Analysis of fatigue measurements on pump rods

*Citation for published version (APA):*

*Document status and date:*
Published: 01/01/1988

*Document Version:*
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

*Please check the document version of this publication:*
- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

*Link to publication*

*General rights*
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

*Take down policy*
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
ANALYSIS OF FATIGUE MEASUREMENTS
ON PUMP RODS

P. BEEKMAN
J. de JOONCH

December 1988

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
P.O. BOX 85
3800 AB AMERSFOORT
THE NETHERLANDS
TABLE OF CONTENTS

SYMBOLS AND DEFINITIONS

INTRODUCTION

1. MEASUREMENTS ON THE CWD5001 WINDMILL
   1.1. Test configuration
   1.2. Measured data
   1.3. Signals

2. MEASUREMENTS ON THE CWD5001 PUMPTESTRIG
   2.1. Test configuration
   2.2. Measured data
   2.3. Signals

3. ANALYSIS OF THE MEASURED DATA
   3.1. Signal analysis
      3.1.1. Maximum force step over one rotation
      3.1.2. Influence of airchamber volume on $\Delta F_{\text{max}}-\omega$ curve
      3.1.3. Signal course as function of rotational speed
      3.1.4. Shock forces
      3.1.5. Comparison $\Delta F_{\text{max}}$ and $\Delta F_{\text{nor}}$
   3.2. Comparison of measured data of the 5001 testrig and the 5001 windmill

4. CALCULATION OF THE PUMP ROD FORCES
   4.1. Input configuration
   4.2. Calculating of signals

5. COMPARISON OF MEASURED AND SIMULATED DATA
   5.1. Comparison of signal course and $\Delta F_{\text{max}}-\omega$ curve
   5.2. Analysis of the simulated signal

6. FAILURE PROBABILITY CALCULATION
   6.1. Evaluation of $\Delta F_{\text{max}}$ method and RCM method
   6.2. Results of some lifetime prediction calculations
7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions
7.2. Recommendations

REFERENCES
APPENDIX A
APPENDIX B
APPENDIX C
APPENDIX D
SYMBOLS AND DEFINITIONS

\( \Delta F \) = Force step, which is a single change of force between a maximum and a minimum.

\( \Delta F_{\text{max}} \) = 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.

\( \Delta F_{\text{nor}} \) = Normalized maximum force step, in which the shock force is not taken into account.

\( F_{\text{shock}} \) = shock force, an additional force caused by valve behaviour characterized with an amplitude \( F_{\text{sh,up}} \) for the upper shock force (closing of piston valve) and \( F_{\text{sh,dn}} \) 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.

\( f_{\text{sh}} \) = 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 \( \Delta F_{\text{max}} \) is more or less constant and the minor force steps are not larger then about 25 % of \( \Delta F_{\text{max}} \), then the load is considered as a constant amplitude load.
Stress can be replaced by force

Stress ration $R$

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

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

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

Stress range

$$= \text{twice the } S_a$$

Fatigue strength

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

---

Fig. 0.1: Nomenclature

---

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:

$$D_t = \sum D_k$$

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 test configurations of the 5001 windmill. A more detailed description is given in [2].

![Test configuration diagram]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>conf 01</th>
<th>conf 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H ) [m]</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>( a ) [mm]</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>( D ) [mm]</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>( L ) [m]</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>( n ) [rps]</td>
<td>0 – 1.1</td>
<td>0 – 1.2</td>
</tr>
<tr>
<td>airchamber vol [l]</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>number of meas.</td>
<td>76</td>
<td>80</td>
</tr>
<tr>
<td>pumpprod dia. [&quot;]</td>
<td>3/4</td>
<td>3/4</td>
</tr>
<tr>
<td>rising main dia.[&quot;]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( \eta_{vol} )</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( \eta_{mech} )</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>pump drawing nr.</td>
<td>E8502/B</td>
<td>see 01</td>
</tr>
</tbody>
</table>

Fig 1.1: Test rig 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].

![Number of measurements histogram]

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].

![Test configuration diagram](image)

<table>
<thead>
<tr>
<th></th>
<th>conf 03</th>
<th>conf 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>H [m]</td>
<td>25.6</td>
<td>25.6</td>
</tr>
<tr>
<td>s [mm]</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>D [mm]</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>L [m]</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>n [rps]</td>
<td>0 - 1.4</td>
<td>0 - 0.6</td>
</tr>
<tr>
<td>airchamber vol [l]</td>
<td>15.9</td>
<td>0</td>
</tr>
<tr>
<td>number of meas.</td>
<td>280</td>
<td>120</td>
</tr>
<tr>
<td>pump prod dia. [&quot;]</td>
<td>3/4</td>
<td>3/4</td>
</tr>
<tr>
<td>rising main dia. [&quot;]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>η_vol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>η_mech</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pump drawing nr.</td>
<td>see 01</td>
<td>see 01</td>
</tr>
</tbody>
</table>

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:

\[
\text{signal} = \frac{\sum_{n=1}^{N} \text{signal}_n}{N}
\]

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

\[n_i = i \cdot 0.1 \quad i = 1 \text{ to } 14 \quad \text{for conf. 03} \]

\[n_i = i \text{ to } 7 \quad \text{for conf. 04} \]

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

n = 0.3

n = 0.7

n = 1.0

n = 1.2

n = 1.4
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 ($\Delta F_{\text{max}}$) over 1 rotation. Figure 3.1 gives a definition of the maximum force step. When all the measurements from chapter 3 are processed a $\Delta F_{\text{max}}$-$\omega$ curve can be made, see figure 3.2. According to ref [6], the force signals characterized by figure 3.1 and 3.2 may be considered as constant amplitude load signals taking $\Delta F_{\text{max}}$ as the constant (double) amplitude.

![Fig. 3.1: Typical force signal, 1 cycle with symbols and definitions](image)

Fig. 3.1: Typical force signal, 1 cycle with symbols and definitions
3.1.2. Influence of airchamber volume on $\Delta F_{\text{max}}-\omega$ curve

From the measurements of chapter 2, configuration 03 and 04, it's also possible to make a $\Delta F_{\text{max}}-\omega$ curve.

Fig. 3.3a: $\Delta F_{\text{max}}-\omega$ curve of conf. 03, pump with 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 $\Delta F_{\text{max}}$. Figure 3.4 shows a $\Delta F_{\text{max}}$ curve of configurations 01, 03 and 04. From this figure it's clear how important it is to:

1° use an airchamber, compare 03 with 04.

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

![Graphs showing signal course as function of rotational speed](image)

\[ n = 0.39 \text{ rps} \quad n = 0.60 \text{ rps} \quad n = 1.17 \text{ rps} \]

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 \( \Delta F_{\text{max}} \) much higher.

<table>
<thead>
<tr>
<th>( n ) (rps)</th>
<th>( \Delta F_{\text{max}} ) [kN]</th>
<th>( \Delta F_{\text{nor}} ) [kN]</th>
<th>( F_{\text{shup}} ) [kN]</th>
<th>( F_{\text{shdn}} ) [kN]</th>
<th>( F_{\text{sh}} ) [kN]</th>
<th>( f_{\text{sh}} ) [Hz]</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>6.80</td>
<td>4.72</td>
<td>0.96</td>
<td>0.72</td>
<td>1.68</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td>1.0</td>
<td>5.81</td>
<td>4.36</td>
<td>0.83</td>
<td>0.78</td>
<td>1.61</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td>0.8</td>
<td>5.20</td>
<td>4.01</td>
<td>1.05</td>
<td>0.56</td>
<td>1.61</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>0.6</td>
<td>4.20</td>
<td>3.40</td>
<td>0.86</td>
<td>0.57</td>
<td>1.43</td>
<td>13</td>
<td>34</td>
</tr>
<tr>
<td>0.4</td>
<td>4.52</td>
<td>4.52</td>
<td>0.25</td>
<td>0.24</td>
<td>0.49</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>0.1</td>
<td>3.76</td>
<td>3.76</td>
<td>0.09</td>
<td>0.08</td>
<td>0.17</td>
<td>2.7</td>
<td>5</td>
</tr>
</tbody>
</table>

\[ (F_{\text{sh}}/\Delta F_{\text{max}})^{\ast}100\% \]

Table 3.1: Percentage of shock force to max force step

3.1.5. Comparison \( \Delta F_{\text{max}} \) with \( F_{\text{nor}} \)

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

<table>
<thead>
<tr>
<th>( n ) (rps)</th>
<th>( \Delta F_{\text{max}} ) [kN]</th>
<th>( \Delta F_{\text{nor}} ) [kN]</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>6.80</td>
<td>4.72</td>
<td>31</td>
</tr>
<tr>
<td>1.0</td>
<td>5.81</td>
<td>4.36</td>
<td>25</td>
</tr>
<tr>
<td>0.8</td>
<td>5.20</td>
<td>4.01</td>
<td>23</td>
</tr>
<tr>
<td>0.6</td>
<td>4.20</td>
<td>3.40</td>
<td>19</td>
</tr>
<tr>
<td>0.4</td>
<td>4.52</td>
<td>4.52</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>3.76</td>
<td>3.76</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ *(\Delta F_{\text{max}}-\Delta F_{\text{nor}})/\Delta F_{\text{max}} \ast 100\% \]

Table 3.2: Percentage of signal with and without shock force
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 $\Delta F_{max} - \omega$ curve of the configurations 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 $\omega$. 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 $\Delta F_{\text{max}}-\omega$ 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 $\Delta F_{\text{max}}-\omega$ 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.
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 $\Delta F$ determines the fatigue life. Especially the negative shock force is contributing considerably to $\Delta F_{\text{max}}$. This negative shock force is probably caused by late valve closure of the foot valve.

6. FAILURE PROBABILITY CALCULATION

6.1. Evaluation of $\Delta F_{\text{max}}$ 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 $\Delta F_{\text{max}}$ over one pump cycle and some lower force steps with a maximum of $\approx 25\%$ of $\Delta F_{\text{max}}$ 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 $\Delta F_{\text{max}}$ method. The lifetime prediction can be calculated using a spreadsheet [ENABLE software] see Appendix B. The results of the RCM or $\Delta F_{\text{max}}$ 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 $\Delta F_{\text{max}}$ method so it is permitted to use the $\Delta F_{\text{max}}$ 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 $\Delta F_{\text{max}} - \omega$ curve is easier to make then a loadspcetrum-\(\omega\) 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.

<table>
<thead>
<tr>
<th>conf</th>
<th>$D_t$ %</th>
<th>$D_t$ %</th>
<th>$D_t$ %</th>
<th>$D_t$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>20.5</td>
<td>1</td>
<td>180</td>
<td>122</td>
</tr>
<tr>
<td>02</td>
<td>10</td>
<td>0</td>
<td>116</td>
<td>52</td>
</tr>
<tr>
<td>03</td>
<td>15</td>
<td>0</td>
<td>138</td>
<td>49</td>
</tr>
<tr>
<td>04</td>
<td>41</td>
<td>30</td>
<td>&gt;&gt;</td>
<td>&gt;&gt;</td>
</tr>
<tr>
<td>sim*</td>
<td>15</td>
<td>0</td>
<td>140</td>
<td>50</td>
</tr>
</tbody>
</table>

*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.

25
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/m², 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 pump test rig.

− 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 $\Delta F_{max}$ 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 been 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


[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.


### APPENDIX A

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

CALCULATION OF PUMP ROD FORCES

<table>
<thead>
<tr>
<th>Deg</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>376</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1168.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>368</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1159.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>343</td>
<td>792</td>
<td>14</td>
<td>2728</td>
<td>494</td>
<td>270</td>
<td>0</td>
<td>0</td>
<td>4640.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>305</td>
<td>792</td>
<td>12</td>
<td>2728</td>
<td>494</td>
<td>269</td>
<td>0</td>
<td>0</td>
<td>4600.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>254</td>
<td>792</td>
<td>10</td>
<td>2728</td>
<td>494</td>
<td>269</td>
<td>0</td>
<td>0</td>
<td>4547.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>195</td>
<td>792</td>
<td>8</td>
<td>2728</td>
<td>494</td>
<td>269</td>
<td>0</td>
<td>0</td>
<td>4485.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>130</td>
<td>792</td>
<td>5</td>
<td>2728</td>
<td>494</td>
<td>269</td>
<td>0</td>
<td>0</td>
<td>4418.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>65</td>
<td>792</td>
<td>3</td>
<td>2728</td>
<td>494</td>
<td>269</td>
<td>0</td>
<td>0</td>
<td>439.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>31</td>
<td>792</td>
<td>0</td>
<td>2728</td>
<td>494</td>
<td>269</td>
<td>0</td>
<td>0</td>
<td>4263.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>-58</td>
<td>792</td>
<td>-2</td>
<td>2728</td>
<td>494</td>
<td>269</td>
<td>0</td>
<td>0</td>
<td>4222.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>-110</td>
<td>792</td>
<td>-4</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4168.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>-153</td>
<td>792</td>
<td>-6</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4122.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>-188</td>
<td>792</td>
<td>-7</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4086.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>-215</td>
<td>792</td>
<td>-9</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4058.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>-234</td>
<td>792</td>
<td>-9</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4038.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>-247</td>
<td>792</td>
<td>-10</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4025.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>-255</td>
<td>792</td>
<td>-10</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4016.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>-259</td>
<td>792</td>
<td>-10</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4012.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>-260</td>
<td>792</td>
<td>-10</td>
<td>2728</td>
<td>494</td>
<td>268</td>
<td>0</td>
<td>0</td>
<td>4010.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>-259</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-8</td>
<td>524.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>-255</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-33</td>
<td>504.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>-247</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-72</td>
<td>473.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>-234</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-124</td>
<td>434.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>-215</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-185</td>
<td>392.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>-188</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-251</td>
<td>352.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>-153</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-315</td>
<td>324.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>-110</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-369</td>
<td>313.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>-58</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-405</td>
<td>329.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>0</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-105</td>
<td>687.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>290</td>
<td>16</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-101</td>
<td>707.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>33</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-90</td>
<td>734.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>310</td>
<td>49</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-74</td>
<td>766.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>320</td>
<td>63</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-54</td>
<td>801.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>330</td>
<td>76</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-34</td>
<td>834.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>340</td>
<td>86</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-16</td>
<td>861.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>92</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-4</td>
<td>879.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>94</td>
<td>792</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>886.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 spreadsheet measured data, simulated or measured S–N curve and some information about the configuration must be know:

1\textsuperscript{e} information about the windmill.
2\textsuperscript{e} information about the wind regime.
3\textsuperscript{e} information about the pump (measured or simulated $\Delta F_{\text{max} - \omega}$ curve)

- After knowing the $\Delta F_{\text{max} - \omega}$ 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 $\Delta F_{\text{max} - \omega}$ curve, so with bins of $\Delta n = 0.1$ rps and number of occurring in that bin in % or parts from 100 % or 1.

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

- At last the lifetime in number of years $D_t$ can be put in.
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
<th>Column 5</th>
<th>Column 6</th>
<th>Column 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
</tr>
</tbody>
</table>

**Note:** The table contains numerical data and is too complex to read naturally. It appears to be a scientific or technical document.
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 $N = \infty$
Information about the CWD5001 on the TE-U testfield [12].

---

**APPENDIX D**

---

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

---

**APPENDIX D**

---

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

---

**APPENDIX D**

---

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

---