Analysis of fatigue measurements on pump rods

ANALYSIS OF FATIGUE MEASUREMENTS ON PUMP RODS

P. BEEKMAN
J. de JONGH

December 1988 R 985 D

WIND ENERGY GROUP
Technical University Eindhoven
Faculty of Physics
Laboratory of Fluid Dynamics and Heat Transfer
P.O. Box 513
5600 MB Eindhoven, the Netherlands

CONSULTANCY SERVICES WIND ENERGY DEVELOPING COUNTRIES
P.O. BOX 85
3800 AB AMERSFOORT
THE NETHERLANDS

TABLE OF CONTENTS

SYMBOLS AND DEFINITIONS

ΔF = Force step, which is a single change of force between a maximum and a minimum.

ΔF_{max} = Maximum Force step; which value is the maximum peak force minus the minimum peak force, taken from the force signal over one rotation.

F_{ji} = Force range, which is a range of bins of certain width (in this case 0.2 kN) in which the force steps can be sorted.

j = Force bin counter.
i = Revolution bin counter.

ΔF_{nor} = Normalized maximum force step, in which the shock force is not taken into account.

F_{shock} = shock force, an additional force caused by valve behaviour characterized with an amplitude $F_{sh,up}$ for the upper shock force (closing of piston valve) and $F_{sh,dn}$ for the lower shock force (closing of foot valve) and a frequency f [Hz].

N_{ji} = Force frequency, which is the number of force steps counted in a particular bin over one revolution.

j = Force bin counter.
i = Revolution bin counter.

Cycle = A phenomenon which returns regularly, which can be defined with a cycles duration time e.g. T or with a signal form in which the begin and end of the cycle are indicated.

f_{sh} = Frequency of shock force [Hz]

LDC = Lowest Dead Center, indicating that the pump piston in it's lowest position, can be taken as the begin/end of one pump cycle.

Constant Amplitude Load

= If for a certain cyclic fatigue load ΔF_{max} is more or less constant and the minor force steps arenot larger then about 25 % of ΔF_{max}, then the load is considered as a constant amplitude load.

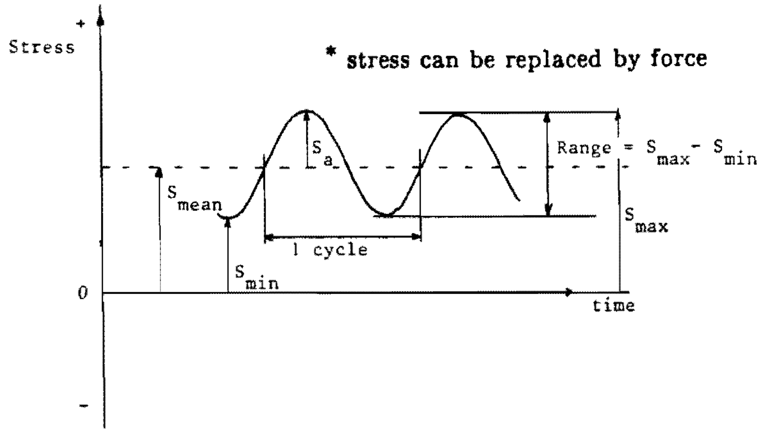


Fig. 0.1: Nomenclature

Stress ration R

$$= \frac{S_{min}}{S_{max}}$$

S_a $= \frac{S_{max} - S_{min}}{2}$

S_{mean} $= \frac{S_{max} + S_{min}}{2}$

Stress range

= twice the S_a

fatigue strength

= The maximum alternating stress which a material will withstand without failure, for a given number of cycles, see [11]

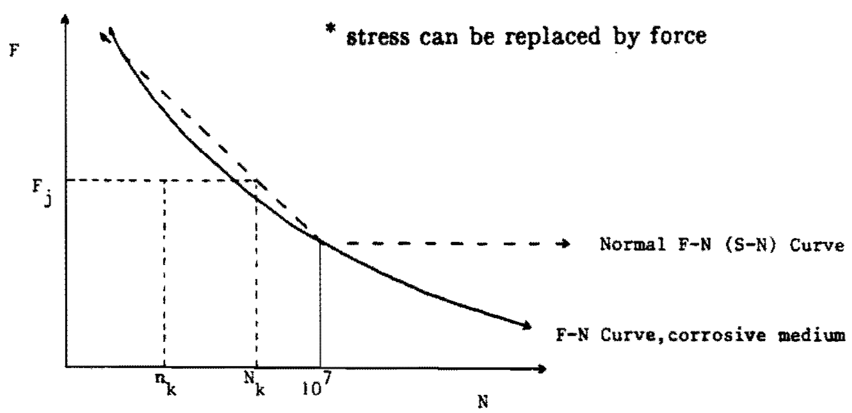


Fig. 0.2: Typical F-N (S-N) curve

S–N curve

= Curve obtained under load or stress control test condition with specimens. S is applied stress range (sometimes S_a). N is number of cycles or life to failure (failure is fracture).

Rule of Palmgren and Miner

= Rule to calculate fatigue damage. The rule relates the number of stress cycles of a specified size and mean to the allowable number of cycles. This is illustrated in figure 0.2 which presents the S–N curves (stress–number of cycles). N_k is the allowable number of force ranges F_j. From the bin counting results the number of counted force ranges, n_k. The fatigue damage of these force range is specified as:

$$D_k = \frac{n_k}{N_k}$$

This analysis can be repeated for all stress cycles. The fatigue life consumption is determined by the probability of failure:

$$D_t = \Sigma D_k$$

The fatigue life is consumed when $D_t = 1$ see [10]

H_{del} = Delivery head [m].

H_{stat} = Static head [m].

H_{tot} = Total head: $H_{del} + H_{stat}$.

D (D_p) = Diameter pump [m].

s = Stroke [m].

L_{pr} = Length pump rod [m].

INTRODUCTION

In the period aug. - sept. 1987 measurements on pump rod forces have been carried out on the CWD5001 windmill with a 108 deepwell pump (108D) at the TU Eindhoven testsite.
Two configurations have been measured in that period. For a total head of 30 m. and a total head of 16 m. over the total rotational speed range.
For information about the measurement system and the measuring method see [1] and [2].

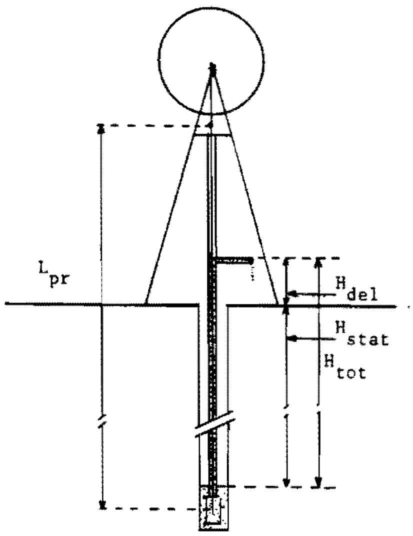
After handling the measurements with the Rainflow Counting Method, as described in [1], it's possible to relate the data to an experimental measured S-N curve [3], to make a lifetime prediction of the 3/4" pump rod of which the couplings are the weakest part.

About oct. 1987 the rotor was removed from the 5001 windmill and an electric-mechanic drive train was mounted, where with a new pumptestrig was created, baptized as 5001 pumptestrig.
In the period june till july 1988 the 5001 testrig was used to do, amongst others, force measurements with a 108D pump, in order to compare these measurements with those from the 5001 windmill.

1. MEASUREMENTS ON THE CWD5001 WINDMILL.

1.1. Test configuration

Figure 1.1 shows the testconfigurations of the 5001 windmill. A more detailed description is given in [2].



	conf 01	conf 02
H [m]	30	16
s [mm]	200	200
D [mm]	108	108
L_{pr} [m]	42	42
n [rps]	0 – 1.1	0 – 1.2
airchamber vol [l]	7.3	7.3
number of meas.	76	80
pumprod dia. ["]	3/4	3/4
rising main dia.["]	2	2
ηvol	–	–
ηmech	–	–
pump drawing nr.	E8502/B	see 01

Fig 1.1: Testrig configuration of the 5001 windmill.

1.2. Measured data

Figure 1.2 and 1.3 show the number of measurements done on configuration 01 and 02. One measurement consist of 1 to 2 rotations on a certain rotational speed. All measurements are binned using a binwidth of 0.1 rps. For a description of the software handling see [4].

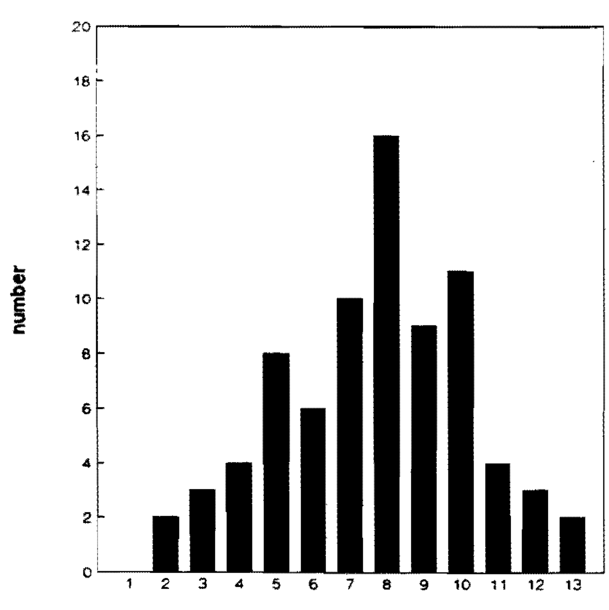


Fig. 1.2: Number of measurements against revolution bins for conf. 01.

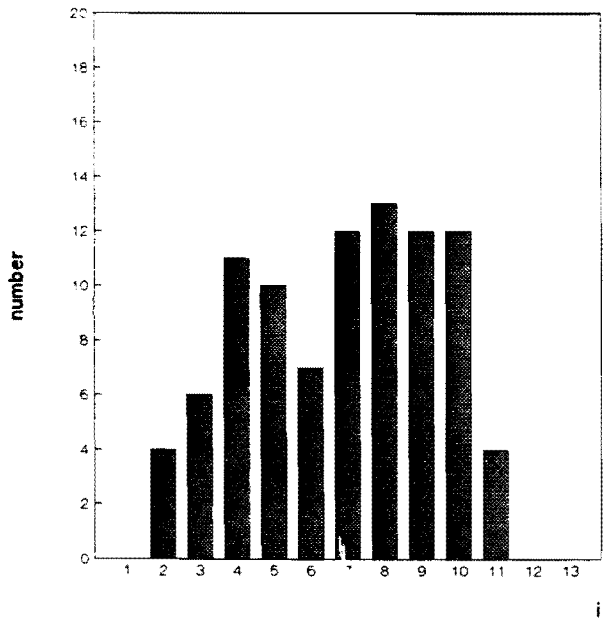


Fig. 1.3: Number of measurements against revolutionbins for conf. 02.

From each measurement exact one rotation is taken. For example, when one measurement consist of 1.5 rotations only the first 2/3 from the samples are taken into account.

1.3. Signals

Figure 1.4a to 1.4e and figure 1.5a to 1.5e show typical force signals of configuration 01 and 02. Figure 1.6 shows a force signal of the 108D pump with a nonworking airchamber (no air).

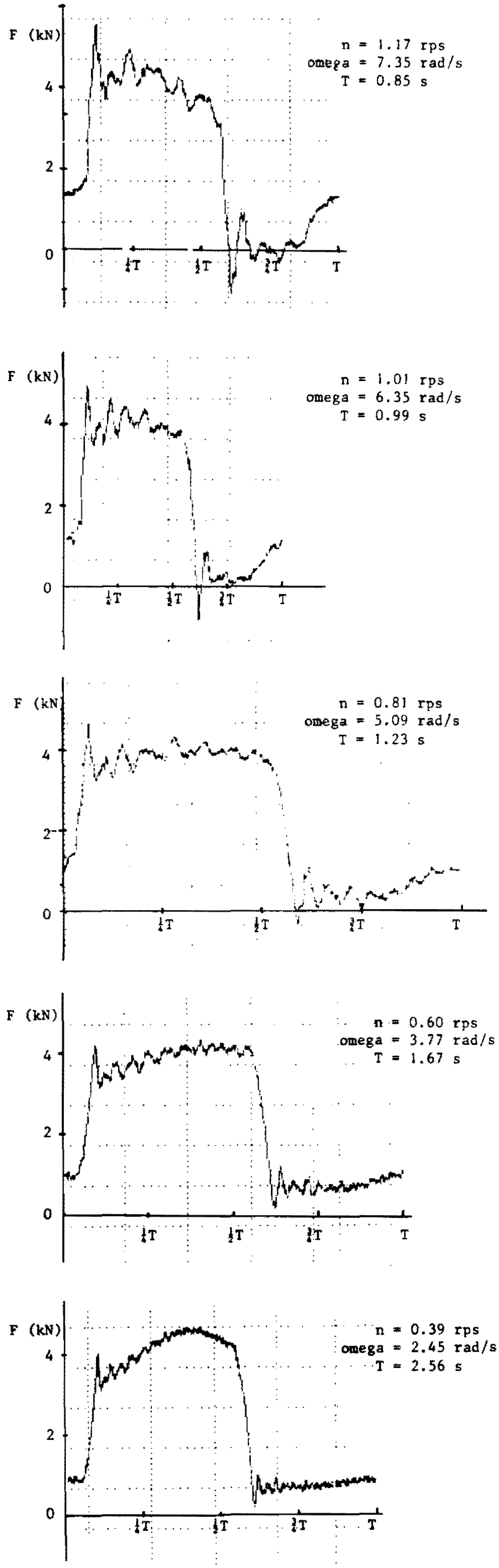


Fig. 1.4a..1.4e: Typical force signals configuration 02.

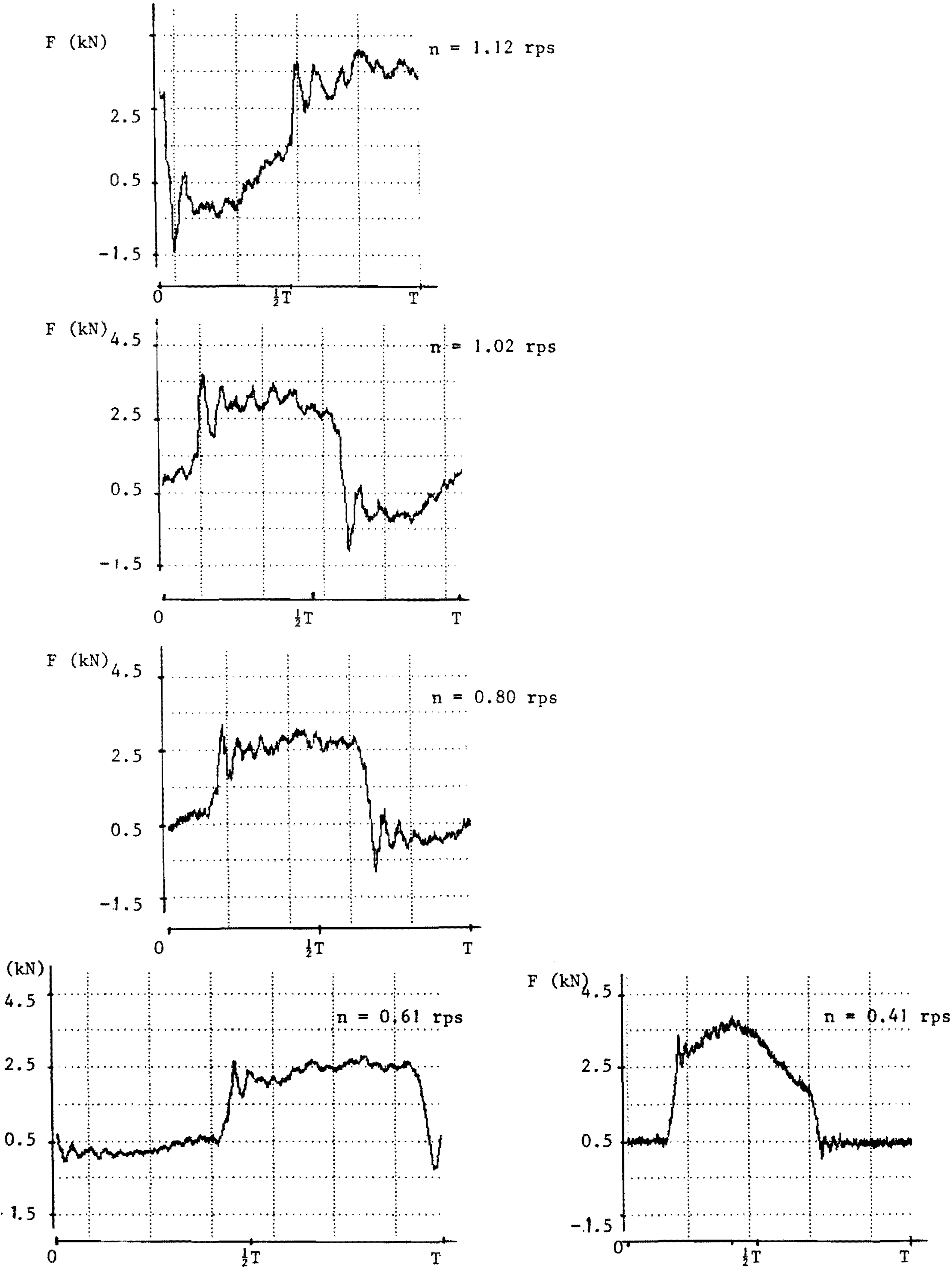


Fig. 1.5a..1.5e: Typical force signals configuration 01

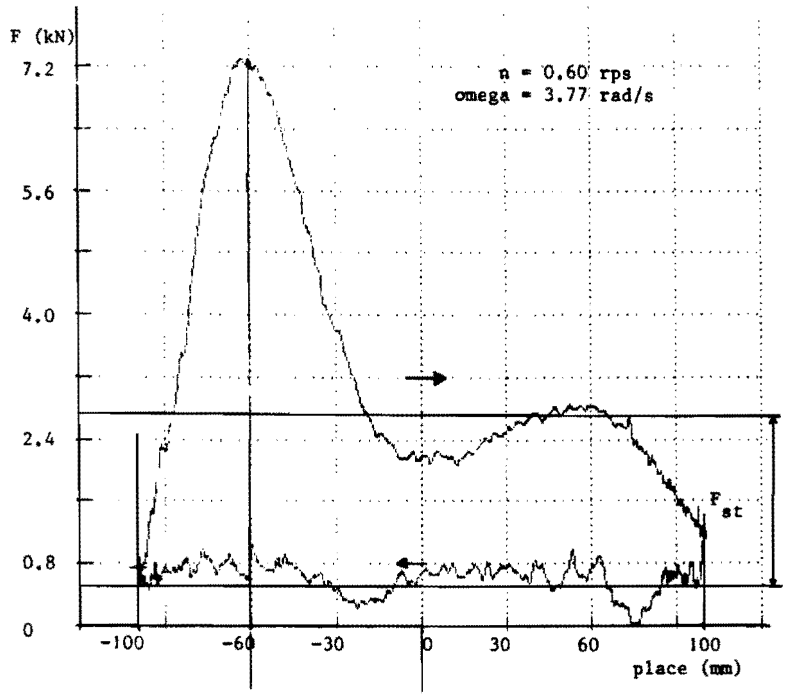
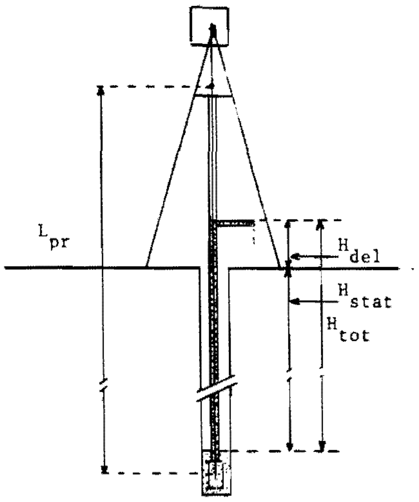


Fig. 1.6: Typical force signal with a nonworking airchamber

2. MEASUREMENTS ON THE CWD5001 PUMPTESTRIG

2.1. Test configuration

Figure 2.1 shows the test configurations of the 5001 pumptestrig. A more detailed description is given in [5].



	conf 03	conf 04
H [m]	25.6	25.6
s [mm]	200	200
D [mm]	108	108
L_{pr} [m]	36	36
n [rps]	0 – 1.4	0 – 0.6
airchamber vol [l]	15.9	0
number of meas.	280	120
pumprod dia. ["]	3/4	3/4
rising main dia.["]	2	2
η_{vol}		
η_{mech}		
pump drawing nr.	see 01	see 01

Fig 2.1: Testrig configuration of the 5001 windmill.

2.2. Measured data

The measurements done on the 5001 testrig are average signals. That means: The average signal is the summation of N measurements of one cycle falling in the bin of a certain rotational speed divided by N. Or:

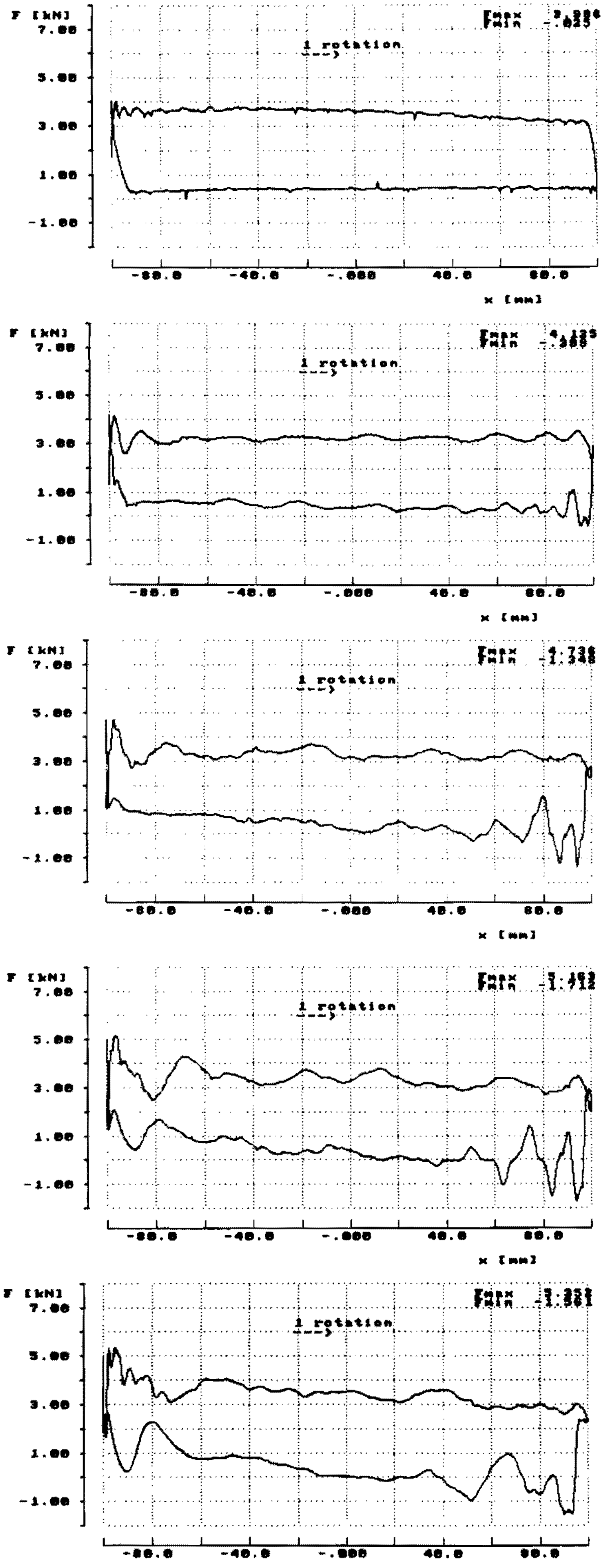
$$\overline{signal} = \sum_{n=1}^{N} \frac{signal_n}{N}$$

On configuration 03 and 04, N was 20. The measured binned rotational speeds were:

$n_i = i \cdot 0.1$	i = 1 to 14	for conf. 03
	i = 1 to 7	for conf. 04

2.3. Signals

Figure 2.2a to 2.2e show typical force signals (indicator diagram) of configuration 03. Figure 2.3a to 2.3e show the force signals for configuration 04.



n = 0.3

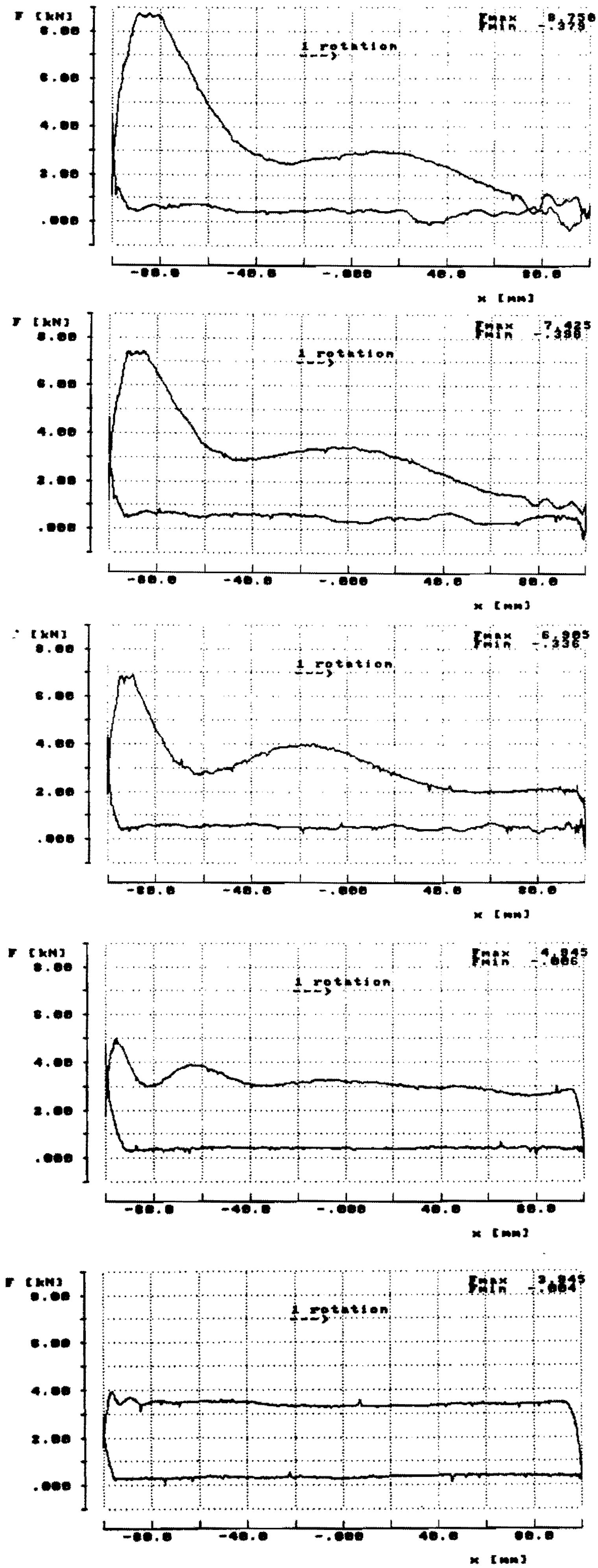
n = 0.7

n = 1.0

n = 1.2

n = 1.4

Fig. 2.2a..2.2e: Typical avarage force signals configuration 03



n = 0.7

n = 0.6

n = 0.5

n = 0,3

n = 0,1

Fig. 2.3a..2.3e: Typical avarage force signals configuration 04

3. ANALYSIS OF MEASURED DATA

3.1. Signal analysis

3.1.1. Maximum force step over one rotation

Important for fatigue investigation is the maximum force step (ΔF_{max}) over 1 rotation. Figure 3.1 gives a definition of the maximum force step. When all the measurements from chapter 3 are processed a ΔF_{max}–ω curve can be made, see figure 3.2. According prof. Overbeeke (TUE) ref [6] the force signals characterized by figure 3.1 and 3.2 may be considered as constant amplitude load signals taking ΔF_{max} as the constant (double) amplitude.

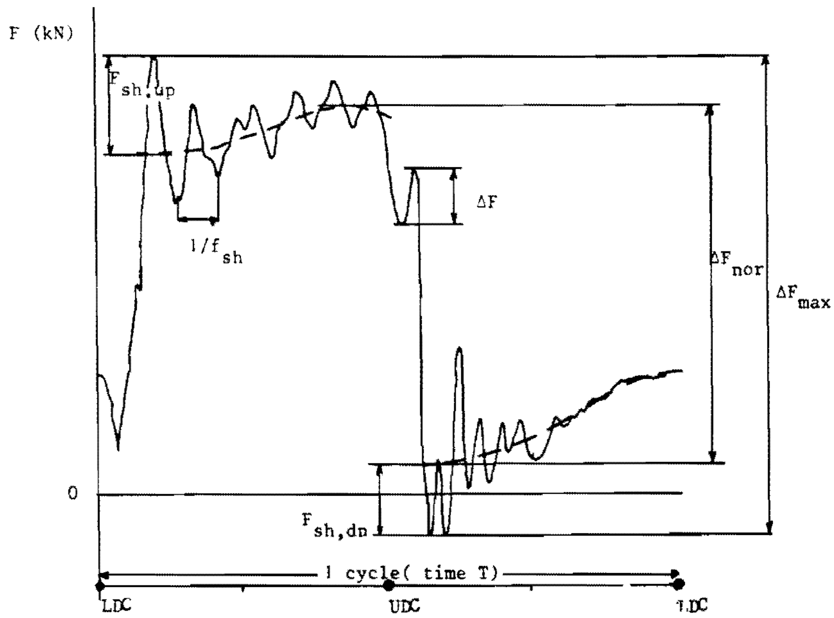


Fig. 3.1: Typical force signal, 1 cycle with symbols and definitions

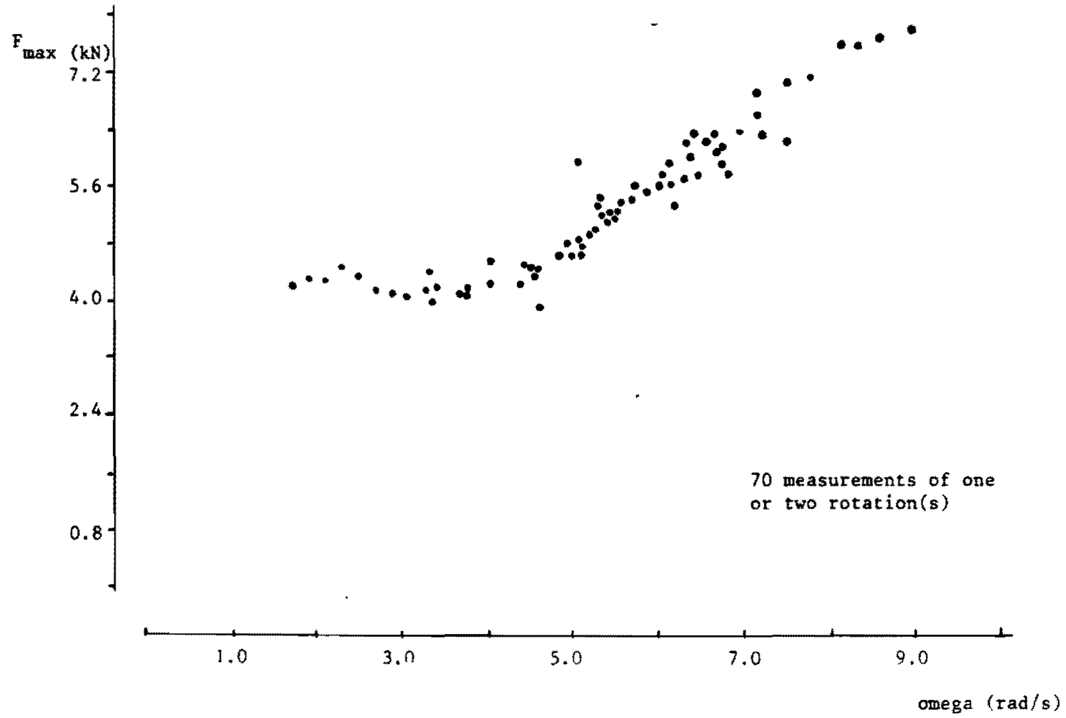


Fig. 3.2: ΔF_{max}–ω curve of conf. 01

3.1.2. Influence of airchamber volume on ΔF_{max}–ω curve

From the measurements of chapter 2, configuration 03 and 04, it's also possible to make a ΔF_{max}–ω curve.

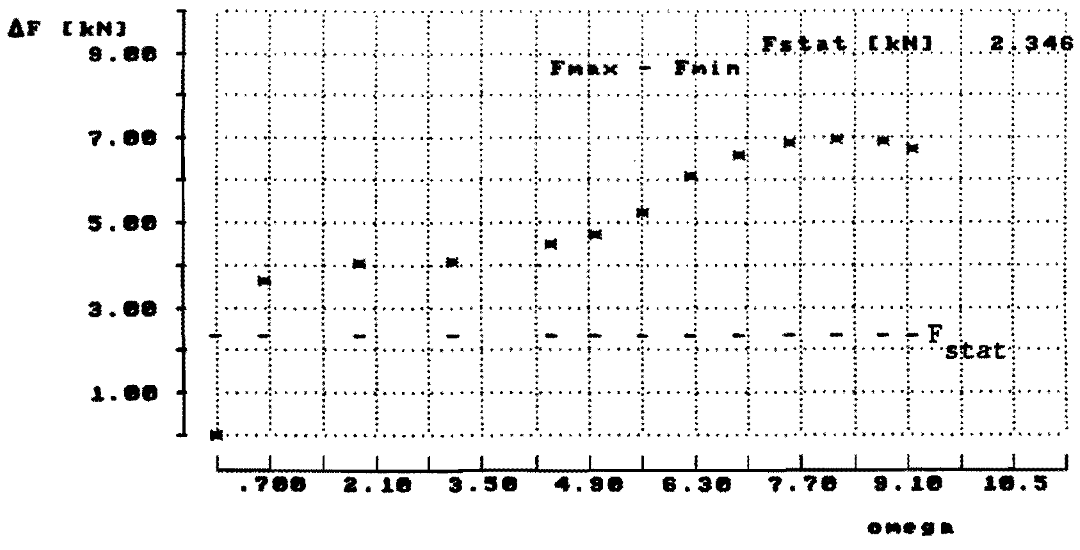


Fig. 3.3a: ΔF_{max}–ω curve of conf. 03, pump with working airchamber

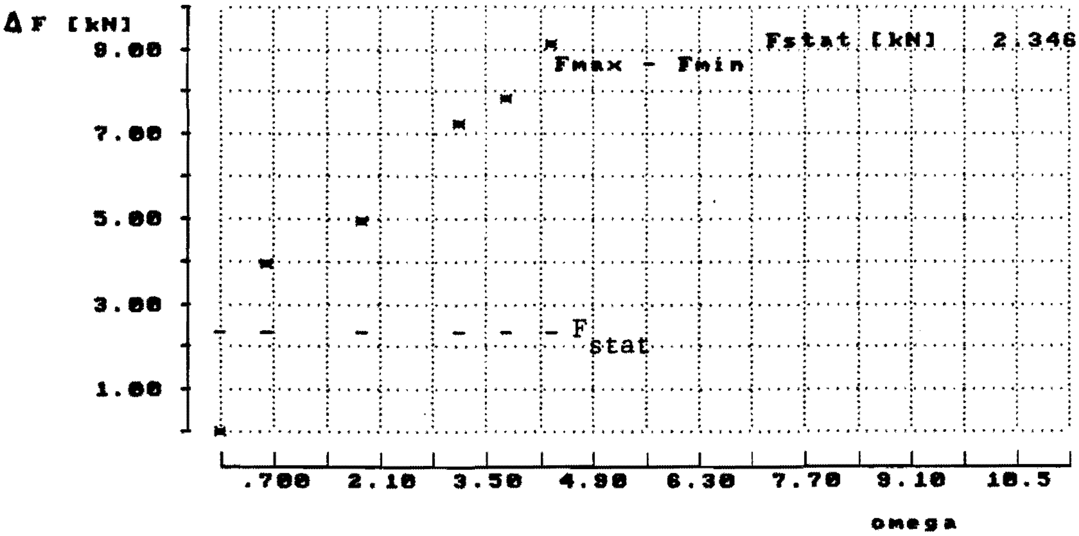


Fig. 3.3b: ΔF_{max}–ω curve for conf. 04, pump without working airchamber

A first look at figure 3.2 and 3.3 shows a lowest maximum force step of configuration 03. The configurations 01, 03 and 04 have different airchamber volumes which make's it possible to see a relation between airchamber volume and ΔF_{max}.
Figure 3.4 shows a ΔF_{max}–ω curve of configurations 01, 03 and 04. From this figure it's clear how important it is to:

1e use an airchamber, compare 03 with 04.

2e keep enough air in the airchamber, compare 01 with 03.(see also ref [8])

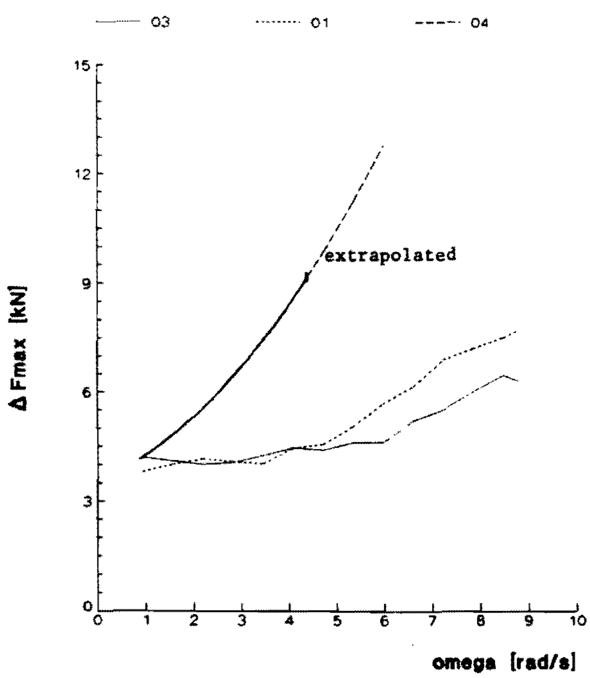


Fig. 3.4: Comparing ΔF_{max}–ω curves of configurations 01, 03 and 04

3.1.3. Signalcourse as function of rotational speed

Figure 3.5 (from figure 1.2 chapter 1) shows a number of signals at different rotational speed of configuration 01.

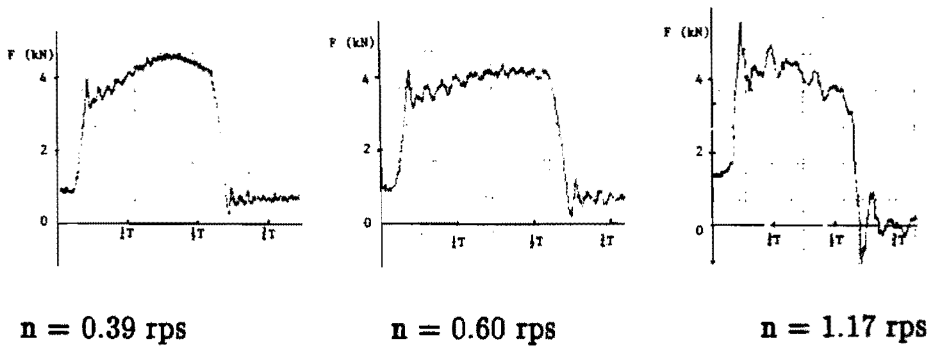


Fig. 3.5: Signal course as function of rotational speed

The maximum force in the signal variates from place with the rotational speed range. At lower speed the maximum force is caused by friction. At higher speed the shock force gives the maximum force. Configuration 03 gives over the whole rotational speed range a maximum caused by the shock force, see figure 2.2 chapter 2. The differences are probably caused by the different airchamber volumes.

3.1.4. Shock forces

-Attribution of shock force to total force.

From the measured signals of configuration 01, see figure 1.5a–e, the contribution of the shock force to the total force and the frequency of the shock force can be calculated, see table 3.1.

-Negative shock force.

Looking at the figures from chapter 1 and 2 a negative shock force occurs just after passing the highest deadcenter. This negative shock force which probably is caused by late closure of the foot valve makes the ΔF_{max} much higher.

n rps	ΔF_{max} [kN]	ΔF_{nor} [kN]	F_{shup} [kN]	F_{shdn} [kN]	F_{sh} [kN]	f_{sh} [Hz]	%*
1.2	6.80	4.72	0.96	0.72	1.68	12	25
1.0	5.81	4.36	0.83	0.78	1.61	13	28
0.8	5.20	4.01	1.05	0.56	1.61	15	31
0.6	4.20	3.40	0.86	0.57	1.43	13	34
0.4	4.52	4.52	0.25	0.24	0.49	13	11
0.1	3.76	3.76	0.09	0.08	0.17	2.7	5

* $(F_{sh}/\Delta F_{max})*100\%$

Table 3.1: Percentage of shock force to max force step

3.1.5. Comparison ΔF_{max} with F_{nor}

Table 3.2 (from table 3.1) and figure 3.6 show the differences between a signal with and without shock force.

n rps	ΔF_{max} [kN]	ΔF_{nor} [kN]	%*
1.2	6.80	4.72	31
1.0	5.81	4.36	25
0.8	5.20	4.01	23
0.6	4.20	3.40	19
0.4	4.52	4.52	0
0.1	3.76	3.76	0

$*(\Delta F_{max}-\Delta F_{nor})/\Delta F_{max} * 100\%$

table 3.2: Percentage of signal with and without shock force

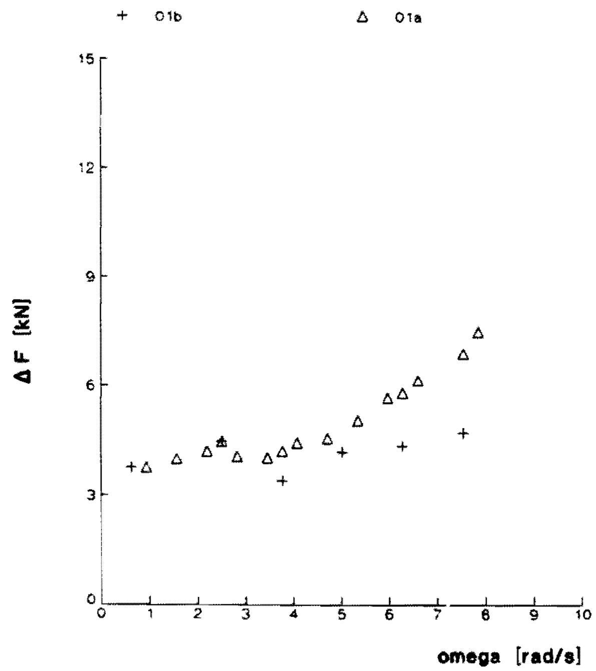
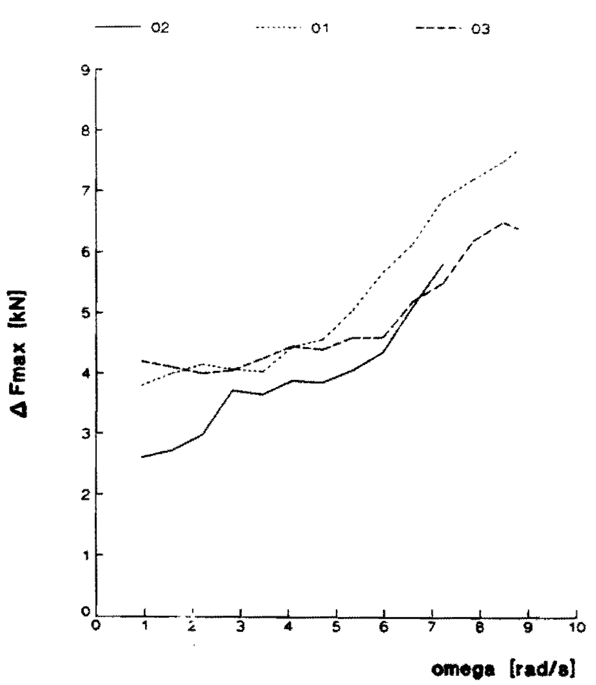


Fig. 3.6: Comparing ΔF_{max}–ω (01a) curve with ΔF_{nor}–ω (01b) curve

3.2. Comparison of measured data of the 5001 testrig and the 5001 windmill

The comparison can in fact not be done yet based on these data because the 108D pump of configuration 03 was destined for the Almere test of the CWD8000 windmill and had therefore a large airchamber volume. In the future the measurement with an equal volume (7.3 l) will be done.
Figure 3.7 shows a ΔF_{max}–ω curve of the configurations 01, 02 and 03.



	mill		testrig
conf	01	02	03
H	30	16	25,6
airch.	6·1	6·1	14·6

Fig. 3.7: Comparing ΔF_{max}–ω curves of configuration 01, 02 and 03

4. CALCULATION OF THE PUMP ROD FORCES

4.1. Input configuration

Some measured configurations have been simulated using a computer program "PUMPROD.FOR". This program makes it possible to simulate the pump rod force as function of the rotational speed ω. It is based on an analytical model which adds all contributing factors to the pump rod force. For a description of the model see [7]. For the input data and an example calculation see Appendix A.

4.2. calculating of signals

Figure 4.1a to 4.1d show the results of the simulation for different rotational speed for configuration 01.

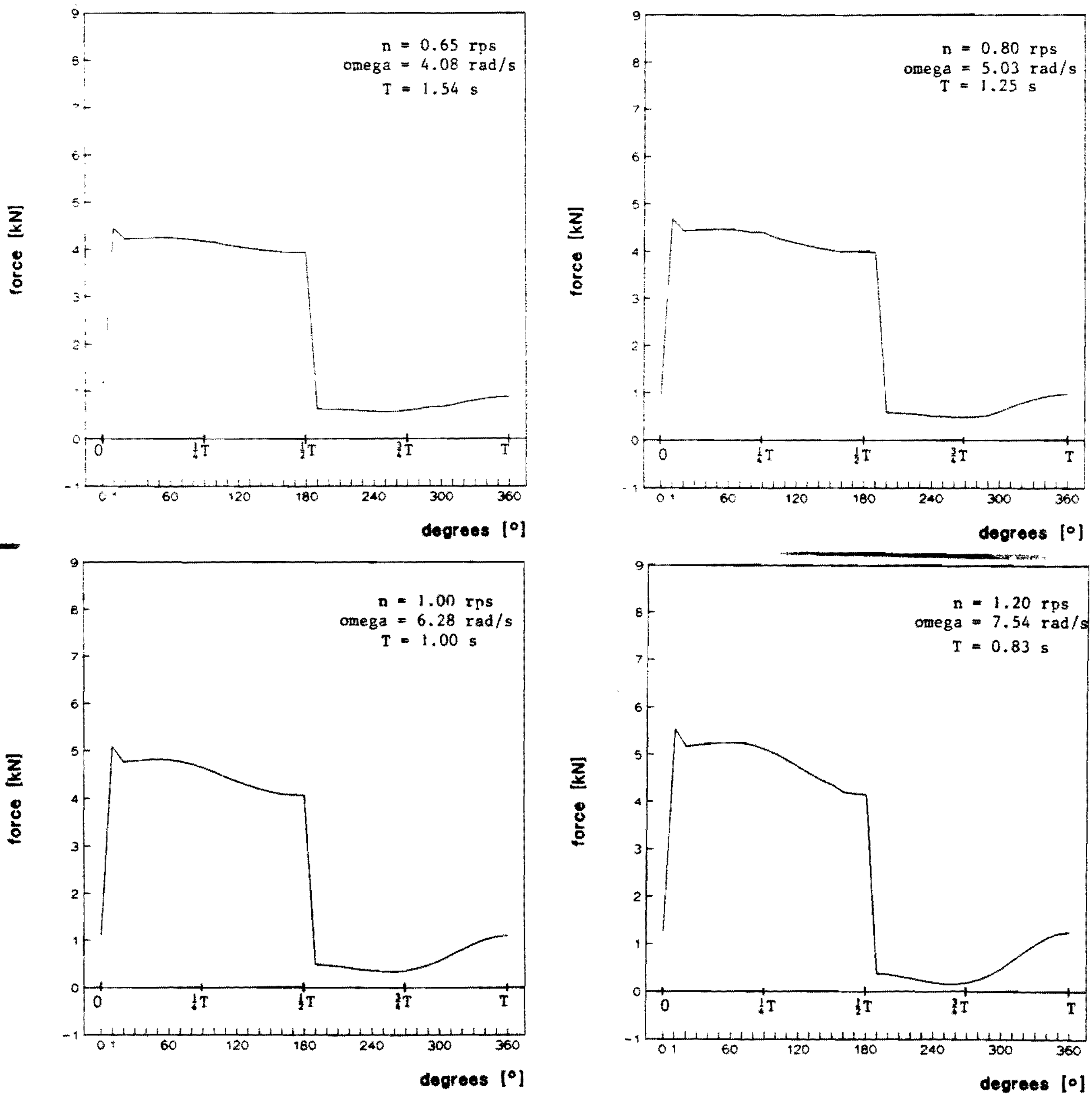


Fig. 4.1a to d: Simulated signal for different rotational speed.

5. COMPARISON OF MEASURED AND SIMULATED DATA

5.1. Comparison of signal course and ΔF_{max}–ω curve

Now the measured data of chapter 3 can be compared with the calculated data of chapter 4. Figure 5.1 shows the measured and simulated ΔF_{max}–ω curve.
Figure 5.2 shows the signal course over one rotation for the measured and simulated configuration 01.

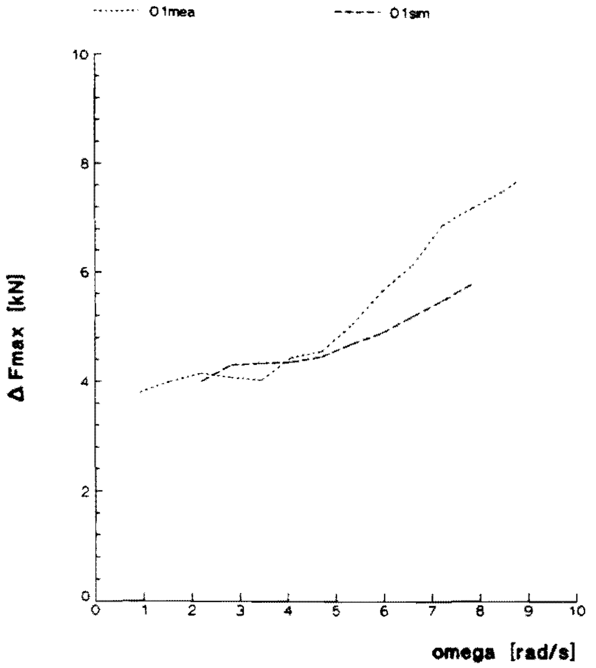


Fig. 5.1: Comparison of the measured and simulated signal for configuration 01.

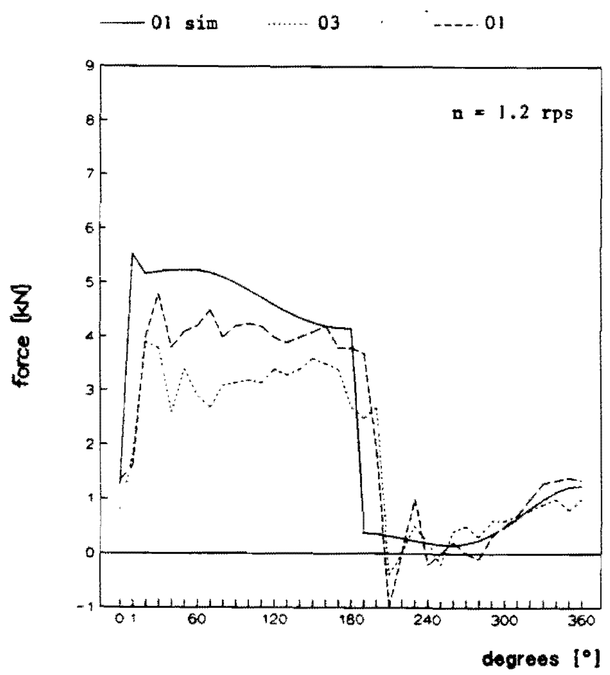


Fig. 5.2: Comparison of the signal course.

5.2. Analysis of the simulated signal

Looking at figure 5.2 it can be stated that with regard to the measured signal, the calculated signal indicates:

- A lower shock force
- No negative shock force
- A higher offset
- The signal course is fairly well in agreement.

The first two items are the most important for fatigue since the max ΔF determines the fatigue life. Especially the negative shock force is contributing considerably to ΔF_{max}. This negative shock force is probably caused by late valve closure of the foot valve.

6. FAILURE PROBABILITY CALCULATION

6.1. Evaluation of ΔF_{max} and RCM method

The Rainflow Counting Method (RCM see [1] and [10]) counts all single force steps, high and low alike of a certain force signal and rearranges them in bins from low to high. In case the force signals looks like those of chapter 1 and 2 with only one large force step ΔF_{max} over one pump cycle and some lower force steps with a maximum of ≈ 25 % of ΔF_{max} it might be sufficient to use only the large force step over one rotation instead of all force steps calculated with the RCM. This will be called the ΔF_{max} method. The lifetime prediction can be calculated using a spreadsheet [ENABLE software] see Appendix B. The results of the RCM or ΔF_{max} method must be put into the spreadsheet together with further information about windmill and wind regime. The lifetime is indicated by the probability of failure of the pump rod, D_t, for a chosen number of years. To calculate this probability, the loadspectrum is set out against the measured S-N curve [3] [9] with the rule of Palmgren and Miner [11].
The difference in D_t is 0.2 % comparing the RCM with the ΔF_{max} method so it is permitted to use the ΔF_{max} method and neglect all smaller force steps. A great

advantage of this method compared to the RCM is the reduced calculation time. Another advantage is the graphical presentation. A ΔF_{max}-ω curve is easier to make then a loadspectrum-ω curve and can be interpreted much better.

6.2. Results of some lifetime prediction calculations

The probabilities of failure of the pump rod, D_t, over 1 year (based on measurements of configuration 01, 02, 03 and 04 and the simulation in chapter 4.1) are given in table 6.1. Column 1 (3) gives the probability of failure of a S-N curve with $D_t = 1$ for $N = \infty$. For column 2 (4) a S-N curve with $D_t = 0$ for $N > 1.10^7$ has been taken, see APPENDIX C. In both cases the safe fatigue limit has been taken as criterium for the calculation.
The probability of failure has been calculated using the the wind density curve of the TU-E testfield for the period 18-05-'85 to 18-12'85, in combination with: 1) the curve of windspeed against mean rotational speed and 2) the curve of windspeed against maximum rotational speed, see APPENDIX D.

	n (mean)		n (max)	
conf ↓	D_t %	D_t %	D_t %	D_t %
01	20.5	1	180	122
02	10	0	116	52
03	15	0	138	49
04	41	30	>>	>>
sm*	15	0	140	50

*simulation 01

table 6.1: Probability of failure over 1 year

Since the windpumps will operate most of the time on n (mean) instead of n (max) the real probability of failure will be close to column 2.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

- The existence of a working airchamber for the tested configurations is a must. Without air in the chamber the test indicated forces resulting in a too short lifetime of the pump rod. If an airchamber should be omitted, then the maximum rotational speed should be lowered or the ratio pump area / rising main area should be lowered.
  A varying volume of the airchamber also varies the pump rod forces. For the pumps tested, 02 and 03, with a working airchamber the maximum measured force nearly reached the safe fatigue force limit of 7.5 kN (admissible stress 38.1 kN/m^2, safety factor 1.7 [9]).
  The maximum measured force of configuration 01 was 7.8 kN which is above the safe fatigue limit, however it is still under the ultimate fatigue strength of 13.6 kN.

- The contribution of the shock force compared to the normalized force is rather high for these configurations, up to 30 %.

- Although a little premature (due to still unexact comparison possibility) it can be concluded that there is not a large difference between measurements done on the CWD5001 windmill and on the 5001 pumptestrig.

- The computer program PUMPROD.FOR gives a reasonable agreement with the measured data of the tested configuration although some adjustments seem necessary.

- When the airchamber is as big as in configuration 03 the pump rod force signals may be considered as constant amplitude signals. For fatigue damage calculations the ΔF_{max} method may be used.

7.2. Recommendations

- In this analysis the comparison between the actual measured force signals and the analytical calculated model, detailed into all contributing forces has not be done yet. it's recommended to investigate this.

- The analytic model should be adjusted for the positive shock force contribution and the negative shock force component should be added.

- The model should be further checked for other configurations.

- In fatigue life calculation the real distribution of the number of revolutions should be taken. For each bin of revolutions a normal distribution can be calculated based on the mean and maximum values of n.

REFERENCES

[1] Measurement installation for fatigue of pumprods, methodology and results. Technical note Nr IN 06.87, P. Beekman/J. de Jongh CWD-TUE.

[2] Een meetsysteem voor meten van pompstang krachten. Thesis Report R 857 S P. Beekman.

[3] Pump rod coupling static and fatigue tests. UT WM 127, H Wisselink E Heukels.

[4] Handleiding meet- en verwerkingsprogramma TESTRIG6.PRG en PLOT1.PRG. P. Beekman.

[5] Technical note P. Kompier CWD5001 testrig 8/5 '87, 3/6 '87 and 29/6 '87.

[6] Bespreking verslag 23-12-87 met prof. Overbeeke.

[7] Calculation of pump rod forces, user's guide to PUMPROD.FOR. UT WM 112, H. F. Veldkamp.

[8] Measurements on the relation between pump rod force and airchamber volume on a CWD 108D pump. UT WM 132, N. W. H. Rijnhart.

[9] Admissible stresses in designs, a literature survey. WM 106 F. Goezinne.

[10] Expert group study on recommended practices for wind turbine testing and evaluation. 3 Fatigue characteristics 1e edition '84. D.W. Dekker (ECN) et. al.

[11] Metal Fatigue in engineering. H. Fuchs/R. Stephens (USA). John Wiley & Sons Inc.USA 1980

[12] Field measurements on the CWD5001 performed in the period 85-05-15 to 85-12-18. TU-E R 834 D, Henk Oldenkamp.

APPENDIX A

Data of CWD 5001 / 108 D design calculations
Latest update : 1988-10-27

=============================

CALCULATION OF PUMP ROD FORCES

=============================

PUMPROD.FOR : Release of Thursday 1988-10-27 : 12:19:54.24
Data from input file : 5001108.IN

5001108.out

Design Wind Speed : 3.73 m/s

Pump rod forces at 6.28 rad/s

Alfa deg	Facppr N	Fstppr N	Facw N	Fstw N	Ffrw N	Ffrcup N	Ffrpv N	Ftotal N
0	376	792	0	0	0	0	0	1168
10	368	792	0	0	0	0	0	1159
20	343	792	14	2728	494	270	0	4640
30	305	792	12	2728	494	269	0	4600
40	254	792	10	2728	494	269	0	4547
50	195	792	8	2728	494	269	0	4485
60	130	792	5	2728	494	269	0	4418
70	65	792	3	2728	494	269	0	43[illegible]9
80	1	792	0	2728	494	268	0	4283
90	-58	792	-2	2728	494	268	0	4222
100	-110	792	-4	2728	494	268	0	4168
110	-153	792	-6	2728	494	268	0	4122
120	-188	792	-7	2728	494	268	0	4086
130	-215	792	-9	2728	494	268	0	4058
140	-234	792	-9	2728	494	268	0	4038
150	-247	792	-10	2728	494	268	0	4025
160	-255	792	-10	2728	494	268	0	4016
170	-259	792	-10	2728	494	268	0	4012
180	-260	792	-10	2728	494	268	0	4010
190	-259	792	0	0	0	0	-8	524
200	-255	792	0	0	0	0	-33	504
210	-247	792	0	0	0	0	-72	473
220	-234	792	0	0	0	0	-124	434
230	-215	792	0	0	0	0	-185	392
240	-188	792	0	0	0	0	-251	352
250	-153	792	0	0	0	0	-315	324
260	-110	792	0	0	0	0	-369	313
270	-58	792	0	0	0	0	-405	329
280	0	792	0	0	0	0	-105	687
290	16	792	0	0	0	0	-101	707
300	33	792	0	0	0	0	-90	734
310	49	792	0	0	0	0	-74	766
320	63	792	0	0	0	0	-54	801
330	76	792	0	0	0	0	-34	834
340	86	792	0	0	0	0	-16	861
350	92	792	0	0	0	0	-4	879
360	94	792	0	0	0	0	-0	886
10	92	792	4	2728	128	238	0	4076

CpMax	Cq0	Dr	LabdaD	LabdaMax		
0.33	0.120	5.0	1.70	3.20		
Apri	Etam	ired	Lcr	Lpr	mprm	Rcrank
202e-6	0.98	1	0.55	46	1.7	0.100
Dp	hcup	hlv	Lov	mp	mu	Zv
0.108	0.015	0.0035	0.295	2.5	0.15	2.85

A	Dhydr	H	k	L	Z	xlr8	
1	1.0	0.0	0.0	0.0	0.0	0	
9.161e-3	0.108	0.35	0.00025	0.35	0.0	1	cylinder
1.391e-3	0.023	30.0	0.00025	34.0	2.0	0	rising main
1	1.0	0.0	0.0	0.0	0.0	0	piping 2"
1	1.0	0.0	0.0	0.0	0.0	0	
1	1.0	0.0	0.0	0.0	0.0	0	
1	1.0	0.0	0.0	0.0	0.0	0	
1	1.0	0.0	0.0	0.0	0.0	0	
1	1.0	0.0	0.0	0.0	0.0	0	
1	1.0	0.0	0.0	0.0	0.0	0	

Data of CWD 5001 / 108 D design calculations
Latest update : 1988-10-27

APPENDIX B

Calculating the break chance with the Enable Spreadsheet

An Enable Spreadsheet is used to calculated the break chance for one configuration.

Before using this speadsheet measured data, simulated or measured S-N curve and some information about the configuration must be know:

1e information about the windmill.
2e information about the wind regime.
3e infomation about the pump (measured or simulated ΔF_{max}-ω curve)

- After knowing the ΔF_{max}-ω curve, a discrete wind density curve and a discrete rotation windspeed curve of the windmill discrete force rotation density curve can be derived.

- The rotation density curve must be presented as a discrete curve with the same bins as the ΔF_{max}-ω curve, so with bins of $\Delta n = 0.1$ rps and number of occuring in that bin in % or parts from 100 % or 1.

- It's also possible to input a measured or theorytical rotation density curve without knowing the wind density curve.

- At last the lifetime in number of years D_t can be put in.

windmill: CWD 5005
Arad: 26.1 m
stroke: 0.2 m.

n (rps) \ Fmax - Fmin <- F (kN) ->	0.8	1	1.2	1.4	3.2	3.4	3.6	3.8	4	4.2	4.4	4.6	4.8	5	5.2	5.4	7	7.2	7.4	7.6	7.8	8	8.2	8.4	9.6	9.8
< 0.05	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.05 - .15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.15 - .25	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.25 - .35	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.35 - .45	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.45 - .55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
.55 - .65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.65 - .75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.75 - .85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
.85 - .95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
.95 - 1.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
1.05 - 1.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
1.15 - 1.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.25 - 1.35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.35 - 1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
> 1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

INPUT	Breakchance over>	1	year(s)
Dtotal %	53.16818		
Dtotal % F < 3E7	20.44291		

INPUT windspeed-rotation curve; INPUT meas. or calc. data; CALCULATION if 10 minutes per measurement

Rule from Basquin: F**3*N=constant
constant =1.1637E10
N is Nmax

n (rps)	windspeed (m/s) mean	min	max	measurements (number)	calculation (% or part)	hours	sec.	mean rot rot/s	s/rot	N meas.	tot. time h year s	k h year	K/number rot. rot./year
<.05	0.25	0	0.5	10	0.003512	1.666667	6000	0	ERR				0
.05 - .15	1	0.5	1.5	30	0.010537	5	18000	0.1	10	1800	347823.5	34782.35	34782.35
.15 - .25	2	1.5	2.5	50	0.017562	8.333333	30000	0.2	5	6000	579705.9	115941.2	115941.2
.25 - .35	3	2.5	3.5	140	0.049175	23.33333	84000	0.3	3.333333	25200	1623176	486952.9	486952.9
.35 - .45	4	3.5	4.5	200	0.070249	33.33333	120000	0.4	2.5	48000	2318823	927529.4	927529.4
.45 - .55	5	4.5	5.5	300	0.105374	50	180000	0.5	2	90000	3478235	1739117	1739117
.55 - .65	6	5.5	6.5	500	0.175623	83.33333	300000	0.6	1.666667	180000	5797058	3478235	3478235
.65 - .75	7	6.5	7.5	800	0.280998	133.3333	480000	0.7	1.428571	336000	9275294	6492705	6492705
.75 - .85	8	7.5	8.5	400	0.140499	66.66667	240000	0.8	1.25	192000	4637647	3710117	3710117
.85 - .95	9	8.5	9.5	200	0.070249	33.33333	120000	0.9	1.111111	108000	2318823	2086941	2086941
.95 - 1.05	10	9.5	10.5	130	0.045662	21.66667	78000	1	1	78000	1507235	1507235	1507235
1.05 - 1.15	11	10.5	11.5	50	0.017562	8.333333	30000	1.1	0.909091	33000	579705.9	637676.5	637676.5
1.15 - 1.25	12	11.5	12.5	20	0.007025	3.333333	12000	1.2	0.833333	14400	231882.4	278258.8	278258.8
1.25 - 1.35	13	12.5	13.5	10	0.003512	1.666667	6000	1.3	0.769231	7800	115941.2	150723.5	150723.5
1.35 - 1.45	14	13.5	14.5	5	0.001756	0.833333	3000	1.4	0.714286	4200	57970.59	81158.82	81158.82
> 1.45	15	14.5	15.5	2	0.000702	0.333333	1200	1.5	0.666667	1800	23188.24	34782.35	34782.35
total mean:	5.520833			sum: 2847		445	1632000	0.825		1098000	32463529		
							19.32353						20579558

m = 30 m.
Force jump kN

	0.8	1	1.2
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
	0	0	0
Nmax	2.27E+10	1.16E+10	6.73E+[illegible]
D	0	0	0
Dtotal	0.531682		
D %	0	0	0
Dtotal %	53.16818		

2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6	6.2	6.4	6.6	6.8	7	7.2	7.4	7.6	7.8	8	8.2	8.4	8.6	8.8	9	9.2	9.4	9.6	9.8
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	34782.35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	115941.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	6492705	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	3710117	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2086941	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1507235	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	637676.5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	278258.8	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	150723.5	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	81158.82	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34782.35	0
0	0	0	0	0	0	34782.35	0	115941.2	6492705	0	0	0	3710117	0	2086941	0	1507235	0	0	637676.5	0	0	0	278258.8	231882.4	34782.35	0
1.45E+09	1.09E+09	8.42E+08	6.62E+08	5.38E+08	4.31E+08	3.55E+08	2.96E+08	2.49E+08	48827666	44391632	46477884	37809591	33027113	31177862	28717450	26500421	24522075	22728515	21105606	19633746	18295358	17076270	19962962	14944367	14010623	13153076	12366108
0	0	0	0	0	0	0.000098	0	0.000465	0.132972	0	0	0	0.109356	0	0.072672	0	0.061464	0	0	0.032479	0	0	0	0.01862	0.01655	0.002644	0
0	0	0	0	0	0	0.009794	0	0.04648	13.29719	0	0	0	10.93535	0	7.267153	0	6.146443	0	0	3.247859	0	0	0	1.861966	1.655067	0.264443	0

APPENDIX C

S–N curves for lifetime calculations in table 6.1 [7] [9].

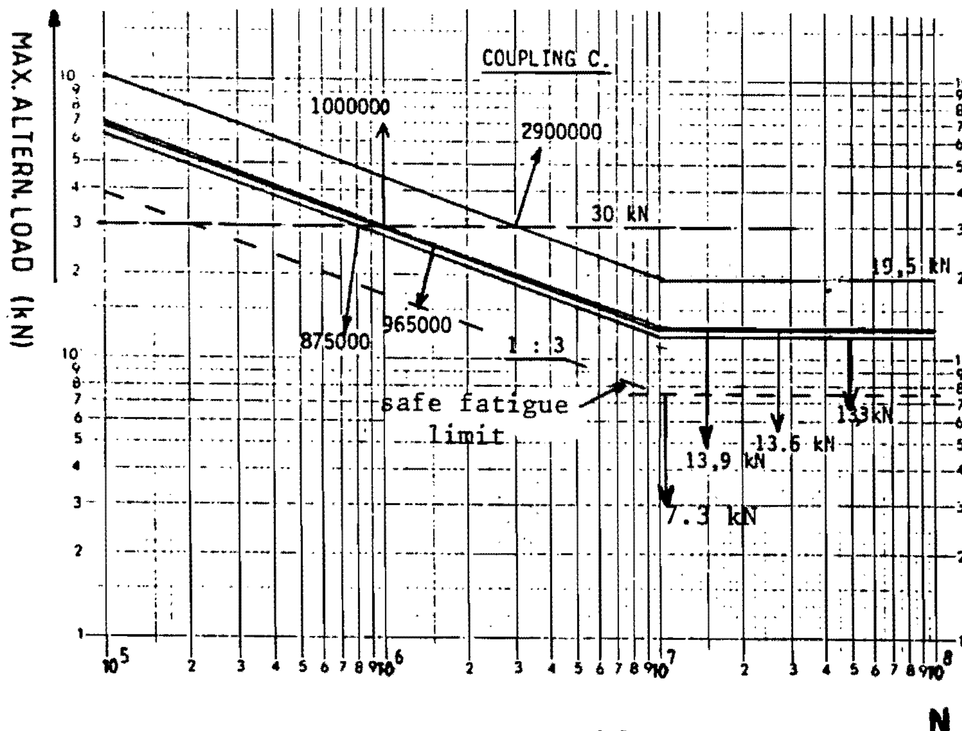


Fig. C1: S–N curve with measured data from [7]

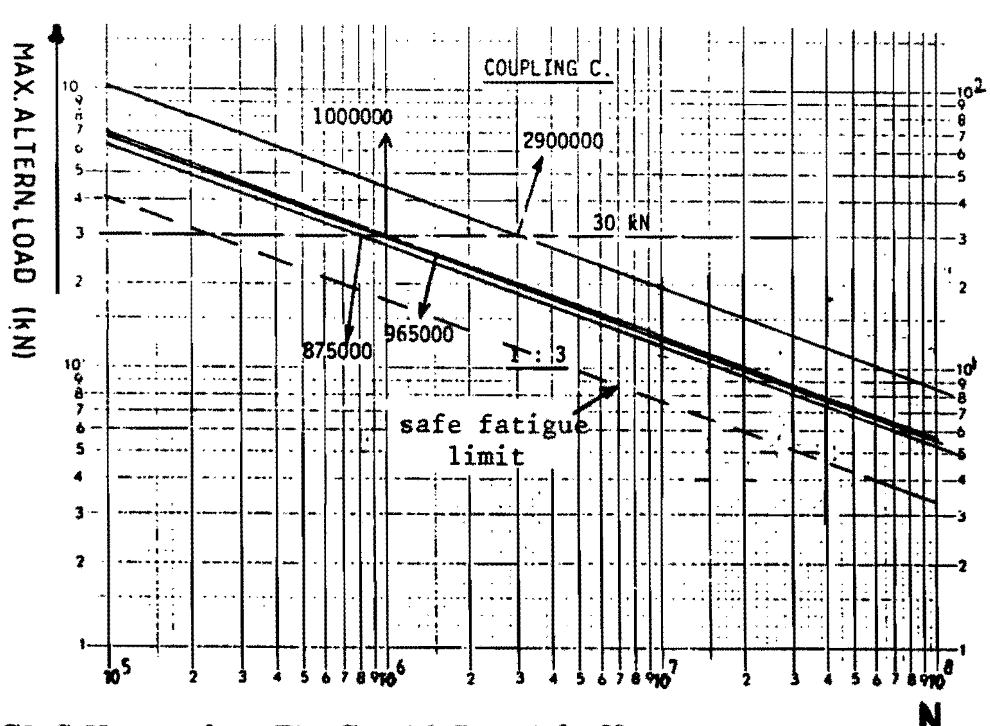


Fig. C2: S–N curve from Fig. C1 with $D_t = 0$ for $N = \infty$

APPENDIX D

Information about the CWD5001 on the TE–U testfield [12].

```
***** BIN SORT OF CWD 5001 SAFETY *****
SORTING PARAMETER: U-12M (M/S); BIN WIDTH=.5
ELABORATED ARE BLOCK 15-26:28-32:1-32:9-31:1-5
```

I	N	U-12M (M/S)		SD/AU U-12M		DIR (DEG)		SD DIR (DEG)		DELTA (DEG)		SD DELTA		N-MAX (R/S)		Y-MAX (R/S)		(N+Y)-MAX	
1	404	.2452	.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	9.00	-18.4	59.6	7.691	9.15	.0642	.141	<.01	<.01	<.01	<.01
3	299	1.267	.143	.4509	.152	175.0	100.	13.87	6.35	-9.40	46.5	12.09	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	18.29	5.91	-3.98	14.6	21.02	6.56	.6257	.275	.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	.6934	.197	.0244	.014	.0163	.010
7	575	3.242	.145	.3091	.057	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	120.5	76.3	20.42	3.29	-2.51	6.82	28.45	5.49	1.258	.132	.0419	.020	.0392	.020
9	369	4.236	.139	.3063	.047	112.5	72.5	20.35	2.73	-1.65	5.83	30.38	5.05	1.191	.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	.2986	.044	91.73	32.4	20.25	2.18	2.266	4.86	33.39	5.30	1.605	.177	.0573	.014	.0646	.019
12	84	5.732	.145	.3063	.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	6.754	.152	.2877	.034	97.29	26.7	19.35	2.09	15.06	3.98	38.50	6.16	1.918	.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	7.512	.068	.2970	.021	85.5	30.4	19.12	2.35	25.71	2.63	36	4.93	1.962	.174	.1125	.055	.1675	.056
17	3	8.213	.199	.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	2.755	1.49	.3117	.136	129.5	86.1	18.04	6.05	-6.69	28.3	23.35	10.0	.6897	.538	.0253	.043	.0257	.037

342 MEASUREMENTS ARE IGNORED