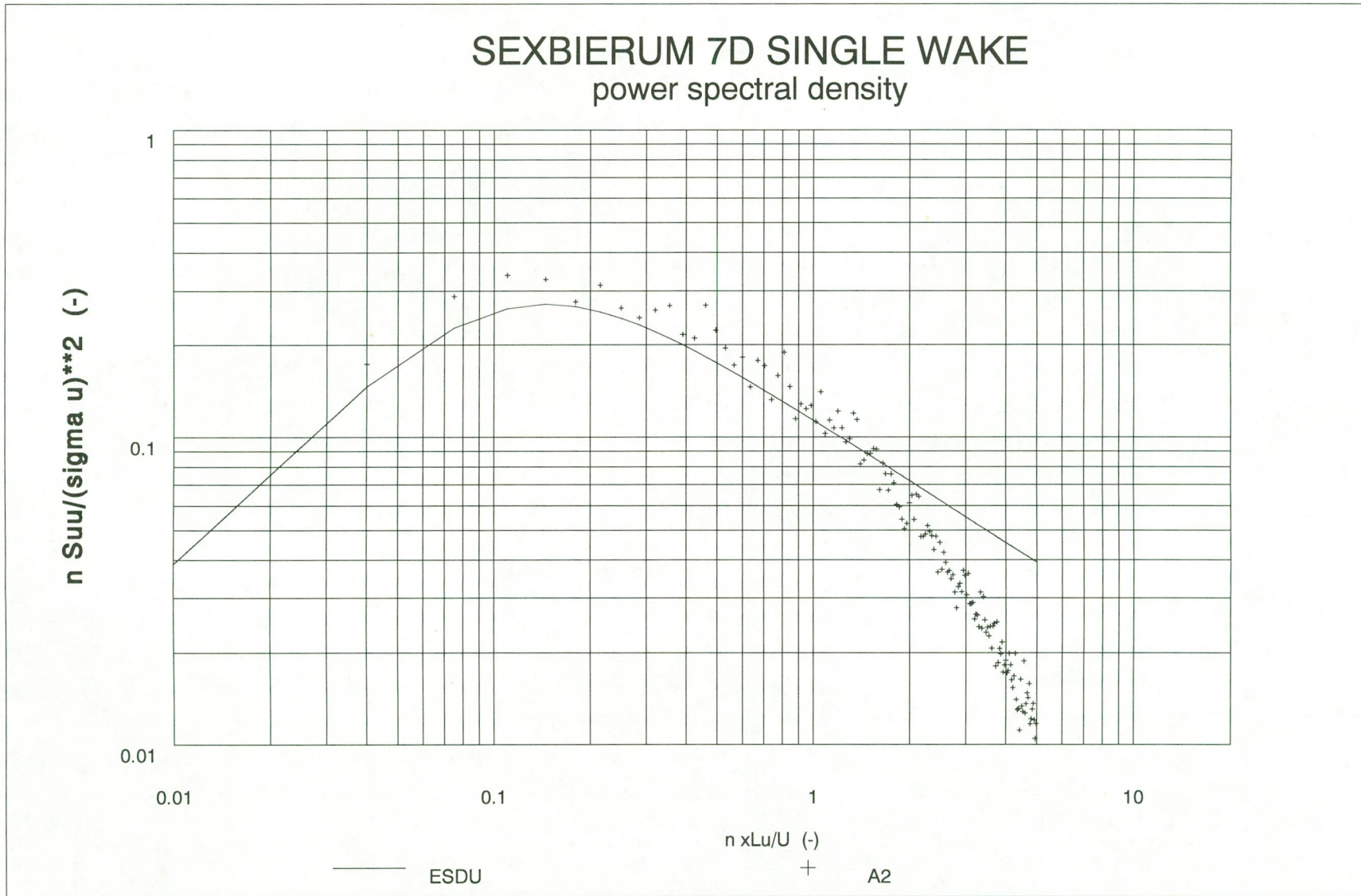


Figure 4.7D.PSD-A2 The power spectral densities measured (anemometer A2) at the centre line of the wake at 7D behind turbine 26 compared with the theoretical spectral densities according to ESDU. The spectra have been presented in non-dimensional parameters

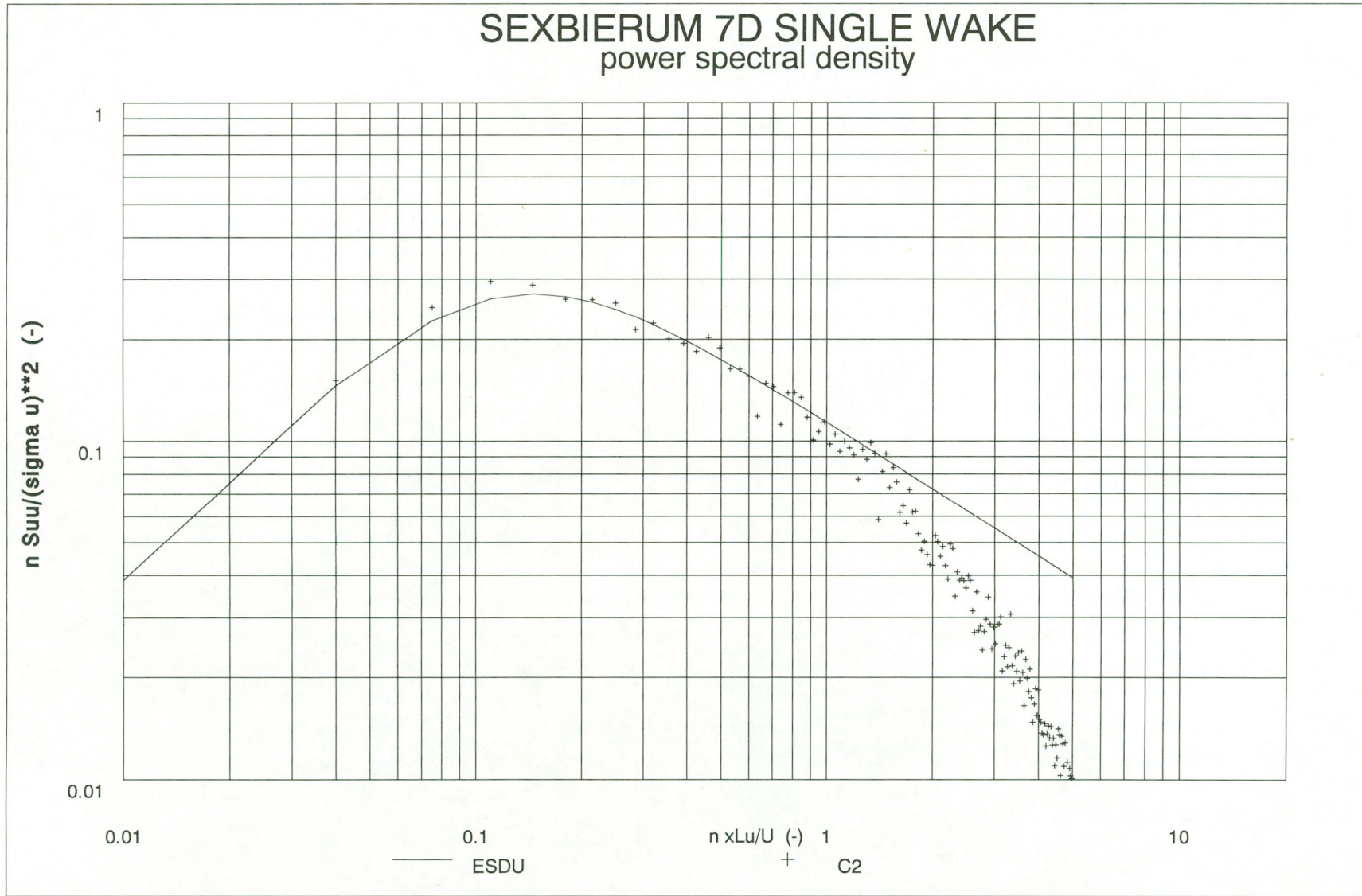


Figure 4.7D.PSD-C2 The power spectral densities measured (anemometer C2) at the centre line of the wake at 7D behind turbine 26 compared with the theoretical spectral densities according to ESDU. The spectra have been presented in non-dimensional parameters

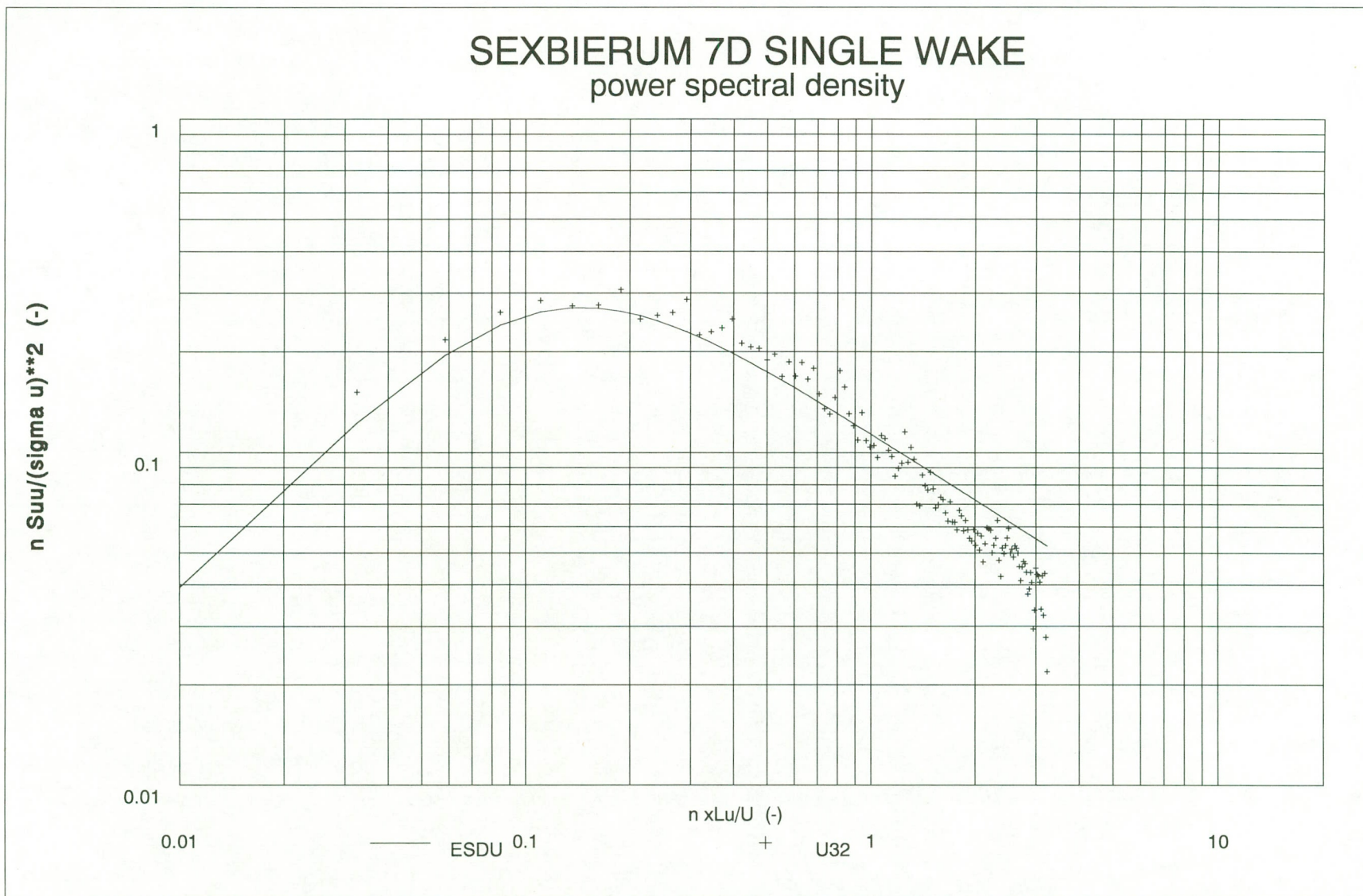


Figure 4.7D.PSD-U32 The power spectral densities measured (anemometer U32) in the undisturbed atmospheric flow compared with the theoretical spectral densities according to ESDU. The spectra have been presented in non-dimensional parameters

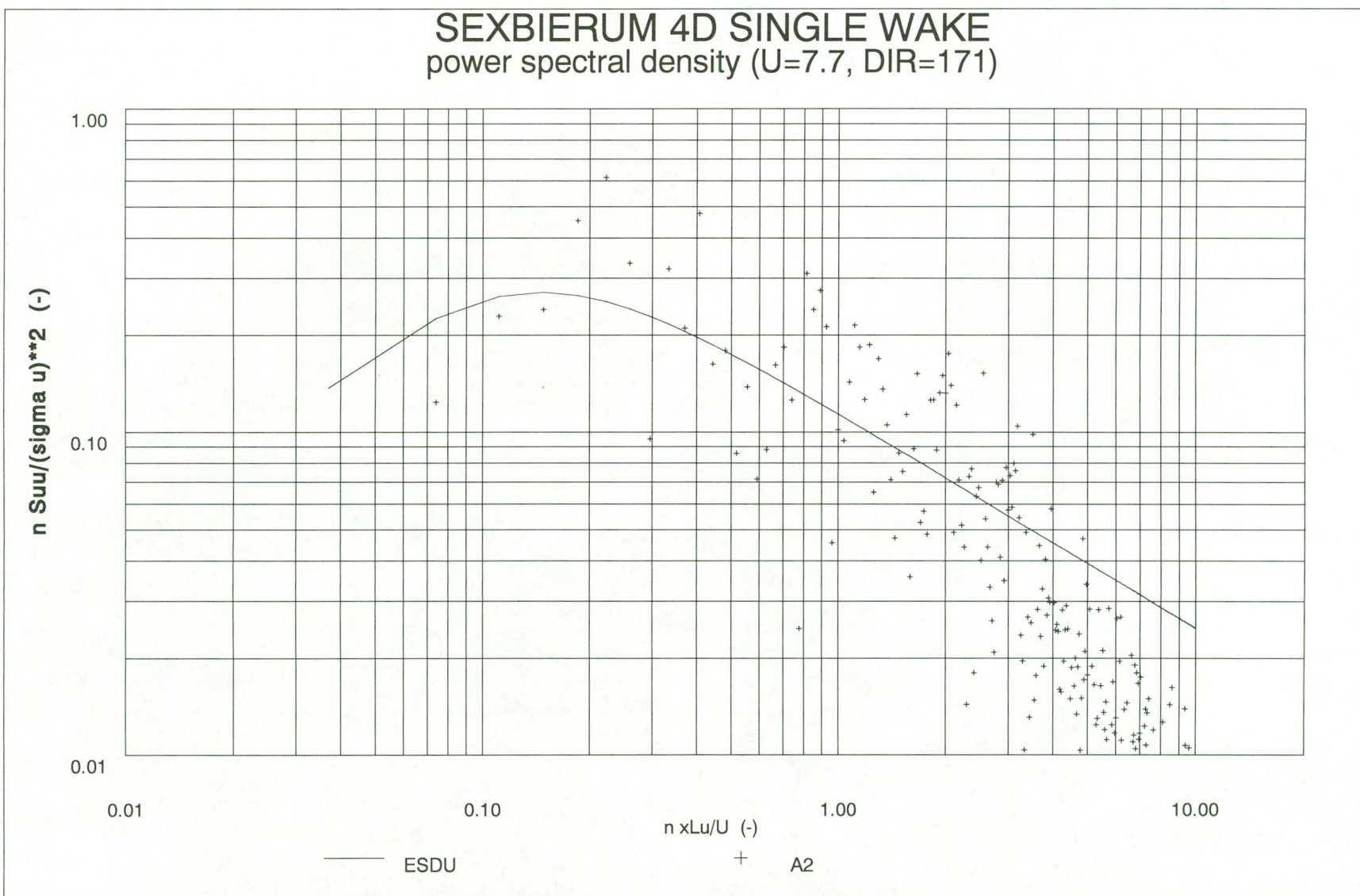


Figure 4.4D.PSD-A2 The power spectral densities measured (anemometer A2) at the centre line of the wake at 4D behind turbine 37 compared with the theoretical spectral densities according to ESDU. The spectra have been presented in non-dimensional parameters

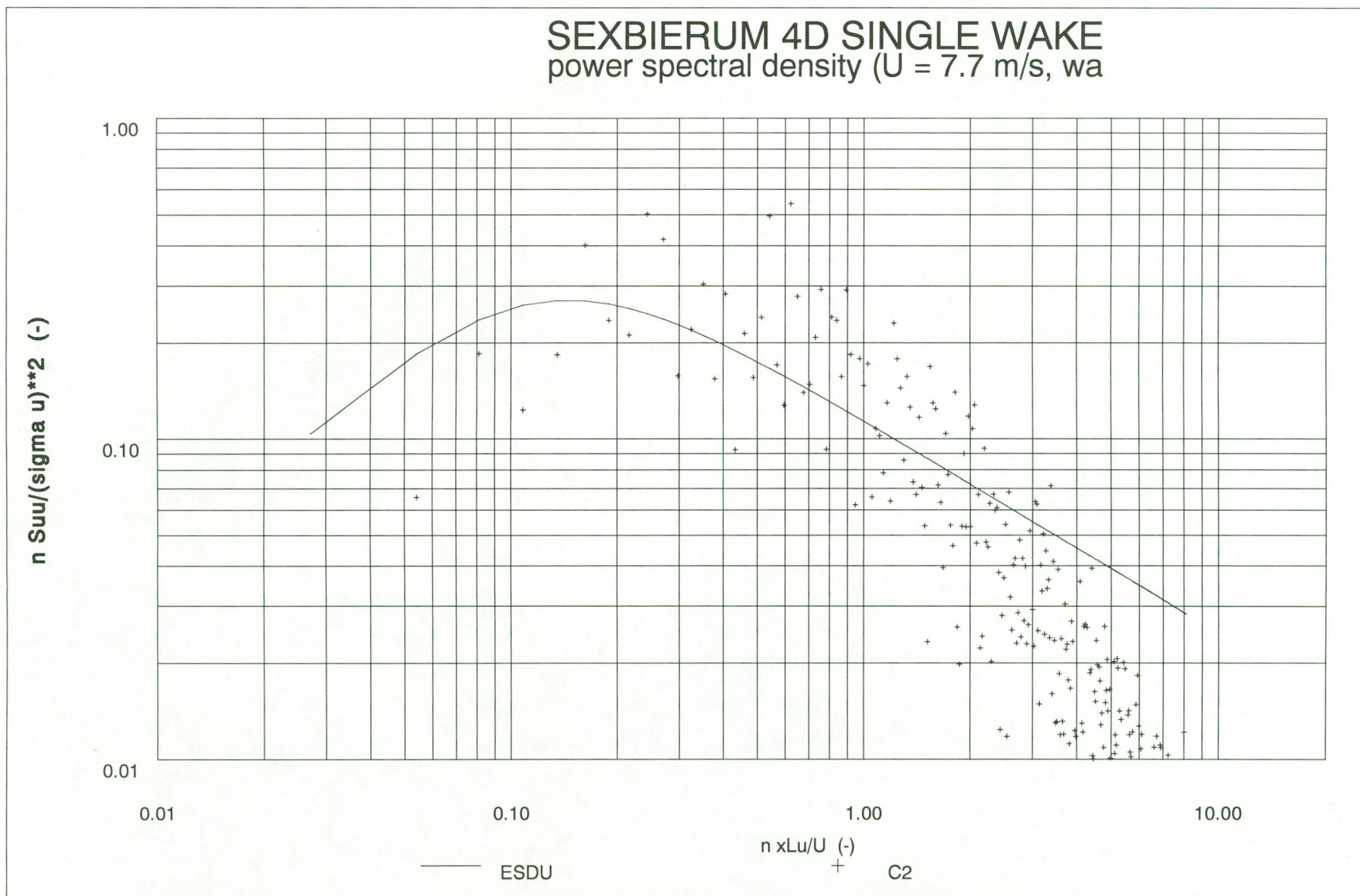


Figure 4.4D.PSD-C2 The power spectral densities measured (anemometer C2) at the centre line of the wake at 4D behind turbine 37 compared with the theoretical spectral densities according to ESDU. The spectra have been presented in non-dimensional parameters

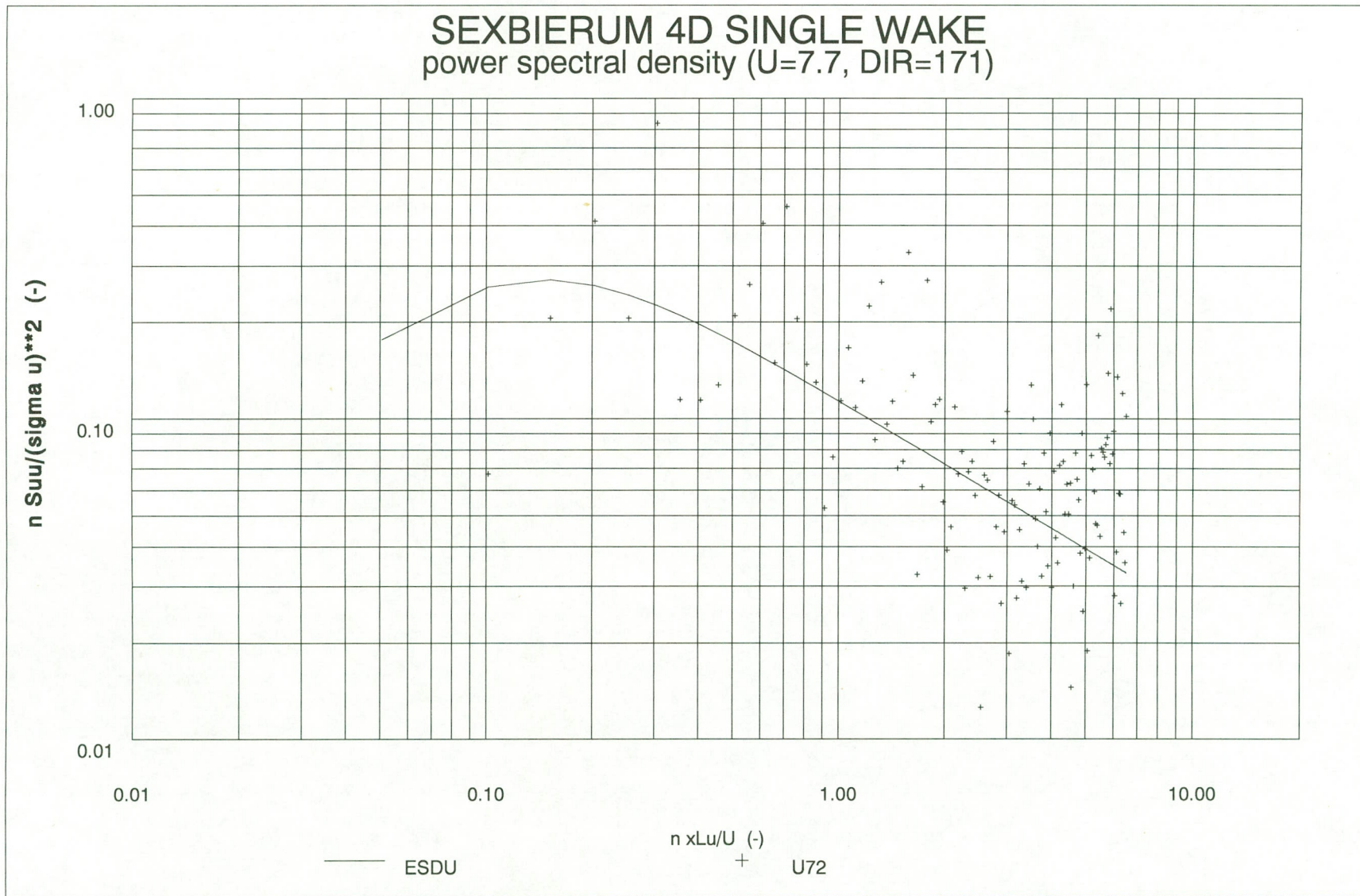


Figure 4.4D.PSD-U72 The power spectral densities measured (anemometer U72) in the undisturbed atmospheric flow compared with the theoretical spectral densities according to ESDU. The spectra have been presented in non-dimensional parameters

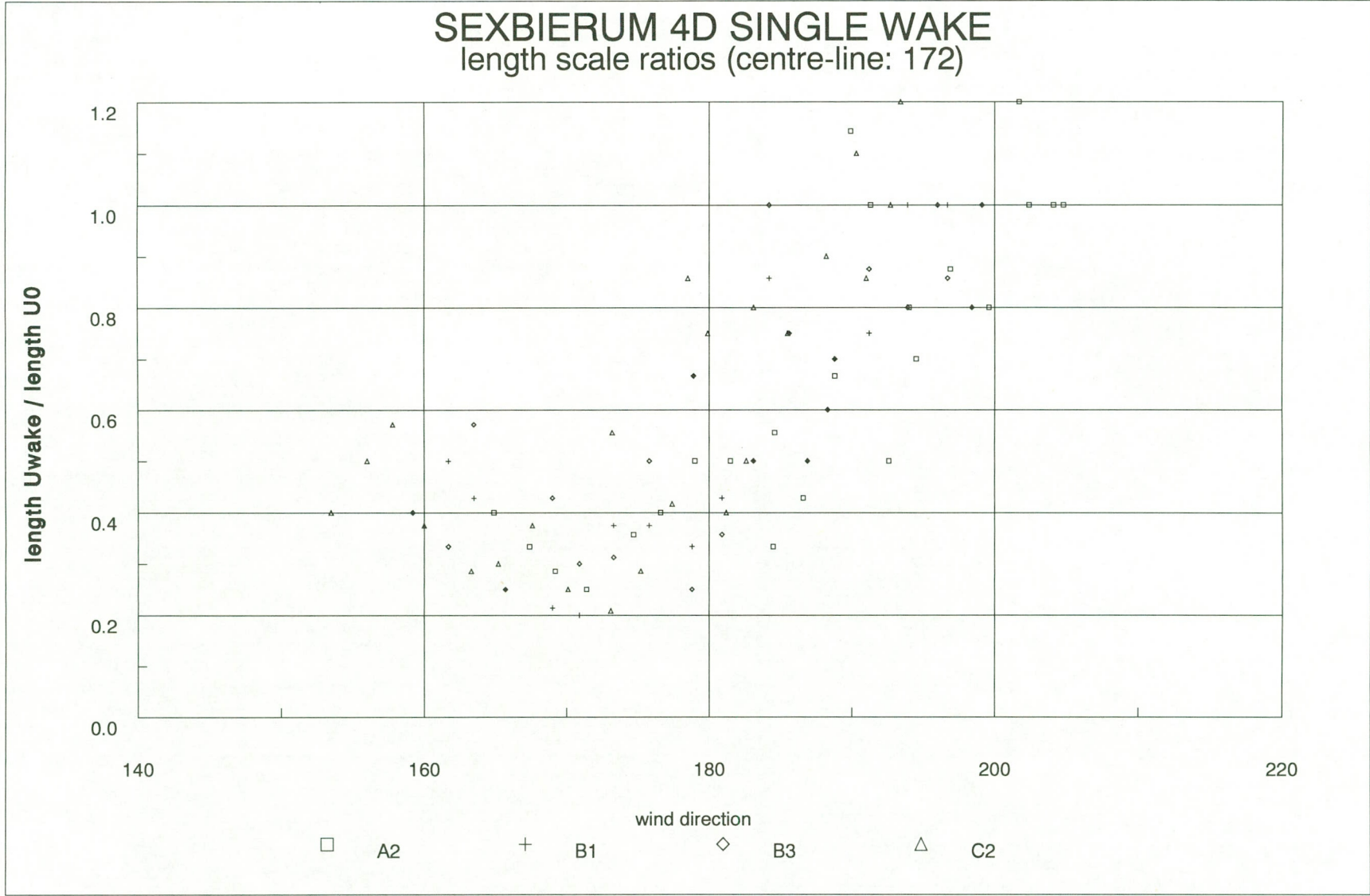


Figure 4.4D.LENGTH The ratio between the integral turbulence length scales measured in the wake at 4D behind turbine 37 and in the undisturbed atmospheric flow as a function of the wind direction. The centre line of the wake is at 172 degrees

Dynamic loads in wind farms. Analysis of wind spectra, coherence functions and integral length scales of the turbulence of the Sexbierum Wind Farm

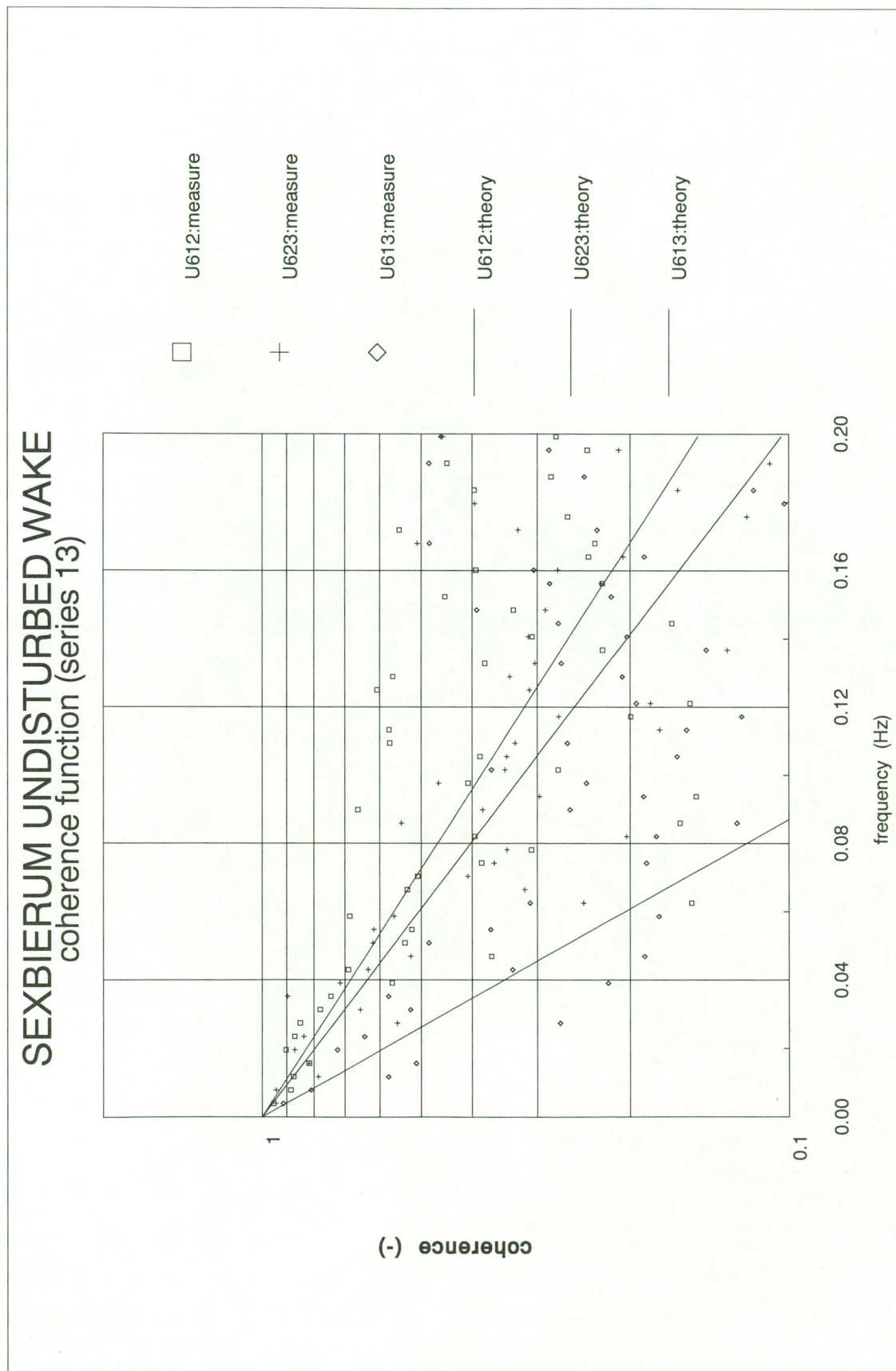


Figure 4. UF.COH The coherence function in the undisturbed atmospheric flow outside the Sexbierum wind farm in vertical direction

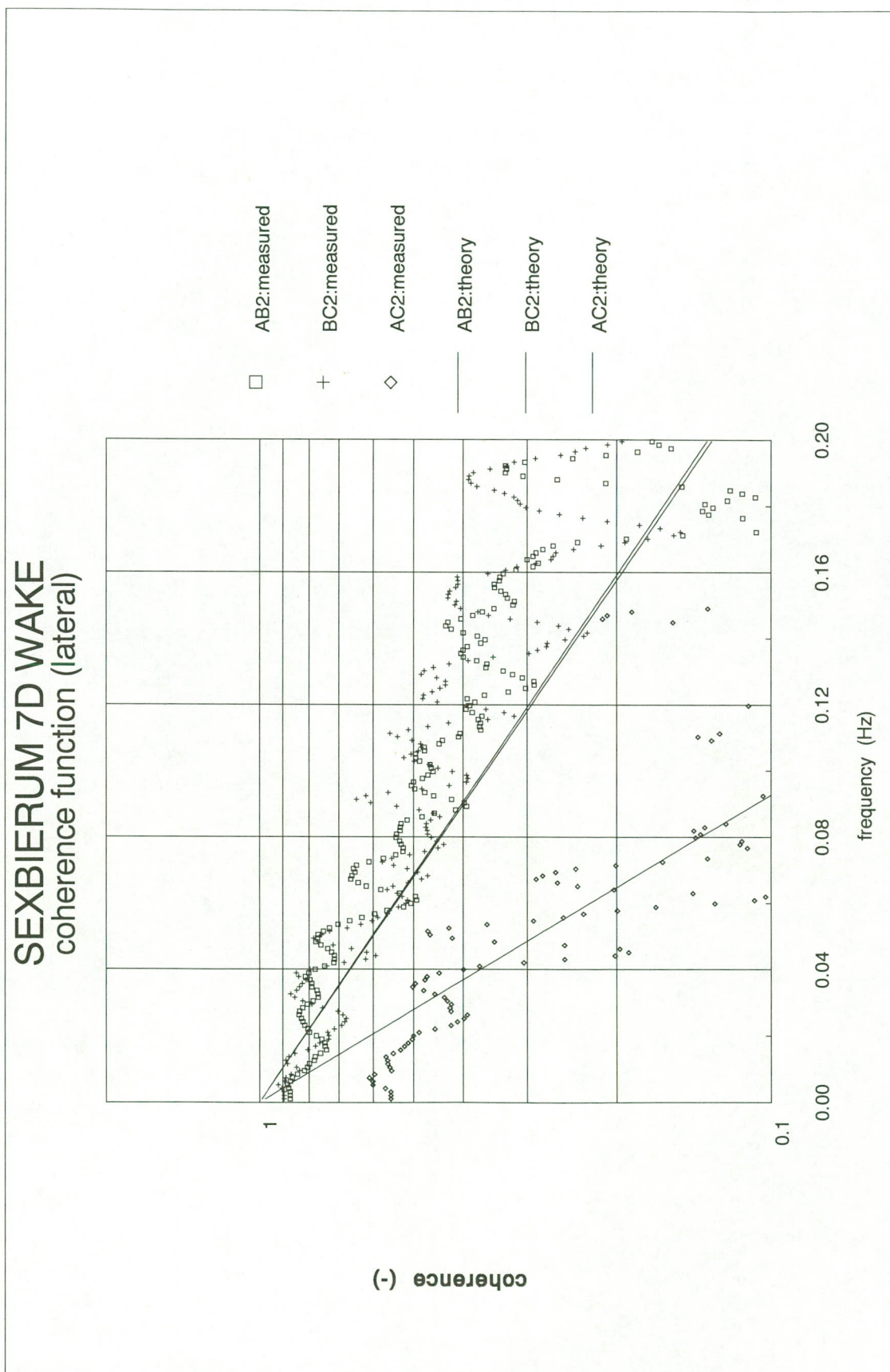


Figure 4.7D. COH-ABC2 The coherence function at 7D behind turbine 26 in lateral direction

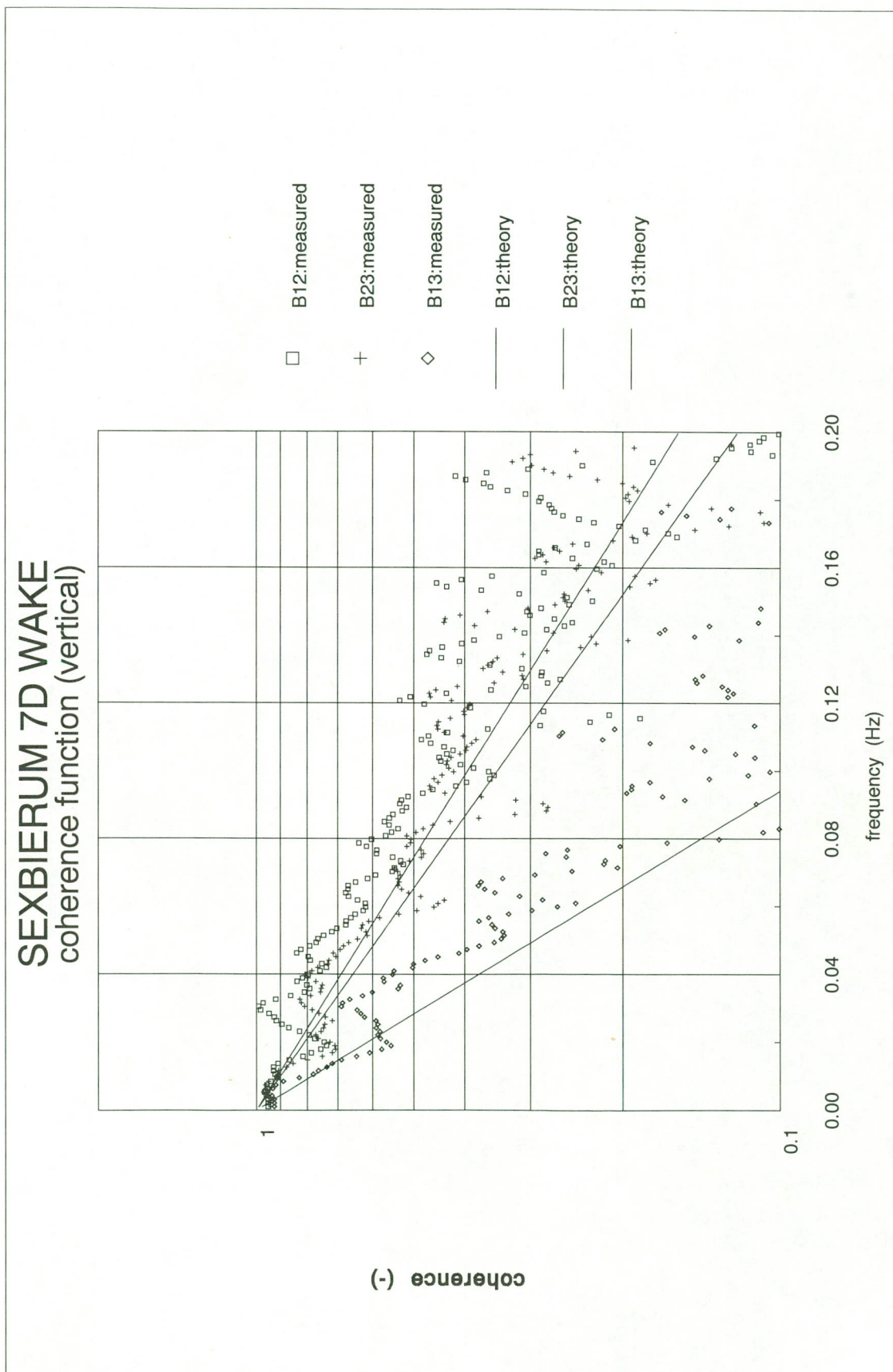


Figure 4. 7D.CO-H-B123 The coherence function at 7D behind turbine 26 in vertical direction

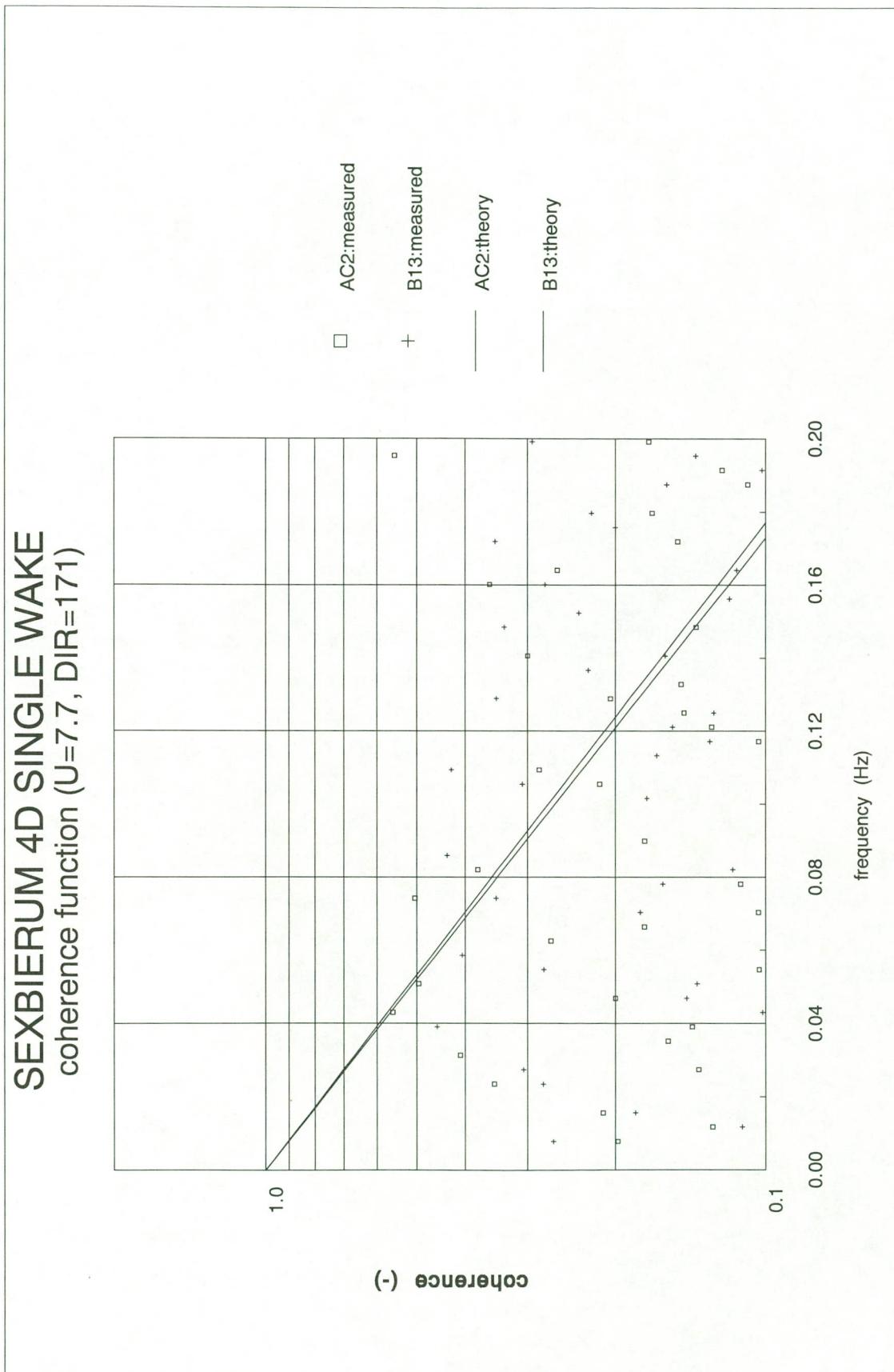


Figure 4.4D.CO2 The coherence function at 4D behind turbine 37