Field measurements on the CWD 5001 performed in the period 85-05-18 to 85-12-18

FIELD MEASUREMENTS ON THE CWD 5001 PERFORMED IN THE PERIOD 85-05-18 to 85-12-18

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<u>CONTENTS</u>

1 Introduction

The Wind Energy Group of the Physics Department of the Eindhoven University is one of the participants in CWD, Consulting Services Wind Energy for Developing Countries. The CWD tries to help governments, institutes and private parties in the Third World, with their efforts to use wind energy and in general to promote the interest for wind energy in Third World countries. Special attention is given to mechanically driven water pumping windmills.
In an early phase of the project the need was felt for a testing facility for full scale water pumping windmills.
In Eindhoven, close to the premises of the Wind Energy Group, a test field was established. Its main objective is testing and improving newly designed windmills, as well as developing testing procedures.
This report describes the results of the measurements performed on the waterpumping, the CWD 5001, in the period 85-05-18 to 85-09-01. This data can be found on DATA DISK 23 until 28 as kept on the test field.

2 Description of the test field

The test field is situated on the terrain of the Eindhoven University of Technology. Eindhoven lies in an inland region of relatively low wind speeds (4.0 to 4.5 m/s in open terrain), moreover, the city and the University buildings shade the site from the predominant south westerly winds. The test site is situated in the middle of an open field on the east side of the University's terrain (see fig. 2.1). The field is covered by grass and low bushes. North, east and south at a distance of approximately 80 meter from the windmill test site, the field is bordered by a row of dense trees and bushes. West of the test site, at a distance of approximately 80 meter, a row of spaced trees is found. The height of these trees is approximately 15 m.
The windmill locations at the test site are arranged in a NNW-SSE line. In this way the windmills will experience a wind flow, which is not affected by each others' wakes, for wind directions from WNW to SSW and from NNE to ESE, which are the most important wind directions to be expected. (see the wind run rose in fig. 2.2). Four wells have been drilled at the test site, ranging from 6 to 50 m. Since the natural ground water level is at 2 to 3 m, and windmills are to be tested to far greater depths, the wells are totally closed to prevent any infiltration of the ground water. In the wells an arbitrary water level can be realized.

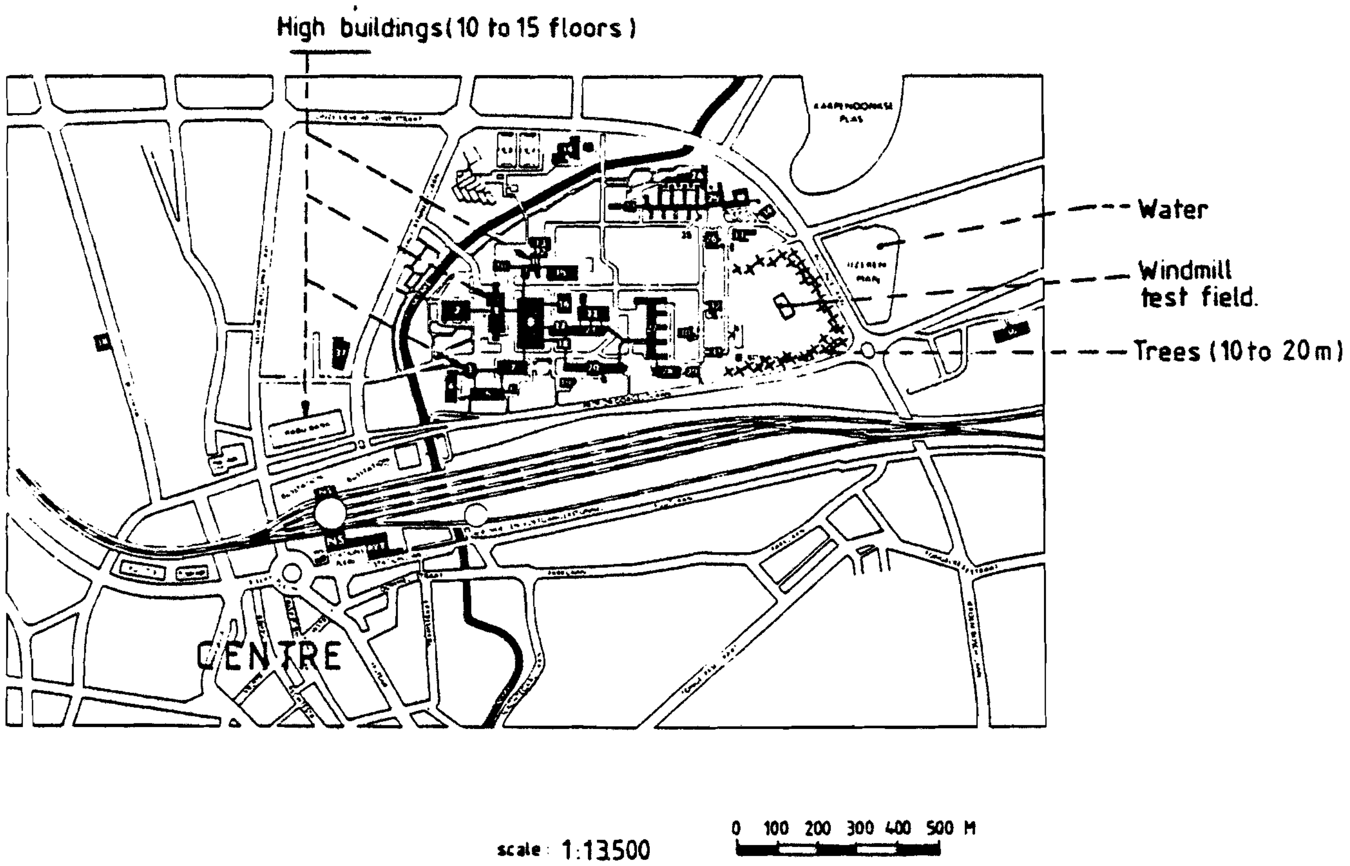


Fig. 2.1 Lay out of the Eindhoven University of Technology

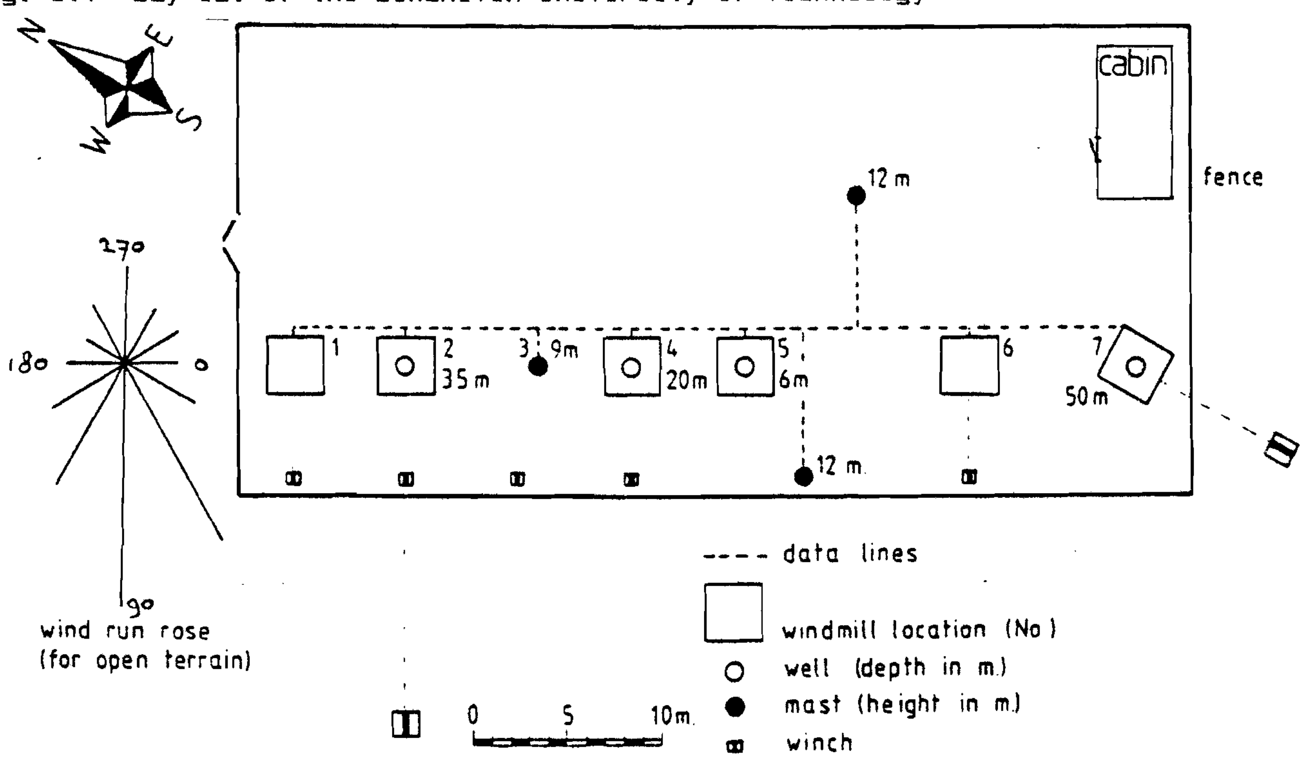


Fig. 2.2 Lay out of the test field

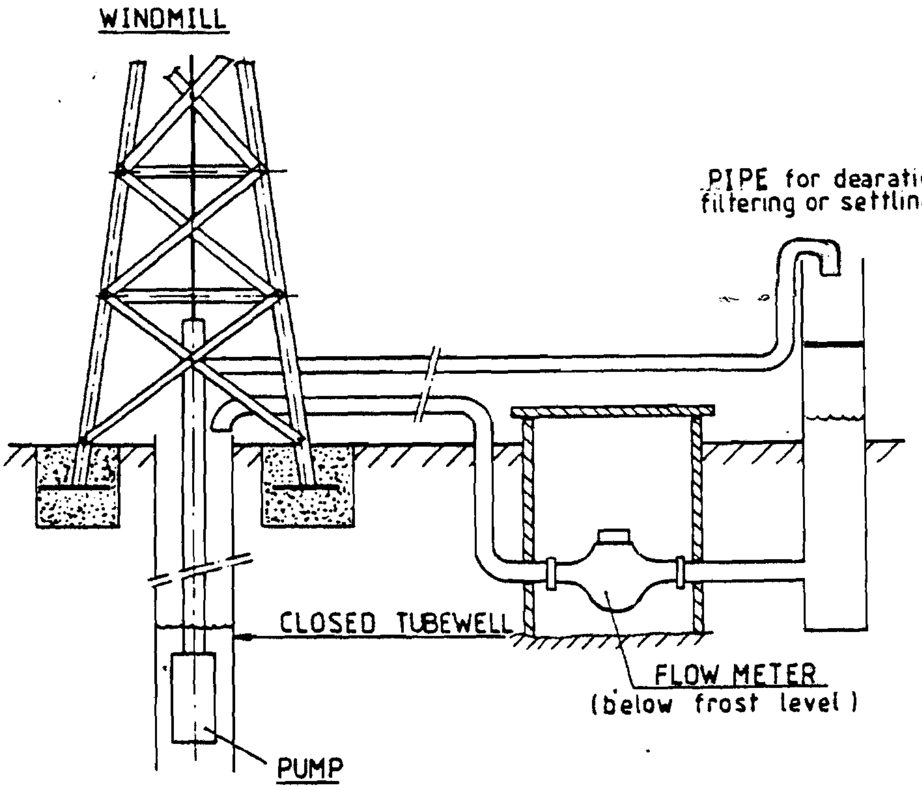


Fig. 2.3 Water circuit of the CWD 5001

The windmill is arranged in a closed loop water circuit (see fig. 2.3). Water is pumped from a well into the flowmeter assembly and from there the water is returned into the well.

Three masts were erected at the test field. A 12 m mast (in this report called kvdl mast) is installed at the west side, and carries anemometers and windvanes as well as water vessels. The distance of this mast is within 2 to 8 rotor diameters from all windmills. Therefore anemometers on this mast may be used for output measurements according to the IEA standards (Reference 1) for wind directions between WNW and SSW. In the line of windmills a mast is included, which may be used for wind run measurements without selection of wind directions. It is well-exposed to the main wind directions WNW to SSW and NNE to ESE, see also above. East of the line of windmills a mast is installed, which is used for testing meteorological equipment, and which may be used for output measurements in easterly winds.

3 Description of the measurements

All data are collected by means of an automatic data acquisition system, based on an APPLE II microcomputer.
Details of the measuring system are described in reference 2, also some details and the considerations which led to the concept, have been published in Wind Engineering (reference 3). Here only a brief overview is presented.

Data is collected by means of a measuring program. This program samples the input channels. The input signals are given by the sensors, which are connected (via a lightning protection) to special interface cards inside the APPLE II. After a certain amount of data has been collected the data will be combined in a data block and registered on a data diskette. After finishing the measurements the elaboration programs can be used to investigate the data (see fig. 3.1).

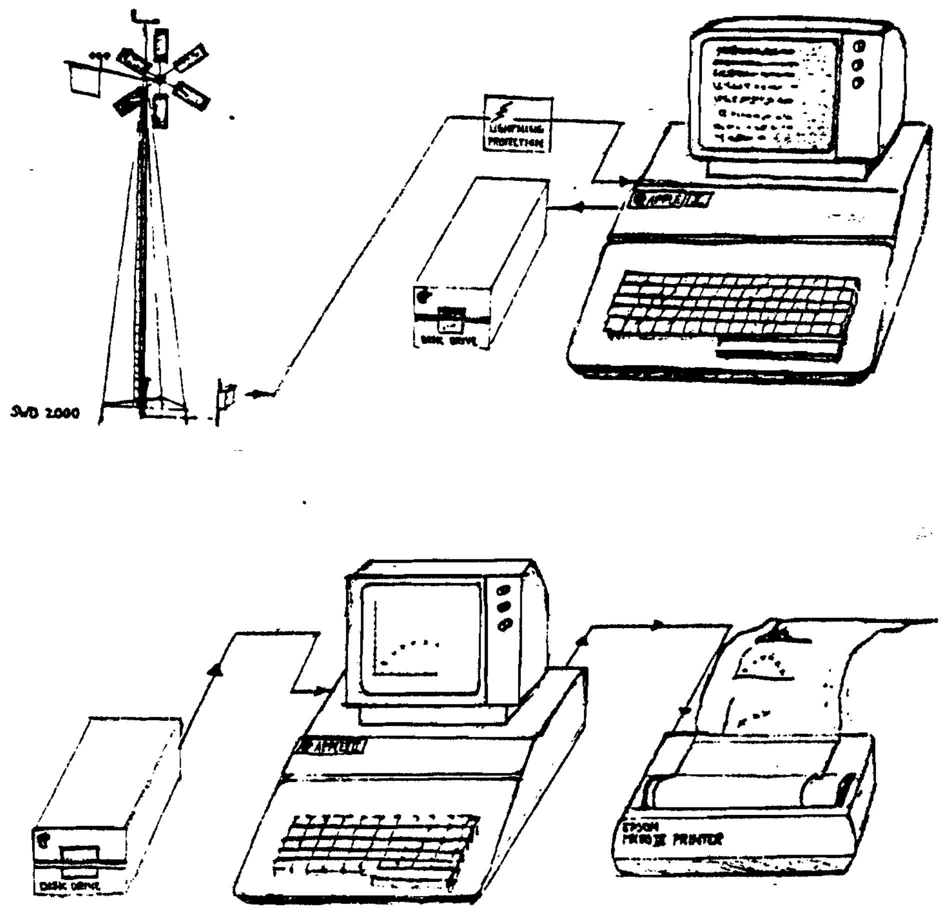


Fig. 3.1 Situation during data collection and data elaboration

During the measuring period the following quantities were registered:

- Wind speed

  two signals of anemometers in the 12 m kvdl-mast (Kaal van der Linden mast) were registered. One at a height of 6 m (to be used for performance measurements of the CWD 2000) and one at 12 m (to be used for performance measurements of the CWD 5001). Also the CWD 5001 was equipped with an anemometer mounted next to the rotor, moving along with the yawing movement. This anemometer was mounted on a special arm at a distance of approximately 10% of the rotor diameter.

  All anemometers are Maximum anemometers using reed contacts. The calibration formula used for these anemometers is: V = 0.39 * f + 0.44 (m/s) with f = the number of contact closures per second. This calibration has been proven to be reliable and constant (see reference 5). For each wind speed three quantities are written on the data disk: the total number of pulses, the maximum, and the standard deviation of the one second averages in a 10 minute time interval. On disk these quantities are stored as:

  V-5001 = QU(13); max = QU(27); sd = QU(32)
  V-6m = QU(18); max = QU(36); sd = QU(38)
  V-12m = QU(17); max = QU(35); sd = QU(37)

- Wind direction

  a wind vane was mounted on top of the 12 m mast to measure the wind direction. This wind vane (manufactered by the WEG at the THE) operates by means of a 360 degree potentiometer. The calibration formula is:

  direction = 360 / 256 * U (degree) with U = the converted value of the voltage on the wiper of the potentiometer (5 V corresponds with the number 255). The reference direction is chosen in line with the test field. (see the wind run rose in fig. 2).

  From this quantity the averaged value and the standard deviation are written on disk as:

  direction=QU(5); sd=QU(39)

- Air pressure

  an electronic barometer (manufactered by the WEG at the THE) is located inside the measuring cabin. The calibration formula is: p = U * 5 (mBar) with U = the converted value of the output voltage (5 V corresponds to the number 255).

  The average value of this quantity is stored on disk as QU(8).

- Temperature

  an electronic thermometer (made by the WEG at the THE) is mounted inside a special radiation shield at a height of 6 m in the 12 m mast. The calibration formula is: T = 1.5 * U - 273 (deg. C) with U is the converted value of the output voltage (5 V corresponds to the number 255). The average value of this quantity is stored on disk as QU(7).

- Rotor speed

  the rotor speed is measured by means of a disk with 16 magnets mounted on the rotor shaft. Close to that disk a reed contact is placed which gives a contact closure every time a magnet passes. Therefore the formula is
  N = f / 16 (1/s), with f = the number of contact closures per second. From this quantity the total, the maximum and the standard deviation of the number of pulses per second are stored on disk as:
  N-5001 = QU(13); max = QU(28); sd = QU(24). Also the value for the rotor speed at the moment that the product of rotor speed and yawing speed reaches a maximum was written on the data disk as QU(30).

- Water flow

  the water flow was me3asured by means of a Spanner Pollux 1.5" water meter with a reed contact, producing two contact closures per liter. Therefore, the formula for the water flow is Q = f / 2 (l/s). The total number of pulses is written on disk as QU(15).

- Yawing speed

  the CWD 5001 has a yawing speed sensor (manufactured by the WEG at the THE) giving a number of pulses proportional to the absolute value of the yawing speed. The calibration formula for the sensor is:
  N-yaw = f * 43 / 113 / 24 (1/s). From this quantities both the sum and the maximum values is written on disk as: Y-5001 = QU(16); max = QU(29)
  Also the value of the yawing speed at the moment the product of the rotor speed and the yawing speed reaches a maximum was registered as QU(31).

- Angle of yaw

  the windmill is equipped with a windvane positioned next to the rotor, fixed to the head frame. This wind vanes operate by means of a 360 degree potentiometer. The calibration formula is: Delta = 360/256 * U - 180 (deg) with U = the converted value of the voltage on the wiper of the potentiometer. (Delta = 0 means: the rotor plane is perpendicular to the wind direction). For this quantity both the average value and the standard deviation are stored as:
  Delta-5001 = QU(3); sd = QU(33)

4 Description of the data processing

During this testing period the CWD 5001 was mostly operated unloaded (exept during data disk 28). For the elaboration of the measurements a formula program is written which calculates all quantities neccesary to judge the safety mechanism of the CWD 5001 (a formula program is a user program for the main elaboration programs, these programs are described in reference 2).
This program is called 'formulas CWD 5001 safety', and calculates the following quantities

1	V-12M (M/S)	(wind speed at 12 m in the kvdl-mast)
2	SD/AV V-12M	(turbulence intencity of V-12M)
3	Dir (deg)	(wind direction related to fig 2)
4	SD DIR (DEG)	(standard deviation of DIR)
5	DELTA (DEG)	(angle of yaw)
6	SD DELTA	(standard deviation of DELTA)
7	N-MAX (r/s)	(maximum rotor speed)
8	Y-MAX (r/s)	(maximum yawing speed)
9	(N*Y)-MAX	(maximum of rotor speed times yawing speed)

In order to exclude measurements for which the windmills would be in each others wake, only measurements during which the angle between the wind direction and the line of windmills was between 30 and 150 degree are elaborated, all other measurements are ignored.
Also it is possible to specify a minimum and maximum value for the range of standard deviation which should be elaborated. Values outside this range will be ignored.
Finally a selection is used which ignores measurements of which the standard deviation of delta is too large. This happens only occasionally, and is caused by a measuring error.

```
100  REM  ***** FORMULAS CWD 5001 SAFETY *****
110  REM  THIS PROGRAM ONLY WORKS AFTER COMPILATION TOGETHER WITH 'BIN SORT'
120  REM  ***** COMPILATION INFORMATION: THE LIBRARY MUST BE LOADED AT 4000
130  REM                                 THE PROGRAM MUST START AFTER HGR1
140  REM                                 THE VARIABLES MUST START AT 2051
150  REM  AFTER COMPILATION THE HIGHEST MEMORY LOCATION IS NOT ALLOWED TO BE HIGHER THAN 18810!!
160  REM ! INTEGER NQ
170  REM ! USECOMMON NQ,QU(50),QF(9),MIN(9),MAX(9),T$(9)
180  REM  THE MAXIMUM VALUE FOR NQ=9;THE MAXIMUM LENGTH OF THE T$'S IS 12 CHARACTERS
190  IF NQ <  > 0 THEN 400
200  REM  DEFINITION OF CONSTANTS & STRINGS
210 NQ = 9
220 T$(0) = "CWD 5001 SAFETY"
230 T$(1) = "U-12M (M/S)":A1 = .39:B1 = .44:MAX(1) = 20
240 T$(2) = "SD/AV U-12M":MAX(2) = 1
250 T$(3) = "DIR (DEG)":A3 = 360 / 256:MAX(3) = 360
260 T$(4) = "SD DIR (DEG)":MAX(4) = 100
270 T$(5) = "DELTA (DEG)":A5 = 360 / 256:B5 =  - 180:MIN(5) =  - 20:MAX(5) = 180
280 T$(6) = "SD DELTA":MAX(6) = 50
290 T$(7) = "N-MAX (R/S)":A7 = 1 / 16:MAX(7) = 5
300 T$(8) = "Y-MAX (R/S)":A8 = 35 / 114 / 30:MAX(8) = .5
310 T$(9) = "(N*Y)-MAX":A9 = A7 * A8:MAX(9) = .5
330  INPUT "SD MIN ";MIN: INPUT "SD MAX ";MAX
390  RETURN
400  REM  DEFINITION OF FORMULAS
410 QF(1) = QU(18) * A1 + B1: IF QU(18) = 0 THEN QF(1) = B1 / 2
420 QF(2) = QU(38) / QF(1) * A1
430 QF(3) = QU(5) * A3
440 QF(4) = QU(39) * A3
450 QF(5) = QU(3) * A5 + B5
460 QF(6) = QU(33) * A5
470 QF(7) = QU(28) * A7
480 QF(8) = QU(29) * A8
490 QF(9) = QU(30) * QU(31) * A9
495  IF QU(5) < 20 OR QU(5) > 235 OR (QU(5) > 108 AND QU(5) < 148) OR QU(33) > 40 OR QU(39) > 40 THEN QF(0) = 1
496  IF QF(4) < MIN OR QF(4) >  = MAX THEN QF(0) = 1
500  RETURN
```

Listing of 'Formulas CWD 5001 safety'

5 Test circumstances of the CWD 5001

For this testing period the following facts need to be mentioned:

- The measurements on the CWD 5001 started on 85-05-18 (block 1 of data disk 23).
- during data disk 23 until data disk 27 the CWD 5001 oparated unloaded (i.e. the pump was not mounted). During data disk 28 the CWD 5001 was loaded, the pumping head was about 30 m. This was not measured exactly.
- During block 1 until block 12 of data disk 23 the anemometer of the CWD 5001 did not function correctly.
- During block 19 of data disk 23 a peak value for the yawing speed of 2.5 r/s occured. This is physically impossible and is probably caused by a write error of the disk drive.
- Block 27 of data disk 23 cannot be loaded into the computer. This is probably caused by a write error of the disk drive during the measurents.
- From block 4 until block 8 of data disk 24 the wind speed of the 12 m mast is did not function.
- From block 1 of data disk 25 until block 8 of data disk 26 the signal cable from the pumprod to the tower was broken. This is caused by the fact that the CWD 5001 had turned much more in the safety direction than had turned against the safety direction. This was not expected, because the CWD 2000, which uses the same safety mechanism as the CWD 5001, has been oparating in the field for over two years, and during this testing period this never happened to the CWD 2000.
- From block 6 until block 20 of data disk 20 the signal cable of the anemometer of the CWD 5001 was short circuited.
- During block 23 of data disk 28 the pumprod connection between the head and the pump got disconnected. This was repaired during block 25.
- About half an hour after the last data block of data disk 28 the pumprod broke. Unfortunately the measuring system was not operating at that moment, however the weather did not change significantly during this half hour. Later, during inspection of the pumprod it appeared that the pumprod was not welded correctly.

During the measuring period the CWD 5001 operated under the following conditions:

Location	2 (see fig. 2)
well	location 2, water level about 28 m below ground level (only during data disk 28)
Pressure line	length 4 m, diameter 2"
Pressure vessel	2 m above ground level
Pump	CWD 108 deepwell pump, mounted 30 m below ground level, stroke volume 1.832 l: stroke 0.2 m (maximum), diameter 0.108 m.

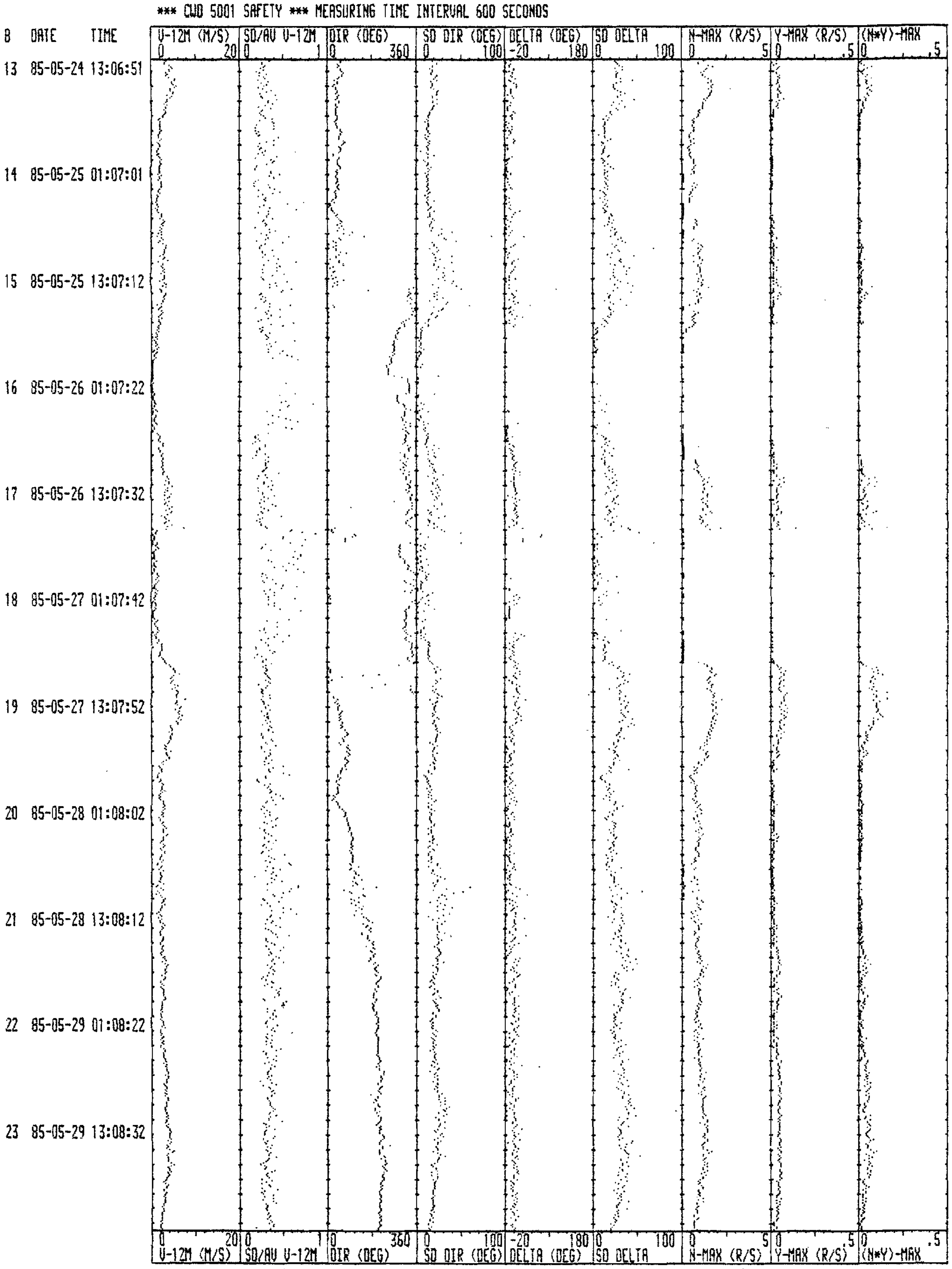
Some design specifications of the CWD 5001 are:

Purpose	water lifting, both a deepwell pump as a suction pump can be applied.
Rotor	horizontal shaft; kept in up wind position by balance of side vane and exentric rotor; rotor diameter 5 m, 8 blades of galvanized steel sheet; fixed pitch
Transmission	direct drive crank mechanism with adjustable stroke and swing arm; strokes 50 - 200 mm; pump rod weight can be balanced.
Control systems	over speed control by yawing, activated by exentric rotor and hinged side vane system
Pump system	single action piston pump with starting nozzle and air chamber
Tower	steel lattice tower; heigth 12 m; can be lowered by means of hinges in the tower base
Aerodynamic properties	lambda-opt = 1.8 with Cp-max = 0.33 Cq-mas = 0.23, Cq-start = 0.11, lambda-max = 3.16

6 Elaboration of the CWD 5001 data

First of all the program PLOT DATA is used to obtain a good impression about the reliability of the registered data. By means of this program it is possible to present a time sequenced representation of the data. The next pages show the PLOT DATA output using 'Formulas CWD 5001 safety'
In these graphs each point represents a 10 minute value, usualy 72 dots are packed as a block, which corresponds to 12 hours.
In order to limit the amount of PLOT DATA output only the interesting data blocks, i.e. the data blocks which are used for further elaboration are shown.
These data blocks are:

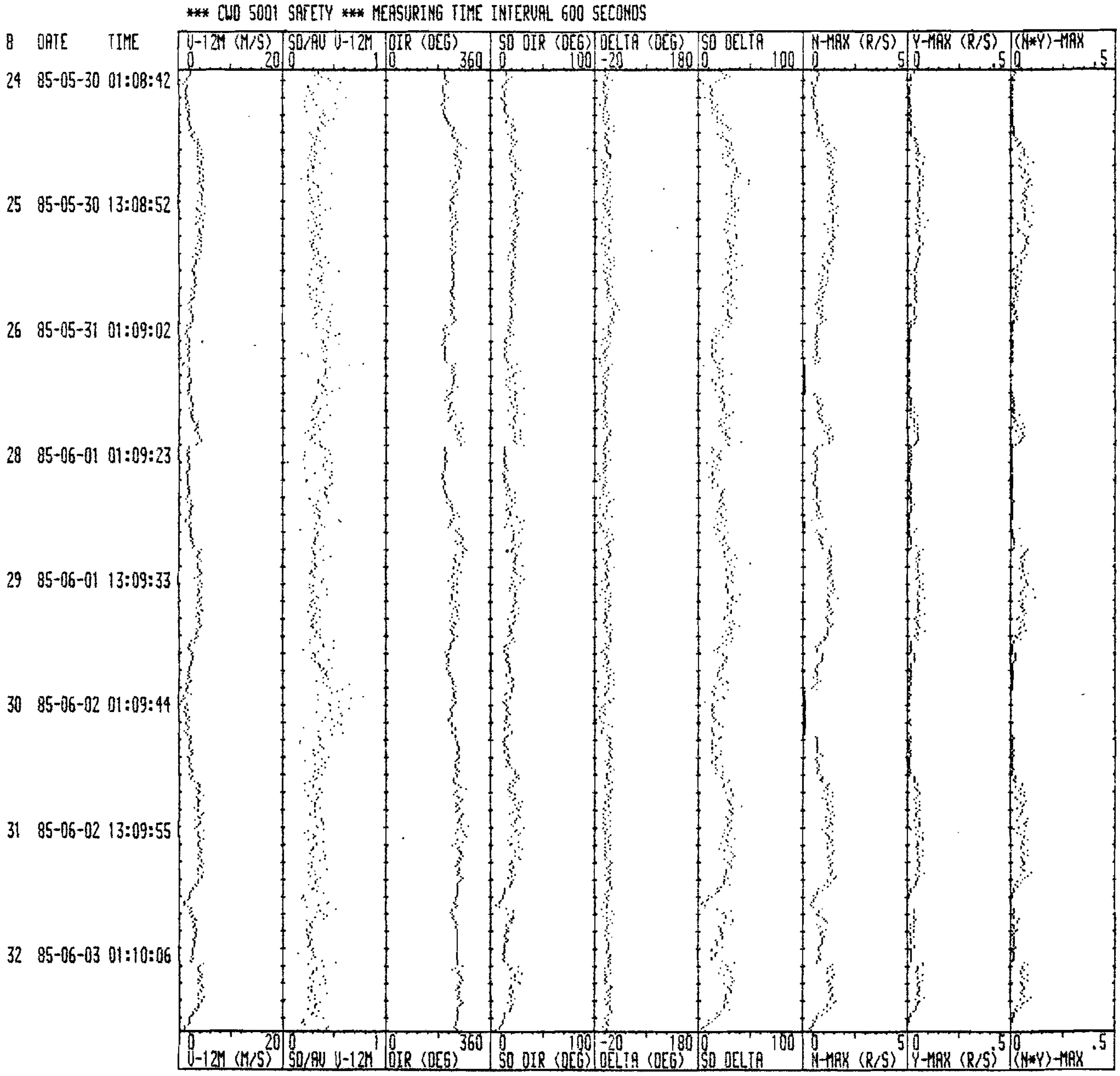
Data disk 23: block 13-26, 28-32
Data disk 24: block 1-32
Data disk 26: block 9-31
Data disk 27: block 1-5
Data disk 28: block 17-27



PLOT DATA output of data disk 23, block 13 until 23.

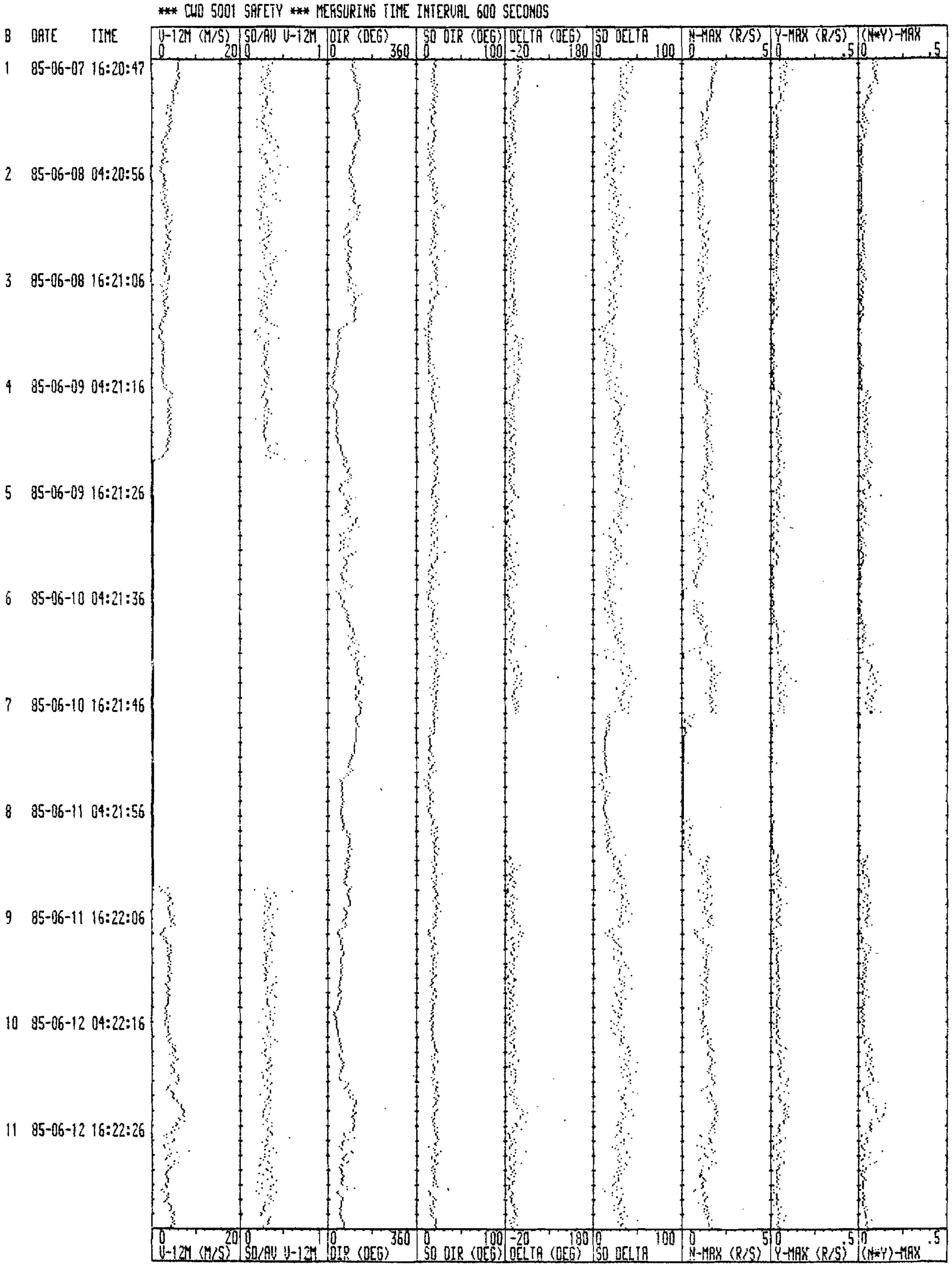
During block 17 the average wind speed increases until about 7.5 m/s, resulting in a peak rotor speed of 2.25 revolutions per second, a peak yawing speed of

0.15 r/s and a peak value of the produkt of rotor speed and yawing speed of 0.15 (r/s.r/s). At the end of block 18 The peak rotor speed reaches about the same value (2.25 r/s), the peak yawing speed is about 0.1 r/s, but the maximum value of the product of rotor speed and yawing speed reaches the same value as during block 17 (0.15 r/s.r/s).



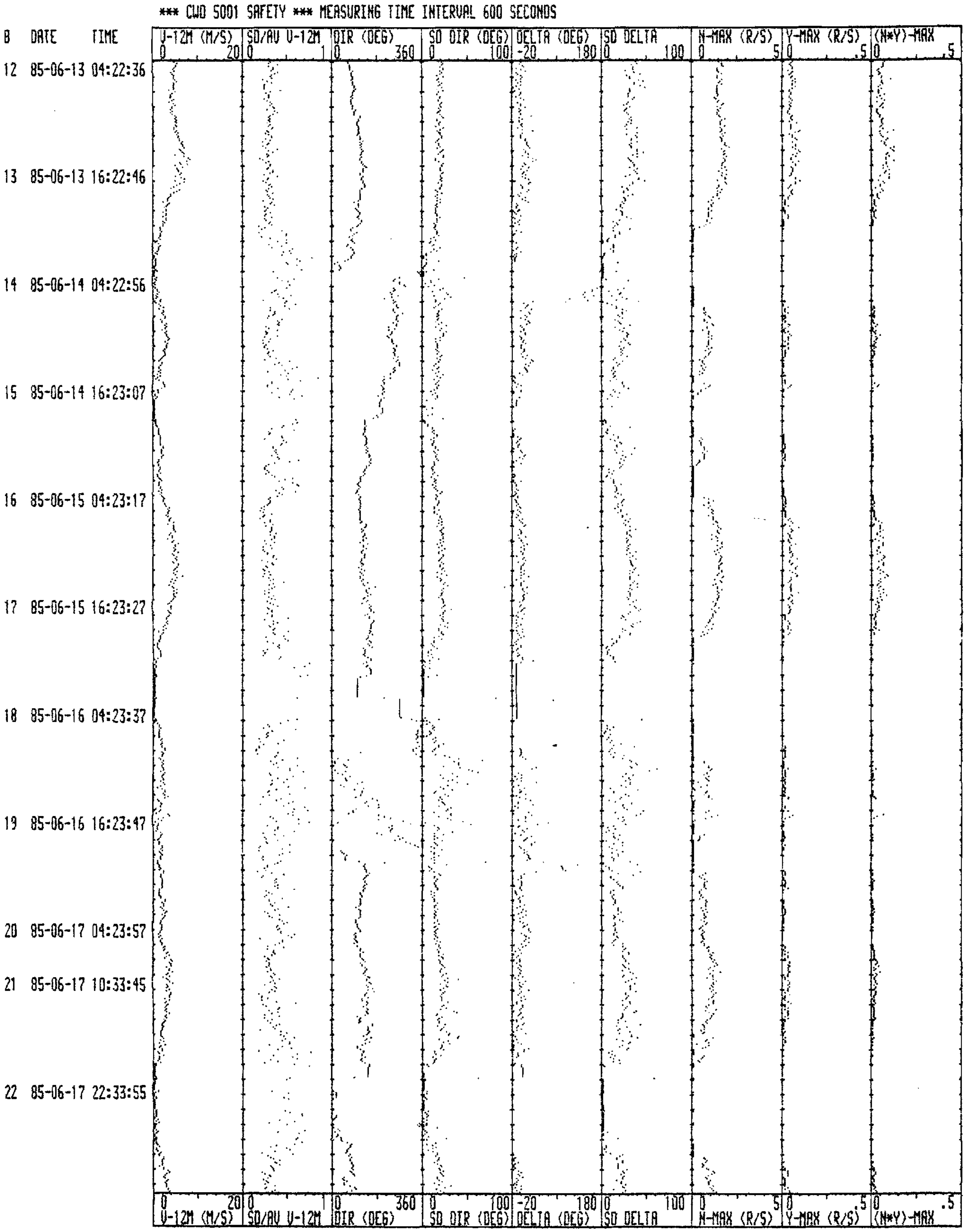
PLOT DATA output of data disk 23 block 24 until 26 and block 28 until 32.

Here average wind speeds until about 5 m/s occure, resulting in peak rotor speeds until about 1.5 r/s, peak yawing speeds until about 0.1 r/s and maximum values for the produkt of rotor speed and yawing speed until about 0.1 (r/s.r/s).



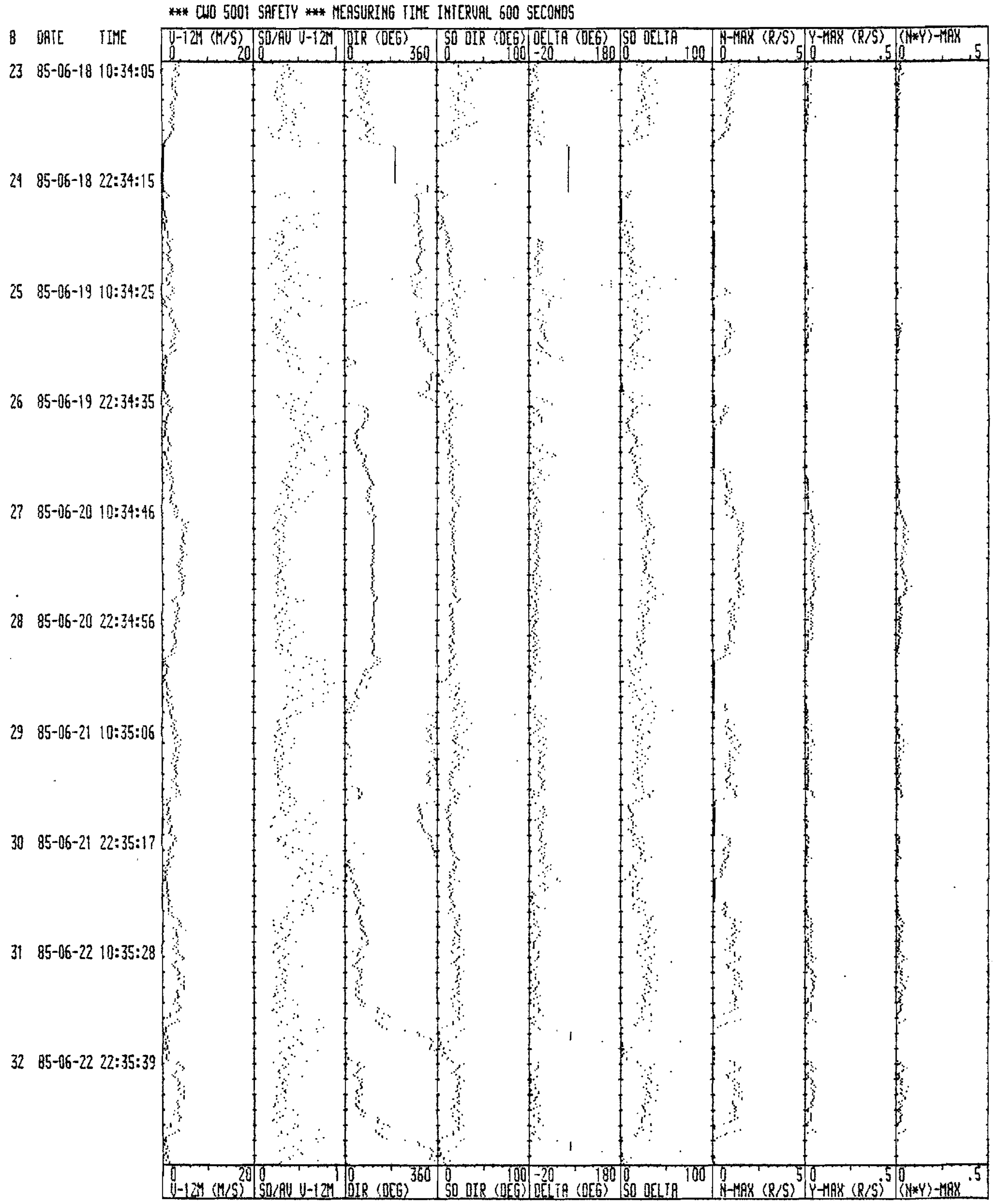
PLOT DATA output of data disk 24 block 1 until 11.

During block 4 until block 8 the measured wind speed is zero, the rotating windmill indicates that the wind speed can not have been zero. The reason is that during that time two Apple II monitoring systems were connected to the same sensor, while one of the computers was turned of.



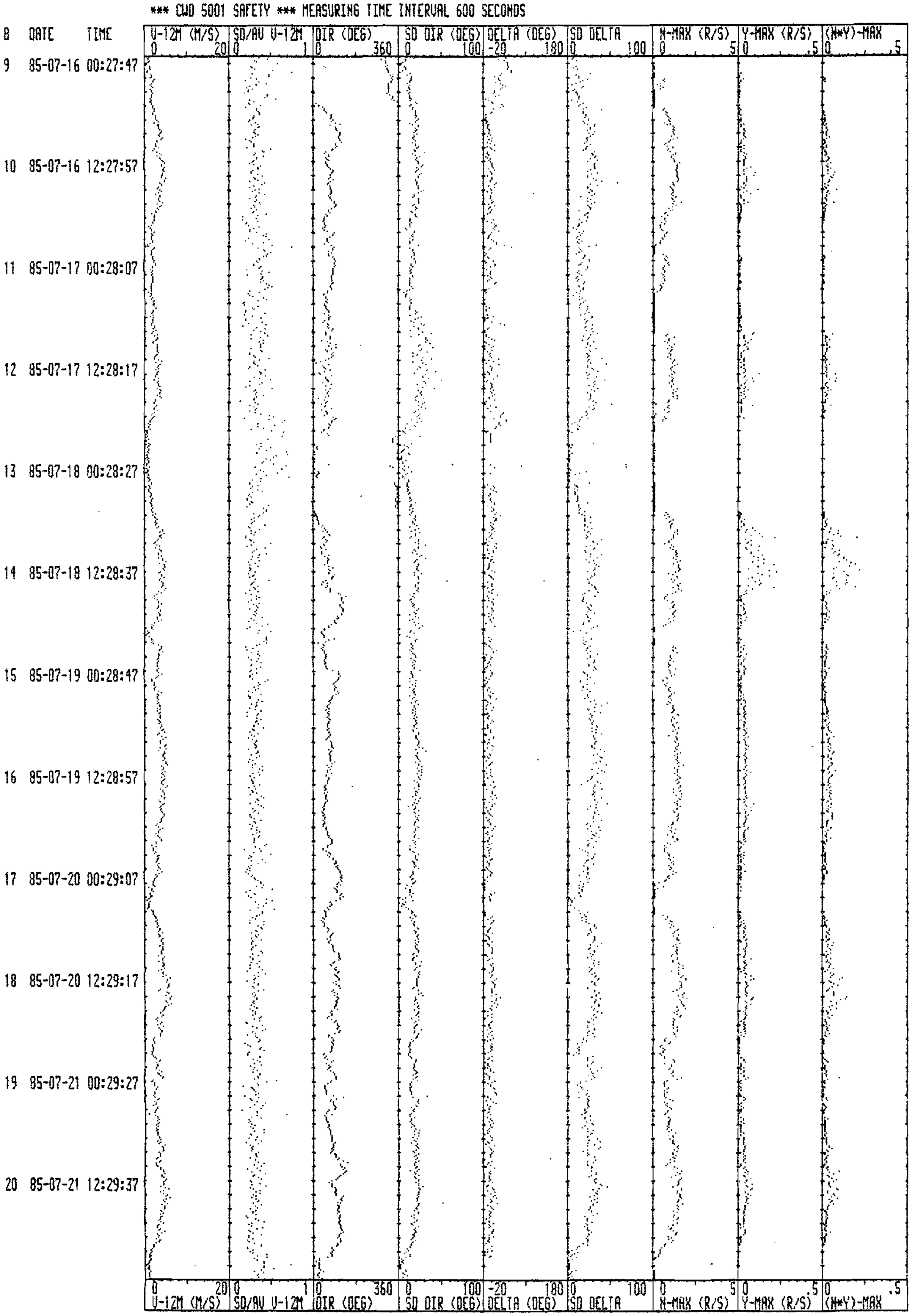
PLOT DATA output of data disk 24 block 12 until 22.

Here average wind speeds until 8 m/s occure, resulting in peak rotor speeds until about 2 r/s, peak yawing speeds below 0.1 r/s, and maximum values for the product of rotor speed and yawing speed of about 0.125 (r/s.r/s).



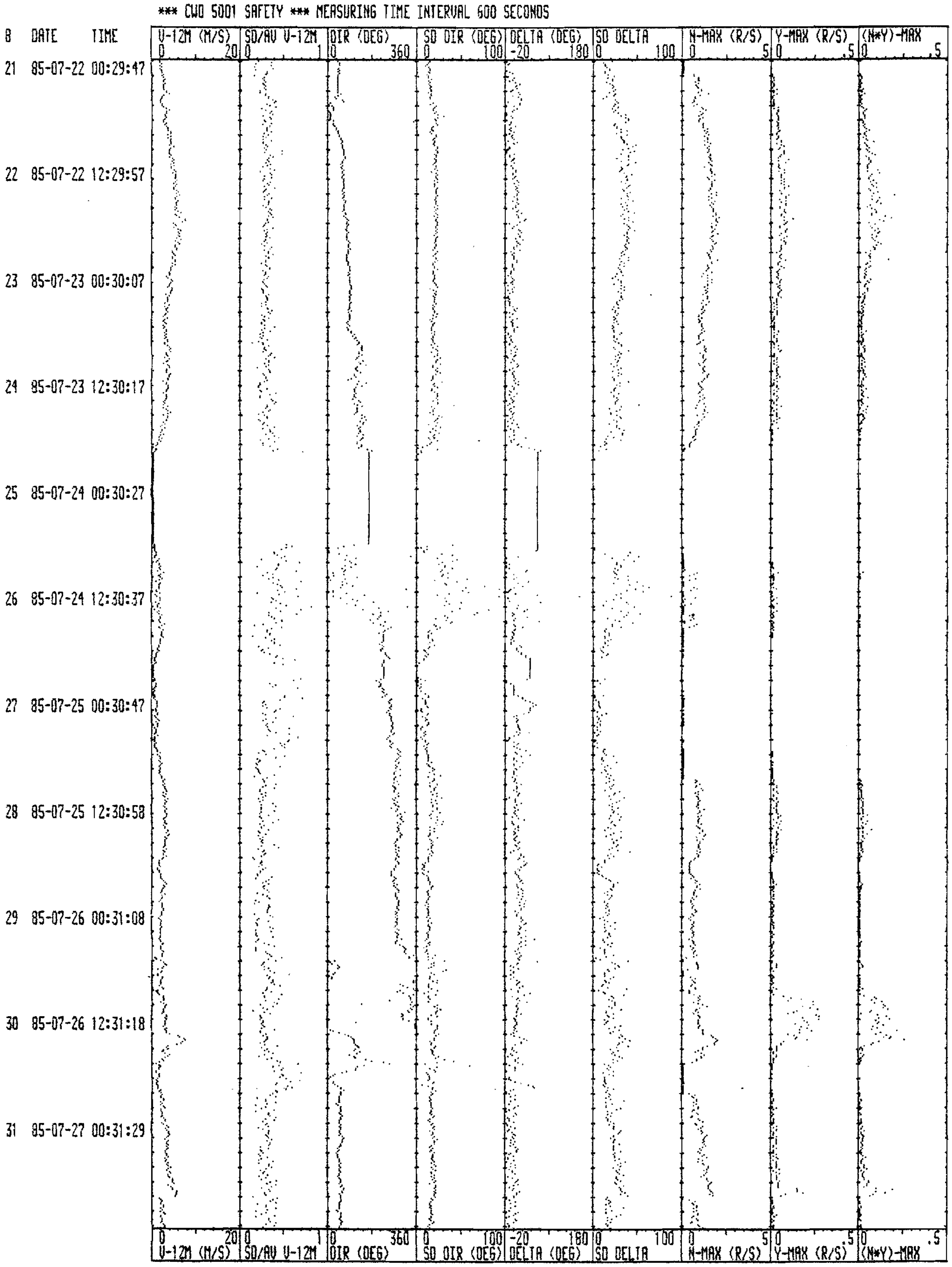
PLOT DATA output of data disk 24 block 23 until 32.

Wind speeds until about 5 m/s, resulting in peak rotor speeds of 1.5 r/s, peak yawing speeds of 0.075 r/s, and zmaximum values for the product of rotor speed and yawing speeds of about 0.075 (r/s.r/s).



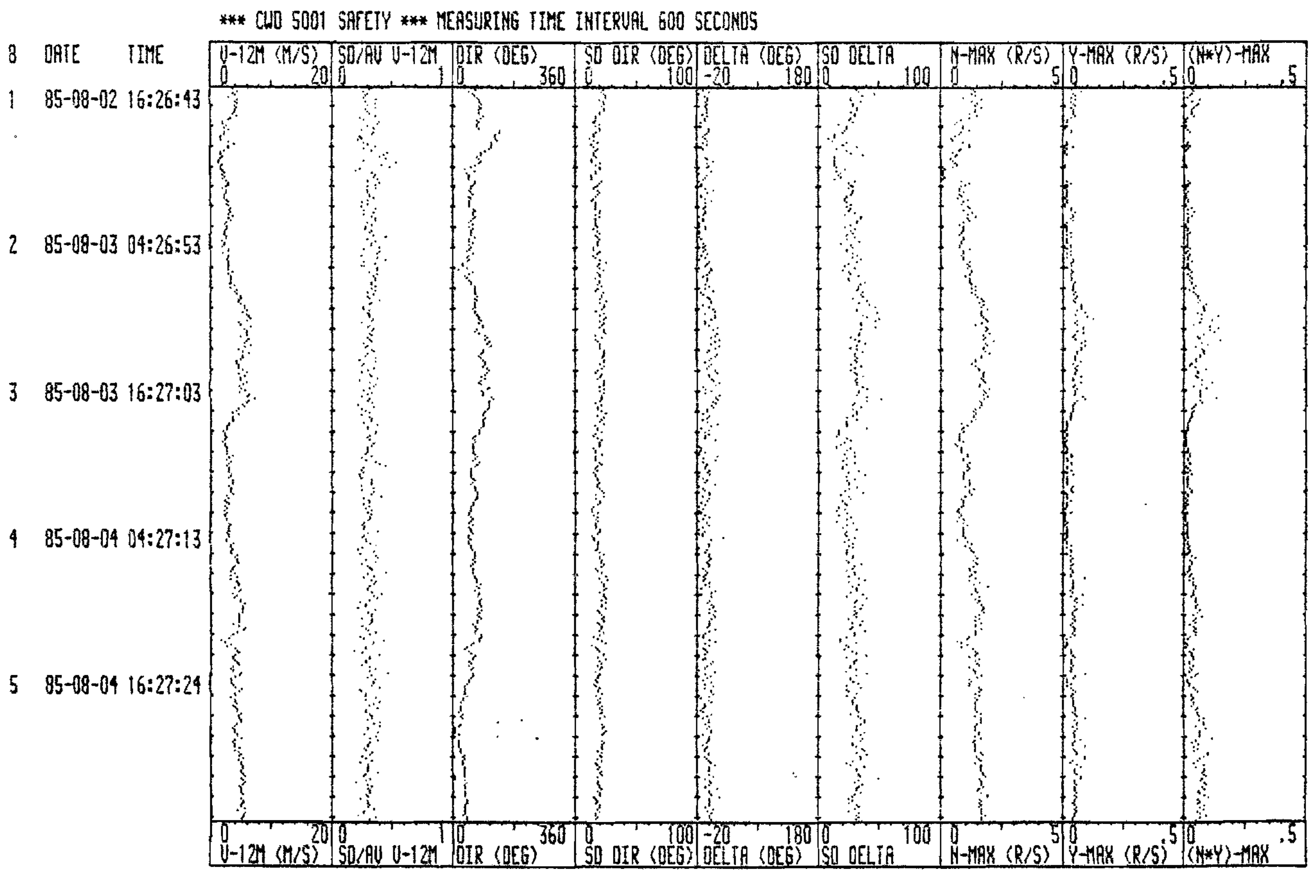
PLOT DATA output of data disk 26 block 9 until block 20.

During block 13 and 14 the wind speed remains below about 5 m/s. The peak value for the rotor speed is about 1.5 r/s. The peak value for the yawing speed several times rises until the very high value of 0.225 r/s. The maximum value for the product of the rotor speed and the yawing speed also reach very high values: about 0.225 (r/s.r/s).



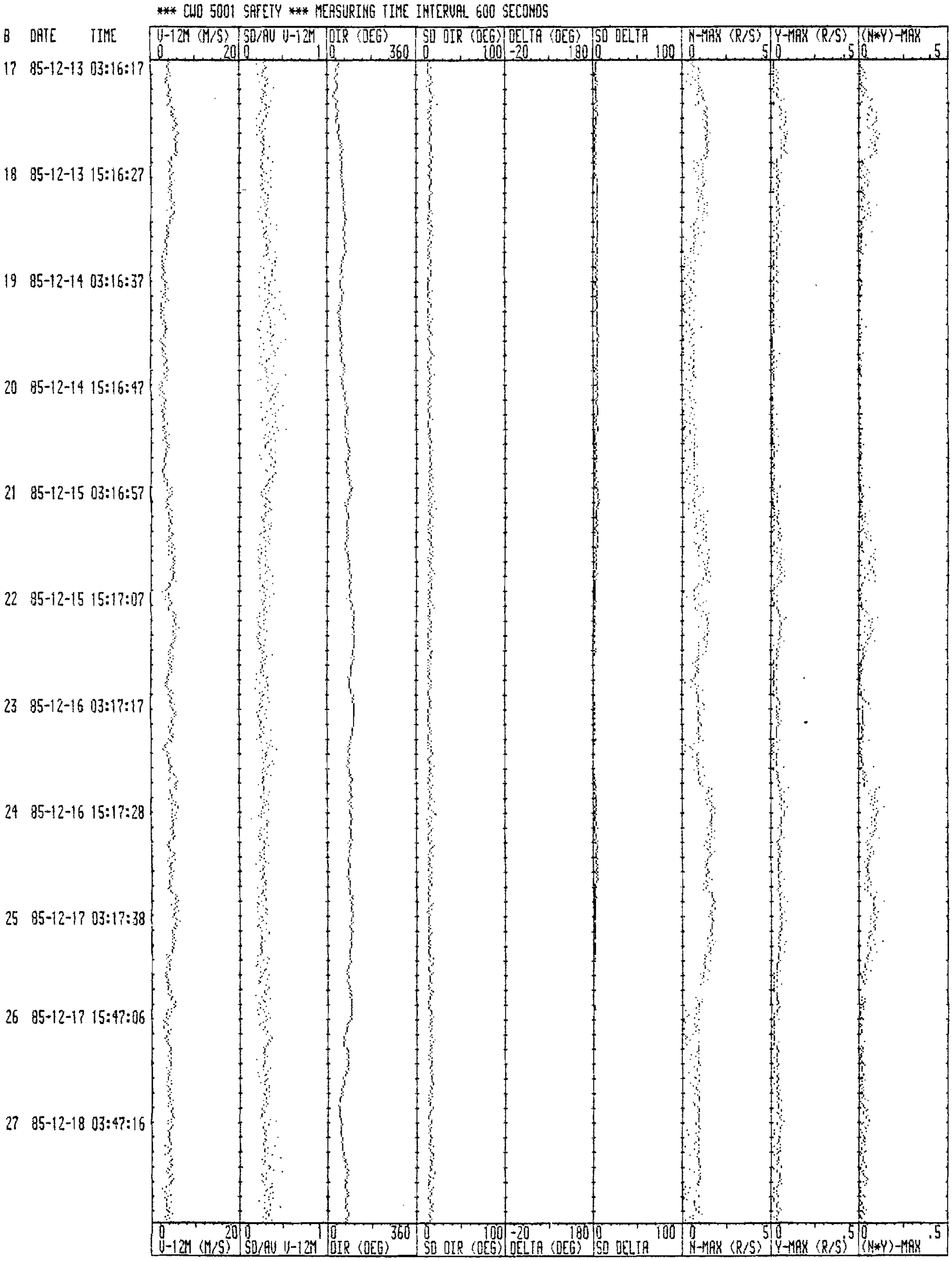
PLOT DATA output of data disk 26 block 21 until 31.

During the end of block 29 and the beginning of block 30 the wind speed is about 3 m/s. The peak rotor speed is about 0.1 r/s. The peak yawing speed reaches very high values until about 0.25 r/s. The maximum value for the product of the wind speed and the rotor speed reaches high values until about 0.175 (r/s.r/s). A little later the wind speed increases until about 8 m/s, causing an increase of the peak rotor speed until about 2 r/s. The peak value for the yawing speed is somewhat lower than before: about 0.2 r/s, however, the maximum value for the product of the rotor speed and the yawing speed reaches a maximum of about 0.27 (r/s.r/s).



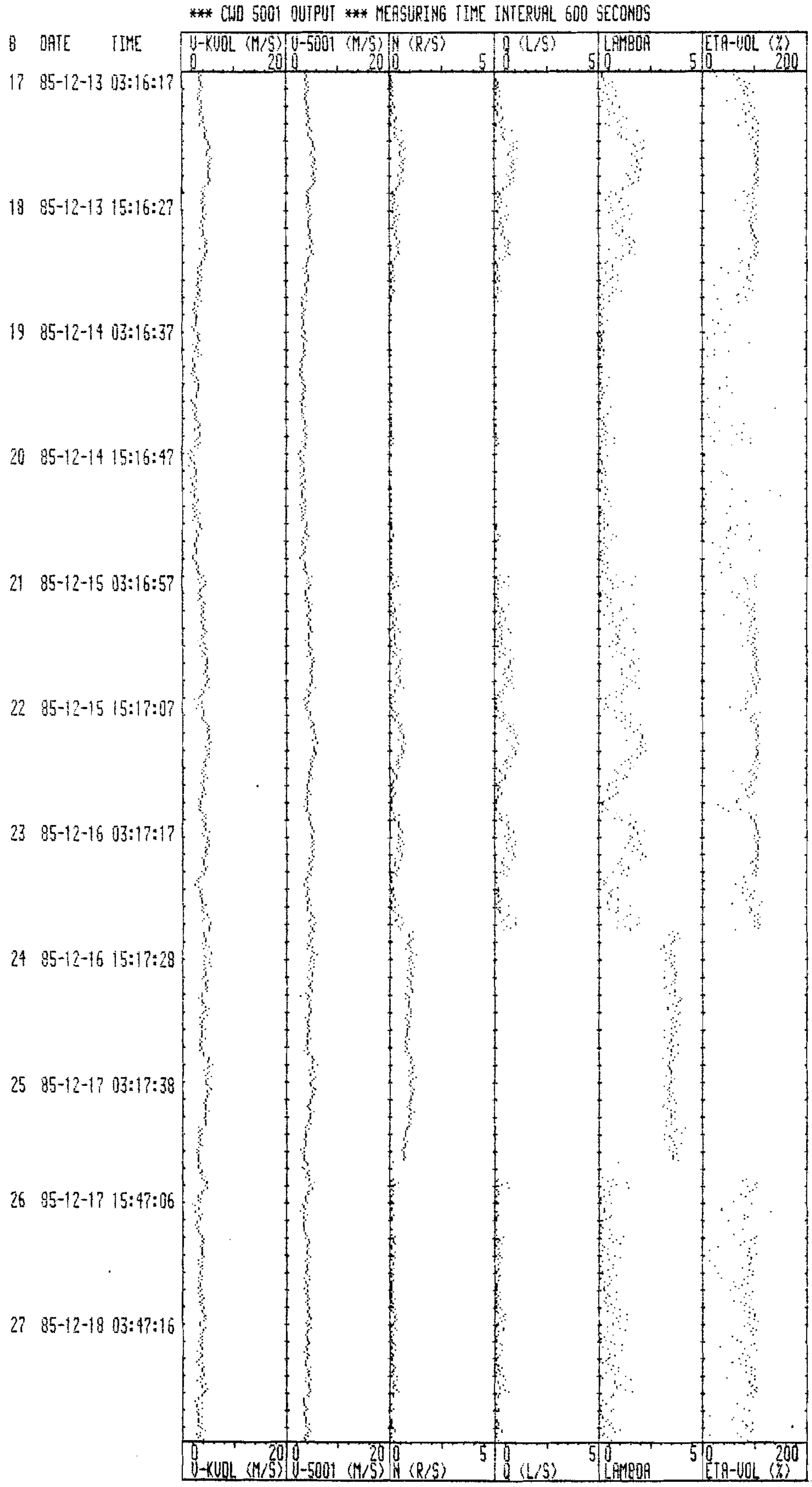
PLOT DATA output of data disk 27 block 1 until block 5.

At average wind speeds of about 6 m/s the peak rotor speed is about 2 r/s, the peak yawing speed is about 0.125 r/s and the maximum of the product of rotor speed and yawing speed is about 0.15 (r/s.r/s).



PLOT DATA output of data disk 28 block 17 until 27.

Now the CWD 5001 no longer operates unloaded until block 23, here the pumprod connection between the head and the pump got disconnected. This was repaired during block 25. The next page shows the same measuring period using another formulas program.



PLOT DATA output of data disk 28 block 17 until 27.

Here the same measuring period as the previus page is shown, however now another formulas program (FORMULAS CWD 5001 OUTPUT) is used. The increase of lambda during block 23 claerly indicates the disconnected pumprod. Also the reconnecting of the pumprod can be seen claerly (block 25).

In the previous pages it can be seen which data is reliable and probably is interesting (see below). The next step is to use the BIN SORT program. By means of this program one of the quantities defined in the formula program can be chosen to be the bin sort parameter (the bin sort procedure is described in reference 1). After that the program calculates the bin sort table and the bin sort graphs for the selected data blocks.

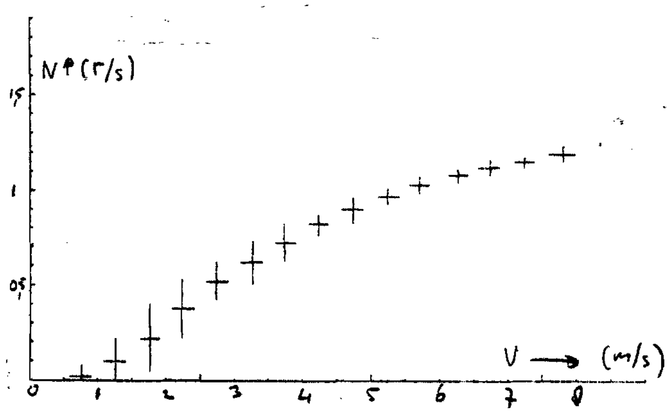
In the bin sort table the first column contains I, the bin number. The second column contains N; the number of times the bin sort parameter occurred in that bin. All other columns occur in pairs of two for each quantity:

- The average value of the measurements in a certain bin;
- The standard deviation of the measurements in a certain bin.

The bin sort graphs on the following pages are preceeded by a frequency distribution of the bin sort parameter. All other graphs give the other quantities versus the bin sort parameter.
The center of each cross gives the average value; the ends of each cross give the average value plus and minus the standard deviation in both directions.

First a bin sort is calculated, using all reliable data of the unloaded windmill, with the wind speed V-12M, as bin sort parameter. The results can be found on the following pages.

Note: The formula programs in this report do not calculate the average rotor speed. This was done on purpose to be able to calculate other quantities, which might be relevant for giving expalanations for the measured values of maximum rotor speed and maximum yawing speed. Therefore, the next graph is added, representing the average rotor speed versus the average windspeed.

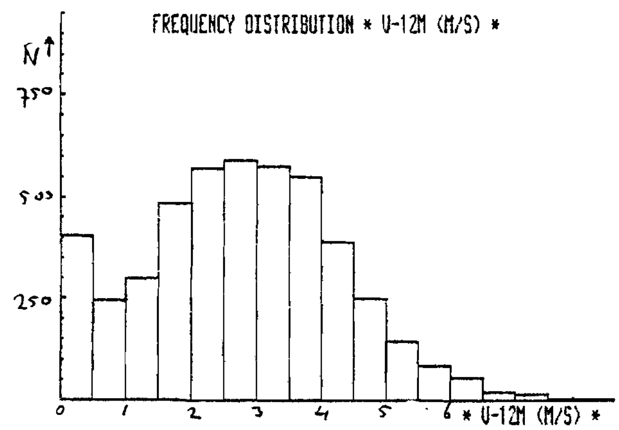


Bin sort graph representing the average rotor speed versus the average wind speed.

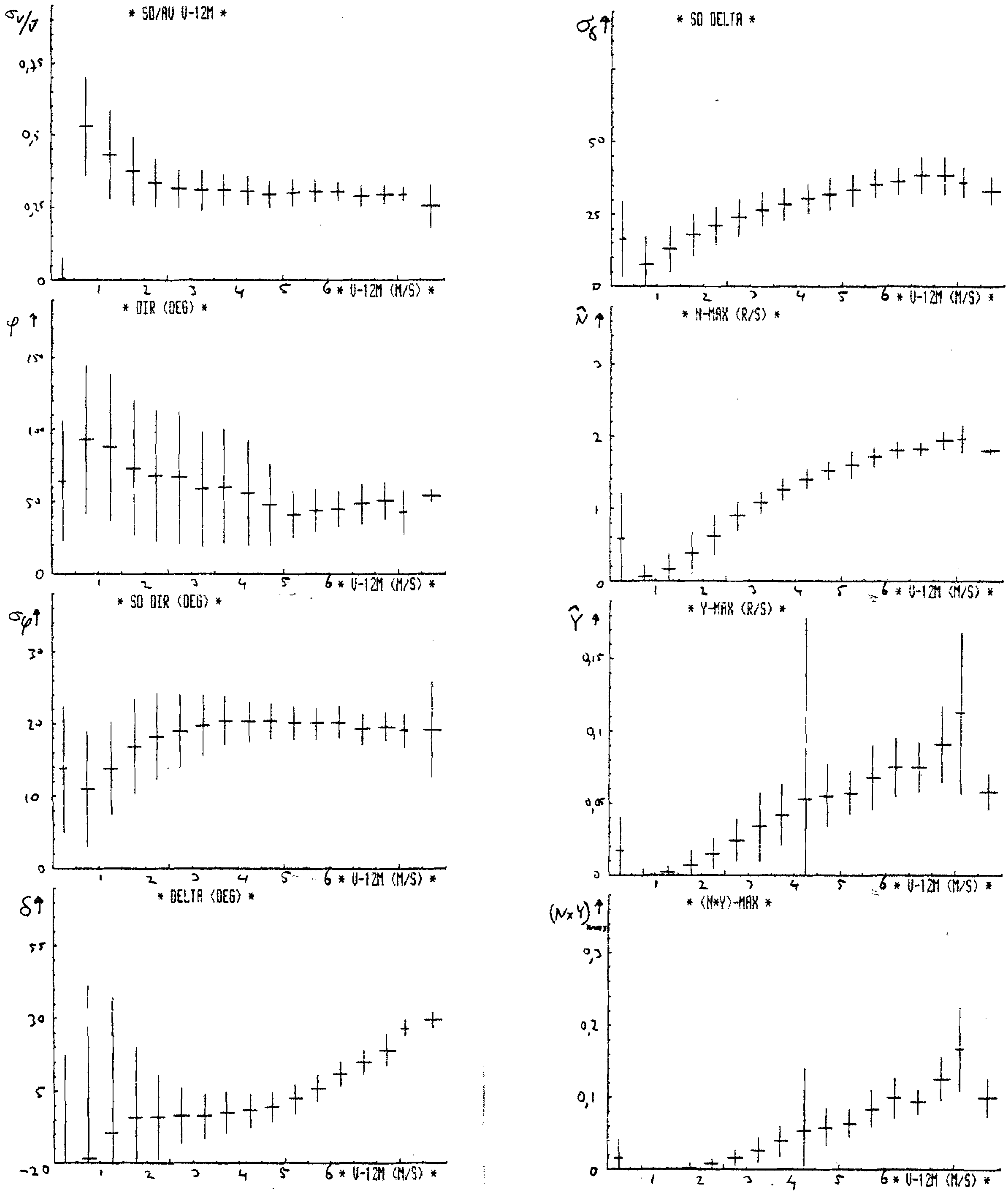
***** BIN SORT OF CWD 5001 SAFETY *****
SORTING PARAMETER: V-12M (M/S); BIN WIDTH=.5
ELABORATED ARE BLOCK 13-26;28-32;1-32;9-31;1-5

I	N	V-12M (M/S)		SD/AV V-12M		DIR (DEG)		SD DIR (DEG)		DELTA (DEG)		SD DELTA		N-MAX (R/S)		Y-MAX (R/S)		(N*Y)-MAX	
1	404	.2432	.071	<.01	.067	128.7	83.2	13.78	8.69	-39.2	56.8	16.45	12.9	.5750	.629	.0174	.022	.0158	.025
2	245	.7603	.149	.5310	.171	185.0	102.	10.92	8.00	-18.4	59.6	7.691	9.13	.0642	.141	<.01	<.01	<.01	<.01
3	299	1.267	.143	.4309	.152	175.0	100.	13.87	6.35	-9.40	46.5	12.89	7.72	.1695	.198	<.01	<.01	<.01	<.01
4	484	1.770	.145	.3750	.114	146.4	93.1	16.86	6.56	-3.86	23.7	17.79	7.44	.3790	.280	<.01	<.01	<.01	<.01
5	572	2.240	.142	.3346	.081	135.7	89.9	18.28	5.91	-3.98	14.6	21.02	6.56	.6257	.273	.0150	.010	<.01	<.01
6	590	2.748	.144	.3135	.063	133.2	90.3	19.07	5.01	-3.37	9.41	23.86	6.22	.8934	.187	.0244	.014	.0163	.010
7	576	3.242	.145	.3091	.067	117.4	78.7	19.88	4.18	-3.66	7.66	26.73	5.77	1.085	.139	.0338	.023	.0266	.016
8	552	3.733	.137	.3118	.049	120.6	78.9	20.42	3.29	-2.51	6.82	28.45	5.48	1.258	.132	.0419	.020	.0392	.020
9	389	4.236	.139	.3069	.047	112.3	72.5	20.35	2.73	-1.65	5.83	30.38	5.05	1.401	.130	.0534	.124	.0531	.086
10	250	4.708	.131	.2971	.045	95.79	56.3	20.39	2.47	-.388	5.09	32.08	5.39	1.516	.121	.0553	.021	.0588	.024
11	147	5.230	.150	.2988	.044	81.73	32.4	20.25	2.18	2.286	4.86	33.39	5.30	1.605	.177	.0573	.014	.0646	.019
12	84	5.732	.145	.3069	.038	87.35	27.9	20.18	2.10	5.959	4.60	35.59	4.67	1.712	.124	.0678	.021	.0843	.024
13	53	6.212	.143	.3044	.028	90.21	24.6	20.24	2.14	11.06	3.91	36.32	4.50	1.804	.109	.0749	.020	.0998	.027
14	21	6.714	.152	.2877	.034	97.29	26.7	19.35	2.08	15.06	3.98	38.50	6.16	1.818	.078	.0750	.016	.0936	.015
15	13	7.226	.170	.2948	.028	101.3	24.9	19.68	1.81	19.03	5.24	38.29	6.34	1.942	.115	.0913	.025	.1260	.029
16	5	7.612	.068	.2970	.021	85.5	30.4	19.12	2.35	26.71	-2.63	36	4.93	1.962	.174	.1125	.055	.1675	.056
17	3	8.213	.189	.2528	.070	107.8	8.23	19.21	6.49	29.53	2.43	32.81	4.52	1.791	.036	.0579	.011	.0997	.026
	---- +																		
	4687	2.785	1.49	.3117	.138	129.5	86.1	18.04	6.05	-6.69	28.9	23.35	10.0	.8887	.538	.0283	.043	.0257	.037

942 MEASUREMENTS ARE IGNORED



Bin sort table and frequency distribution graph of data disk 23 block 13-26 and 28-32, data disk 24 block 1-32, data disk 26 block 9-31 and data disk 28 block 1-5. Only measurements during which the standard deviations in the wind direction was smaller than 50 degrees are elaborated. The bin sort parameter is the wind speed V-12M.

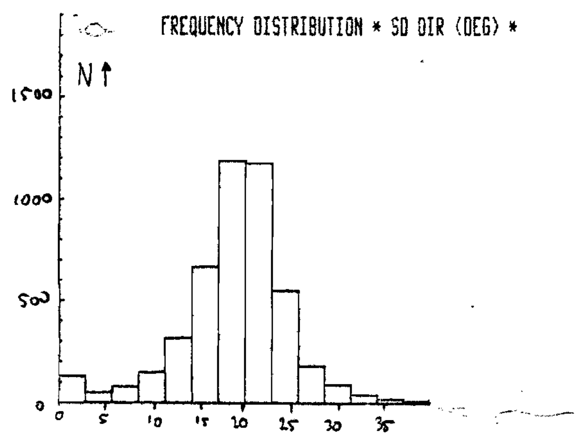


Bin sort graphs of data disk 23 block 13-26 and 28-32, data disk 24 block 1-32, data disk 26 block 9-31 and data disk 28 block 1-5. Only measurements during which the standard deviations in the wind direction was smaller than 50 degrees are elaborated. The bin sort parameter is the wind speed V-12M.

From the graphs the following can be concluded:

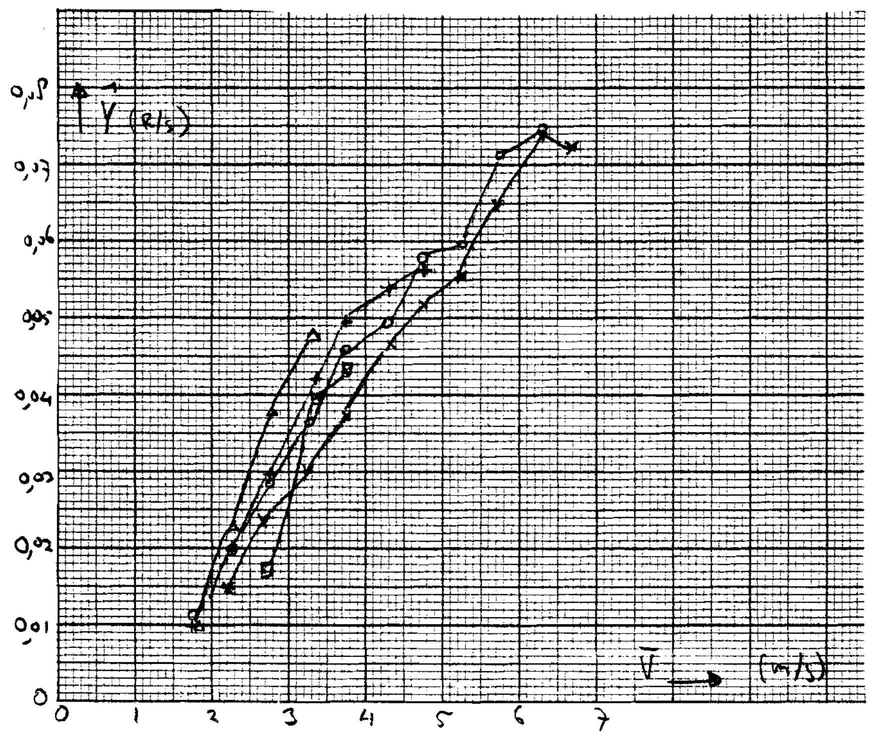
- The turbulence intensity (SD/AV V-12M) is about constant (0.3) above 2.5 m/s. The increase of the turbulence intencity at lower windspeeds is caused by the limited resolution of the anemometers.
- The standard deviation in the wind direction increases for higher wind speeds, and becomes about constant (20 degrees) above 3 m/s.
- At wind speeds from 1.5 m/s until 5 m/s the average value for delta is about zero, which means that the rotor area is perpendicular to the wind speed. As to be expected at wind speeds above the rated wind speed (5 m/s) the value for delta increases.
- The standard deviation of delta (SD DELTA) rises from about 20 degrees at 2 m/s to about 40 degrees at 7.5 m/s. Because the standard deviation in the wind direction is about constant in this range of wind speeds this implies that the angle of yaw becomes more variable at higer windspeeds, indicating an increase in yawing activity.
- The peak value for the rotor speed is very well related to the average value of the wind speed. This in spite of the variations in both turbulence intensity and standard deviation in wind direction Obviously the turbulence intensity and the standard deviation in the wind direction do not have much influence in peak rotor speeds occuring during a 10 minute time interval.
- The peak value for the yawing speed is not very well related to the average value of the wind speed. The peak yawing speed tends to increase with the wind speed, however, the high values of the standard deviations within one bin interval mean both high and low values have occured for the yawing speed at both high or low wind speeds. This can also be seen clearly in the PLOT DATA output of data disk 26 block 29 and 30.
- The maximum value for the product of rotor speed and yawing speed tends to follow the curve for the yawing speed. This means both high and low values for the product of these speeds at both high and low average wind speeds.
- The maximum value for the product of rotor speed and yawing speed is about 70 % of the value for the product of peak rotor speed and peak yawing speed. This means that the peak values do not occur at the same time.

From the conclusions it can be seen that for a given averaged wind speed the peak rotor speed is very well predictable, while the peak yawing speed hardly predictable (because of the high values of the standard deviation).
Because the time constants which will describe the dynamical behaviour of the windmill are in the order of seconds, and the measuring time interval was 10 minutes, the high values for the standard deviations can only be caused by (unpredictable) changes in wind speed and wind direction. Therefore, it was tried to find a relation between the peak yawing speed, the standard deviation of the wind direction and the wind speed.
First a bin sort was made using the standard deviation of the wind speed as bin sort parameter. This gives the frequency distribution of the standard deviation of the wind direction.



Frequency distribution of the standard deviation of the wind speed.

After that bin sorts were made using the wind speed as bin sort parameter, while only measurements with a standard deviation of wind direction inside a specified range are elaborated. The ranges are choosen to be 10 to 15, 15 to 20, 20 to 25, 25 to 30 and 30 to 35 degrees.The result of all these bin sorts are shown in the following graph.



Peak yawing speed versus wind speed for several values of the standard deviation of the wind direction: □ = 10 to 15 degrees, X = 15 to 20 degrees, O = 20 to 25 degrees, + = 25 to 30 degrees, Δ = 30 to 35 degrees.

Unfortunately the higer wind speeds do not occur at higher values for the standard deviation in the wind direction. Therefore, the graph is not complete. The relation between peak yawing speed and standard deviation in the wind direction is not as clear as one might hope, but still it can be seen that the peak value of the yawing speed tends to be much higher at high values of the standard deviation of the wind direction than at low values.

7 Conclusions and recommandations

By means of the previous data the following can be concluded:

- The peak value for the rotor speed derivied from the time sequenced graphs is about 2 r/s. The same value (1.96 r/s at 7.6 m/s) can be obtained by a bin sort procedure (see the table and graph of the peak rotor speed versus the wind speed). Because this graph becomes reasonable flat at the end it is not expected that the value for the maximum rotor speed will increase much at higher wind speeds.
- The peak value for the yawing speed derivied from the time sequenced graphs is about 0.25 r/s. The bin sort procedure gives about 0.1 r/s with a standard deviation of about 0.02 r/s, however, because of the high standard deviation inside one bin this value cannot be used as the real maximum. Also the peak value of the yawing speed depends of the standard deviation in the wind direction.
- The maximum value for the product of rotor speed and yawing speed is about 0.27 (r/s.r/s), according to the time sequenced graphs. The bin sort graph of the maximum value of the product or rotor speed and yawing speed versus the wind speed gives values of about 0.16 (r/s.r/s), however because of the high values of the standard deviation inside one bin this value cannot be used as the real maximum.

Comparison with field measurements on the CWD 2000.

The CWD 2000 (rotor diameter 2 m)uses the same safety mechanism as the CWD 5001, and was tested on the same testing field as the CWD 5001. Although the dimensions of the CWD 5001 are not excatly scaled from the CWD 2000, it can be of interest to compare the peak speeds of both windmills. Reference 3 gives the following values for these speeds: peak rotor speed is 5 r/s, peak yawing speed is 0.5 r/s, and the maximum value for the product of rotor speed and yawing speed is 1.2 (r/s.r/s). According to the laws of scale for a wind mill with a 5 m rotor these values should become 5/2.5 = 2 r/s for the peak rotor speed, 0.5/2.5 = .2 for the peak yawing speed, and 1.2/2.5/2.5 = 0.19 (r/s.r/s) for the maximum value of the product of the rotor speed and the yawing speed. Comparing these values with the measured values, it can be seen that the peak rotor speed behaves according to the laws of scale,the peak yawing speed is 25 % higher than was expected according to the laws of scale and the maximum value for the product of rotor speed and yawing speed is about 40 % higher than was expected according to the laws of scale.

NOTE: one must keep in mind that the dimensions of the CWD 5001 are not exacly scaled from the dimensions of the CWD 2000.

Comparison with field measurements on the CWD 5000

The CWD 5000 uses the same rotor as the CWD 5001, but the safety mechanism uses a side vane together with a hinged tail vane. The CWD 5000 was tested at the testing field in Vriezeveen. At this field two versions of the CWD 5000 are operating: one with the side vane on the left side of the rotor and one with the side vane on the right side of the rotor. The field measurements show a much better behaviour of the version with the side vane on the right side of the rotor. From the draft of the performance report of this windmill (the vane on the right side) the following values can be obtained by means of the bin sort tables: the peak rotor speed is about 1.6 r/s, the peak yawing speed is about 0.1 r/s with a standard deviation of about 0.08 r/s. This report does not give the maximum of the product of the rotor speed and the yawing speed.
Comparing these values with the field measurements of the CWD 5001 it can be seen that the average peak rotor speed of the CWD 5000 is about 25 % lower than the average peak rotor speed of the CWD 5001 and the average peak yawing speed is about the same as the average peak yawing speed of the CWD 5001. The standard deviation of the peak yawing speed of the CWD 5000 however, is about 4 times higher than the standard deviation of the peak yawing speed of the CWD 5001. This indicates that the peak yawing speed of the CWD 5001 is probably much lower than the peak yawing speed of the CWD 5000. Probably the same result will appear for the maximum of the product of rotor speed and yawing speed.

NOTE: During the testing the CWD 5001 operated unloaded, while the CWD 5000 opareted loaded. It is not certain which situation will result in the highest speeds.

Comparison between field measurements and simulation.

In order to compare the field measurements with the theory the following simulations ware carried out by means of the simulation model as described in reference 4.
In the beginning of the simulation the wind speed is Vo and the windmill is in the stable situation corresponding to the wind speed Vo. Then in a time Tc the wind speed increases linearly until 2Vo and remains at 2Vo. The simulation is carried out for Vo = 4 until 12 m/s in steps of 1 m/s, every time for Tc = 1 second and Tc = 2 seconds. The results are given in the tables on the next page:

Vo (m/s)	N-max (r/s)	Y-max (r/s)	(N*Y)-max (r/s.r/s)
4	1.29	0.0194	0.023
5	1.45	0.0559	0.081
6	1.60	0.0846	0.134
7	1.69	0.1018	0.169
8	1.73	0.1064	0.181
9	1.66	0.0975	0.158
10	1.63	0.0903	0.144
11	1.45	0.0747	0.107
12	1.40	0.0615	0.086

Result of simulation for Tc = 1 second (Tc is the time in which the windspeed increases from Vo to 2 Vo).

Vo (m/s)	N-max (r/s)	Y-max (r/s)	(N*Y)-max (r/s.r/s)
4	1.30	0.0191	0.024
5	1.47	0.0547	0.081
6	1.59	0.0805	0.126
7	1.66	0.0932	0.152
8	1.66	0.0938	0.154
9	1.58	0.0837	0.129
10	1.53	0.0759	0.114
11	1.37	0.0617	0.084
12	1.33	0.0512	0.068

Result of simulation for Tc = 2 seconds (Tc is the time in which the windspeed increases from Vo to 2 Vo).

From the tables it can be seen that a peak rotor speeds occures of 1.73 r/s, which is about 15 % lower than was measured in the field. The peak yawing speed is 0.106 r/s which is less than half the value than was measured. The maximum value for the product of rotor speed and yawing speed is 0.18 (r/s.r/s), which is 2/3 of the measured value. This can be explained by the fact that the model does not include changes in wind direction which, as can be seen from the field measurements, is an importand factor for the maximum value of the yawing speed. Also it may be possible that the wind speed increased faster as supposed.

Recommendations

Comparing the behaviour of the CWD 5001 with the behaviour of the CWD 2000 have shown a less stable behaviour. This is also experienced by the fact that the CWD 5001 sometimes yaws a whole revolution in the safety direction, causing the measuring cable to brake (in one weekend the CWD 5001 may yaw 10 revolutions). Watching and comparing both windmills during windy days also give the impression that the CWD 2000 is more stable than the CWD 5001.
Therefore, it is recommended to modify the CWD 5001 in such a way that the behaviour becomes compareble with the CWD 2000. According to the designers this may be achieved by changing the tower in such a way that the distance between rotor area and center of the tower becomes smaller.

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