Measurements executed on a 108D pump with and without air chamber

MEASUREMENTS EXECUTED ON A 108D PUMP WITH AND WITHOUT AIR CHAMBER

J. DIEPENS,
P. BEEKMAN,

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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
holland

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1. INTRODUCTION

In the past CWD pumps always have been equipped with air chambers. This was done because an air chamber smooths the pulsating flow of the pump and due to this the dynamic forces are reduced.

A problem with the actually air chambers is to keep the air in the air chamber and the supply of air to the air chamber.

To solve this problem much investigation is necessary. To show the importance of finding a way out to make air chambers available in the field, some tests have been done on a CWD 108 deepwell pump with and without air chamber.

The results of these tests can be compared with each other.

2. DESCRIPTION OF THE TEST STAND

The pump test stand used was the so–called CWD 5001 test rig, see fig. 2.1. For this test rig the CWD 5001 windmill was used, in which the rotor was replaced by a DC motor with speed control.

The stroke can be adjusted from 80 to 200 mm with steps of 40 mm. The speed range is from 0 upto 3.3 rps. Depending on the load the maximum rps can be lower than 3.3 rps.

The force in the pump rod is measured with a force transducer type E. Brosa + 50 kN. The flow is measured with an inductive flow meter: Disco mag. DMI 6531/H50 Endress + Hauser. The data acquisition was done with a IBM.XT personal computer equipped with a Metrabyte Dash 16 data acquisition board, an Intel 8087 Math co–processor and a Hercules graphics card.

To collect and process data use was made of the scientific software package ASYST.

An analysis of the accuracy of measurement is given in Annex IV.

The well under the test rig has a depth of 33 meter. The CWD 108D pump was installed at a depth of 27.6 meters ground level to foot valve. The static head was taken at 26.4 meters. For the rising main 2" GI pipe was used with a 3/4" CWD pump rod inside. From the delivery T to the de–aeration vessel 3 meter 2" plastic hose was used. The stroke was adjusted at 200 mm

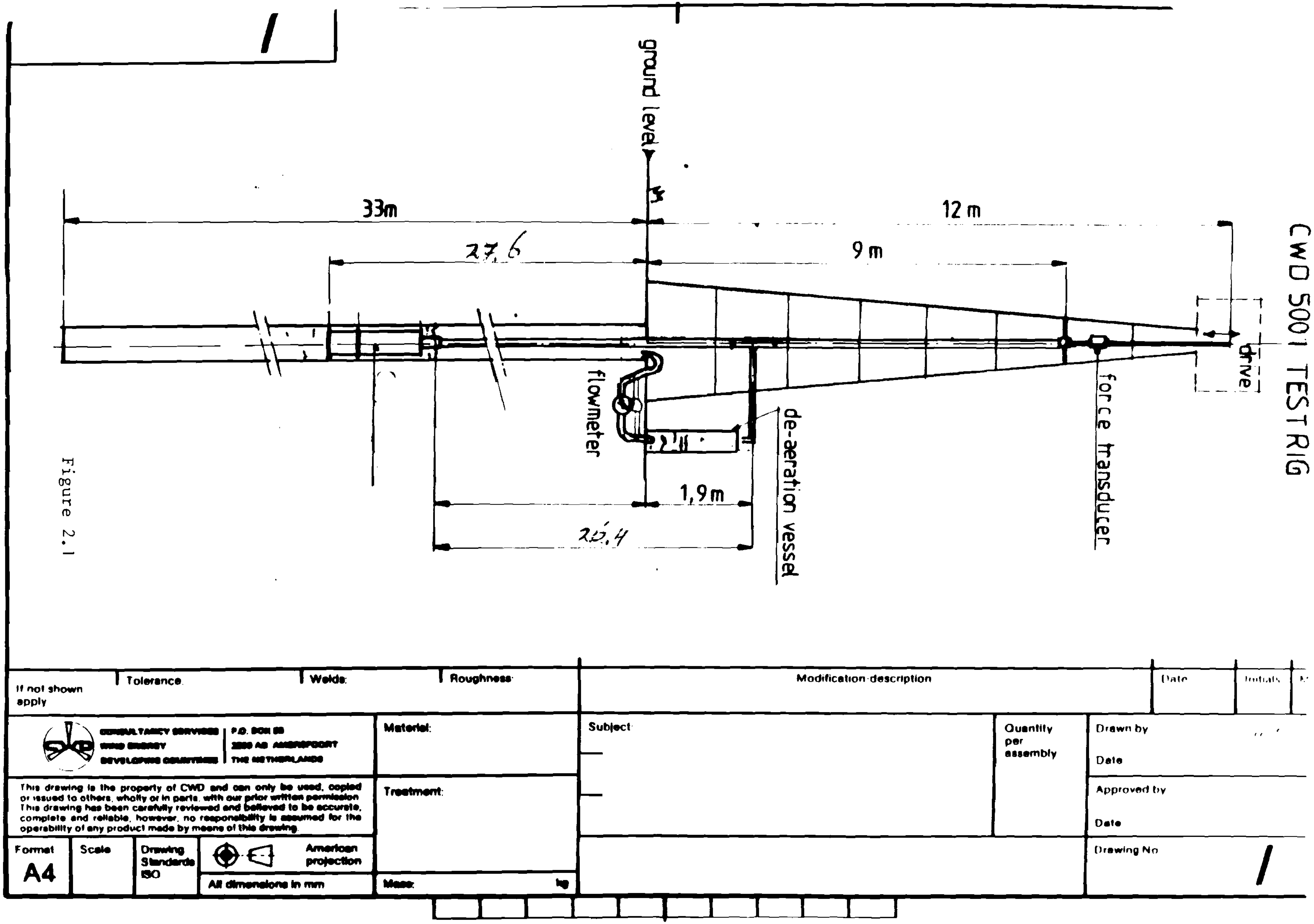

ground level
33m
12 m
27,6
9 m
CWD 5001 TESTRIG
drive
flowmeter
de-aeration vessel
force transducer
1,9 m
25,4
If not shown apply
Tolerance
Welds
Roughness
Modification description
Date
Initials
P.O. BOX 85
3800 AB AMERSFOORT
THE NETHERLANDS
Material:
Subject:
Quantity per assembly
Drawn by
Date
This drawing is the property of CWD and can only be used, copied or issued to others, wholly or in parts, with our prior written permission. This drawing has been carefully reviewed and believed to be accurate, complete and reliable, however, no responsibility is assumed for the operability of any product made by means of this drawing.
Treatment:
Approved by
Date
Format
A4
Scale
Drawing Standards ISO
American projection
All dimensions in mm
Mass
kg
Drawing No

Figure 2.1

3. DESCRIPTION OF THE MEASURED CONFIGURATIONS

3.1 Configuration 02 (fig. 2.1)

Pump tested: CWD 108D pump

Installation depth: 27.6 m foot valve to ground level

Imersion depth: 3.1 m

Static head: 26.4 m

Static pump rod force: 2.3 KN

Internal diameter pump: 108 mm

Internal diameter rising main: 52 mm (2" GI pipe)

External diameter pump rod: 27 mm (3/4" GI pipe)

Stroke: 200 mm

Air chamber: yes 16 l

Valve lifting height: piston valve 3.5 mm
foot valve 3.5 mm

3.2 Configuration 07 (fig. 2.2)

Pump testes: CWD 108D pump

Installation depth: 27.6 m foot valve to ground level

Imersion depth: 3.4 m

Static head: 26.1 m

Static pump rod force: 2.4 KN

Internal diameter pump: 108 mm

Internal diameter rising main: 52 mm (2" GI pipe)

External diameter pump rod: 27 mm (3/4" GI pipe)

Stroke: 200 mm

Air chamber: no

Valve lifting height: piston valve 3.5 mm

foot valve 3.5 mm

4. ELUCIDATION OF THE MEASUREMENTS

Each measurement has an index number according the following format:

```
pxxx yy zz
 A   B  C
```

where in A: p = for pump

xxx = diameter pump in mm

B: yy = configuration

C: zz = number of measurement

The results of the measurements are given in the annexes.

Configuration 02 Annex I p10802.....

Configuration 02 Annex II p10807.....

The results are represented as indicator diagrams for each rotation speed measured. Also the total results, F_{max}-F_{min}, η_{vol} and η_{mech} are given as function of the rotational speed. In the indicator diagrams the value of the pump rod weight (G_{pr}) and pump rod weight + static force ($F_{st} + G_{pr}$) are marked.

4.1 Configuration 02

Force, flow and speed are measured for n=0.1 to 1.47 rps (maximum attainable) in steps of 0.1 rps. The results of the measurements are given in indicator diagrams (annex I-1 to I-13) Out of these measured values the force step peak peak ($\Delta F = F_{max}-F_{min}$) mechanical efficiency (η_{mech}) and the volumetric efficiency (η_{vol}) are calculated. Annexes I-14 to I-18 give the results of ΔF, η_{mech} and η_{vol} versus the rotational speed. The best fitting polynomial approximations have been calculated and are for $0.5 \leq \omega \leq 9.5$.

$$\Delta F = 0.01553\ \omega^2 + 0.565\ \omega + 2.818 \quad [kN]$$

$$\eta_{mech} = 0.00195\ \omega^3 - 0.0358\ \omega^2 + 0.196\ \omega + 0.644 \quad [-]$$

$$\eta_{vol} = 0.0022\ \omega^3 - 0.0437\ \omega^2 + 0.236\ \omega + 0.524 \quad [-]$$

In the force signal two vibrations can be seen with different frequency one in the upward stroke and the other in the downward stroke.

The natural frequency of pump rod and the accelerated water mass (assumed an ideal air chamber behaviour) is:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

$$k = \frac{E_{pr} \cdot A_{pr}}{l_{pr}}$$

$$m = m_{wc} + m_p\ 1/3\ m_{pr}$$

f_o	=	natural frequency	[Hz]
E_{pr}	=	elasticity modulus pump rod	$[N/m^w]$
A_{pr}	=	cross section pump rod	$[m^2]$
l_{pr}	=	length pump rod	[m]
m_{wc}	=	mass water in cilinder	[kg]
m_p	=	mass piston	[kg]
m_{pr}	=	mass pump rod	[kg]

upward stroke

$$k = \frac{2.1x10^{11}.2.02x10^{-4}}{36} = 1.18x10^6 \text{ N/m}^w$$

m = 6 + 3 + 1/3 65 = 30.6 kg

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1.18x10^6}{30.6}} = 31 \text{ Hz}$$

downward stroke

$k = 1.18x10^6$

m = 0 + 3 + 1/3x65 = 24.6 kg

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1.18x10^6}{24.6}} = 34 \text{ Hz}$$

The frequencies found in the upward stroke range from 22 to 25.6 Hz and in the downward stroke from 22.4 to 36.7 Hz.
From this result it can be concluded that the vibrations in the force are caused by the give of the pump rod and accelerated water mass and that a model with lumped parameters can be used for pumps with air chambers.

A strange valve behaviour is observed at rotational speeds above 1.3 rps. A suddenly delay in valve closure and opening angle is found for n<1.3 rps.
Up to now no good explanation can be given for this strange valve behaviour.

4.2 Configuration 07

Force, flow and speed are measured for n=0.1 to n=0.7 rps. The results of the measurements are given in indicator diagrams (annex II-1 to II-5). Out of these measured values the force step peak-peak ($\Delta F = F_{max}-F_{min}$), mechanical efficiency (η_{mech}) and the volumetric efficiency are calculated. Annexes II-6 to II-10 give the results of ΔF, η_{mech} and η_{vol} versus the rotational speed.

The best fitting polynomial approximations have been calculated and are for $0.5 \leq \omega \leq 5$ rad/s.

ΔF	$= 0.168\ \omega^2 + 0.550\ \omega + 3.509$	[kN]
η_{mech}	$= 0.0013\ \omega^3 - 0.141\ \omega^2 + 0.506\ \omega + 0.273$	[-]
η_{vol}	$= 0.010\ \omega^3 - 0.104\ \omega^2 + 0.381\ \omega + 0.489$	[-]

In the force signal a vibration with a circle frequency of ≈ 3.1 Hz is found during upward stroke.

The natural frequency of pump rod and accelerated water mass is

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m^*}}$$

$$m^* = m_{wc} + m_p + 1/3\ m_{pr} + \frac{A_p^2}{A_{rm}} \times l_{rm} \cdot \rho_w$$

l_{rm} = length rising main [m]

ρ_w = density water [kg/m^3]

$$k = \frac{2.1\text{x}10^{11}\text{x}2.02\text{x}10^{-4}}{36} = 1.18\text{x}10^{-6}\ \text{N/m}^2$$

m^* = 1200 kg

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1.18\text{x}10^{6}}{1200}} = 5\ \text{Hz}$$

In this case the computed and measured frequencies are not equal and the lumped parameter model used is not correct. A more sofisticated model has to be used for pumps without air chambers.

5. CONCLUSIONS

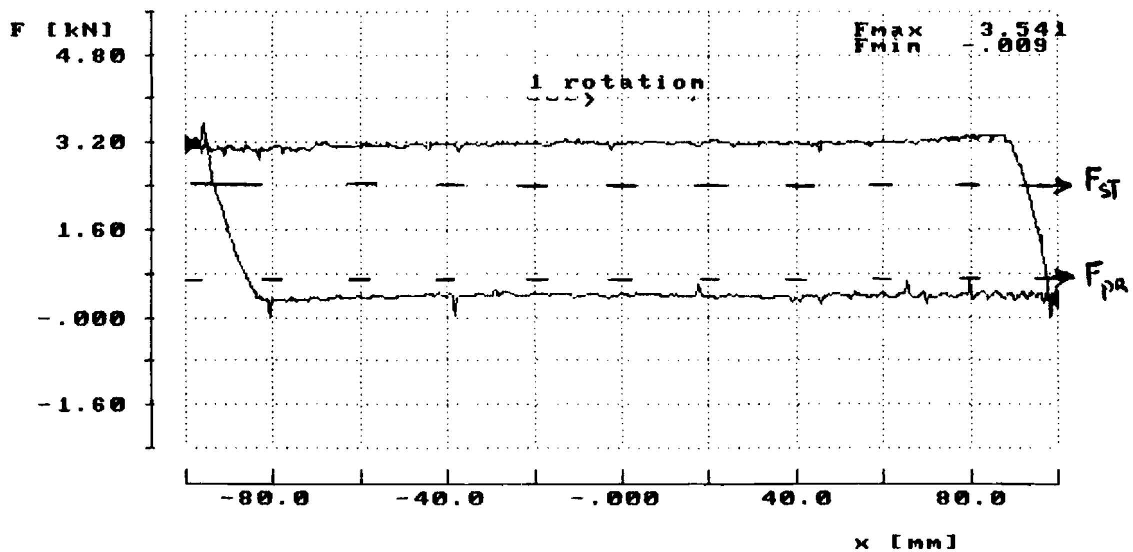
- Using a pump without an air chamber or with a not working air chamber leads to very high forces, see Annex III-3.
- Comparison of the measurements of configuration 02 and 07 shows no differences between the volumetrical and mechanical efficiency, see Annex III I-2.
- If air chambers are used a lumped parameter model can be used to compute pump rod forces.
- If no air chambers are used the lumped parameter model is not correct, a model including waves in pump rod and water colom will probably fit better to the measured results.

filename --> B:P1080227._

Pin [W]:
154.470
Pout[W]:
129.753

Evol :
.912
Emech :
.840

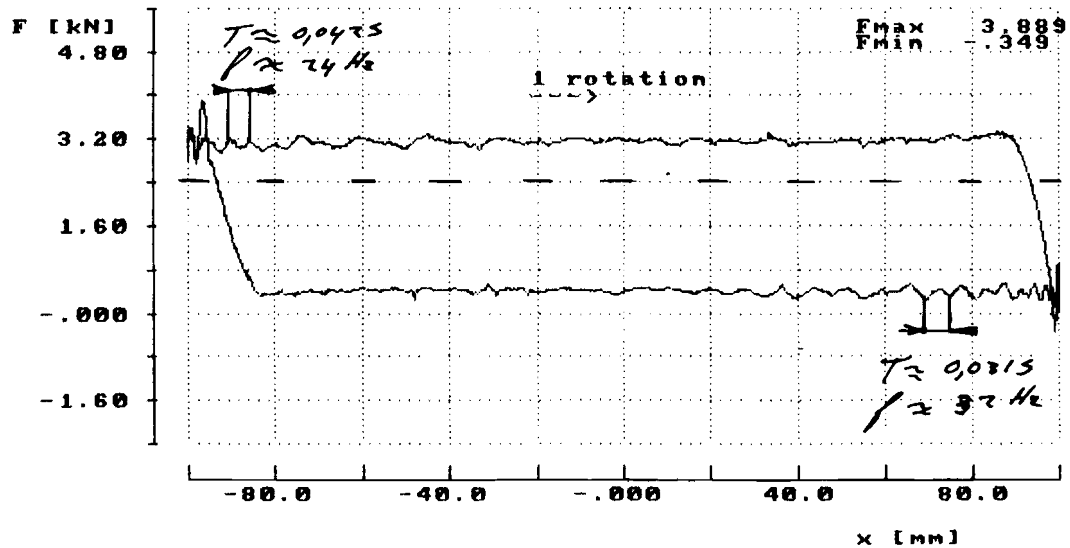
head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2



rotationspeed (rps): .300
meanflow (dm3/s) : .501 sample frequency (Hz): 613.961

2

filename --> B:P1080226._



Pin [W]:
203.971
Pout[W]:
178.175

Evol :
.941
Emech :
.874

head [m] :
26.4
pump [mm] :
100.0
stroke [m]:
.2

rotationspeed (rps): .399
meanflow (dm3/s) : .688 sample frequency (Hz): 817.310

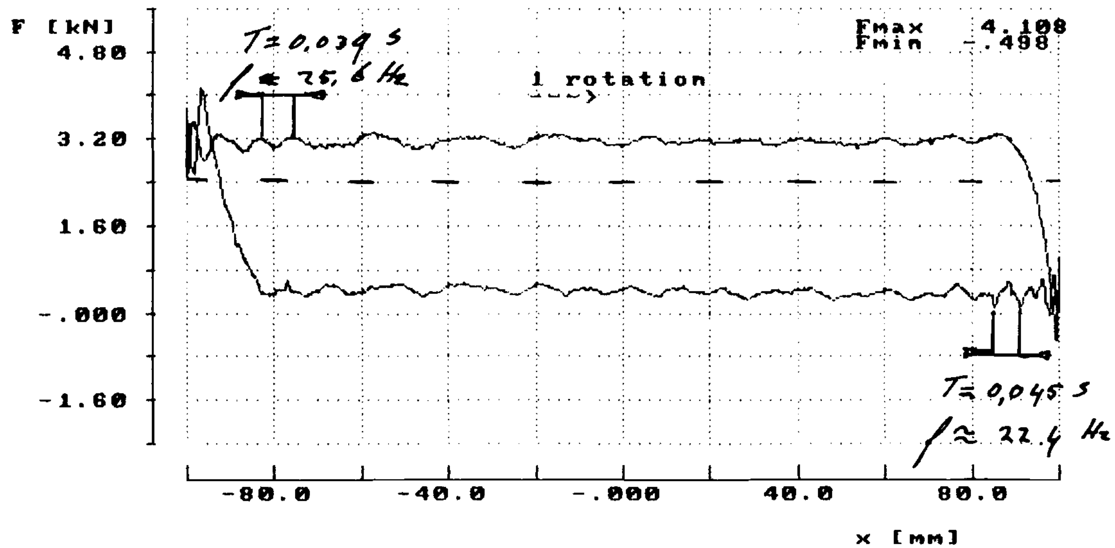
3

filename --> B:P1080225._

Pin [W]:
252.771
Pout[W]:
231.159

Evol :
.978
Emech :
.914

head [m] :
26.4
pump [mm] :
100.0
stroke [m]:
.2



rotationspeed (rps): .498
meanflow (dm3/s) : .893 sample frequency (Hz): 1019.754

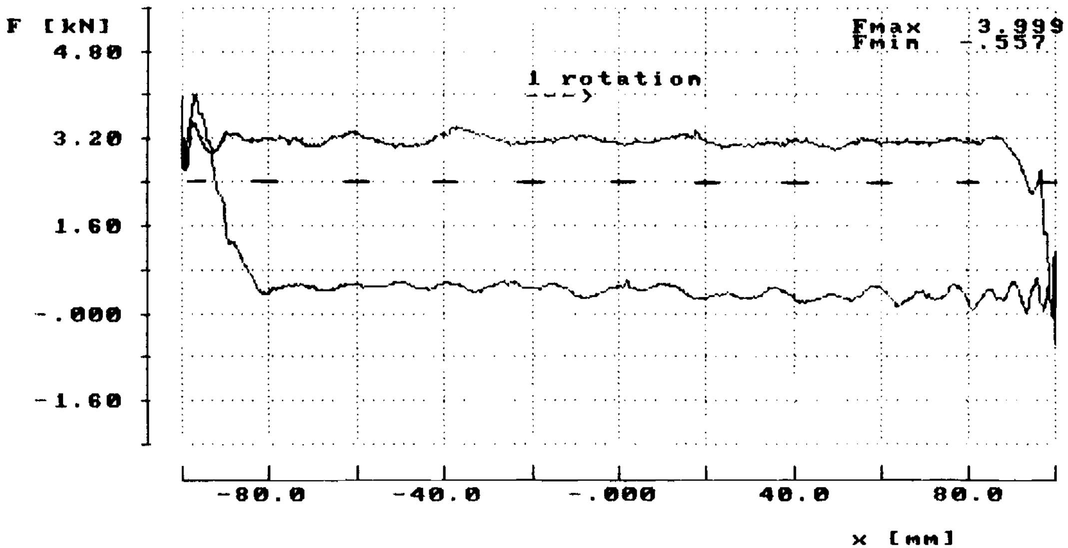
4

filename --> B:P1080224._

Pin [W]:
305.789
Pout[W]:
276.686

Evol :
.971
Emech :
.905

head [m] :
26.4
pump [mm] :
100.0
stroke [m]:
.2



rotationspeed (rps): .601
meanflow (dm3/s) : 1.068 sample frequency (Hz): 1230.031

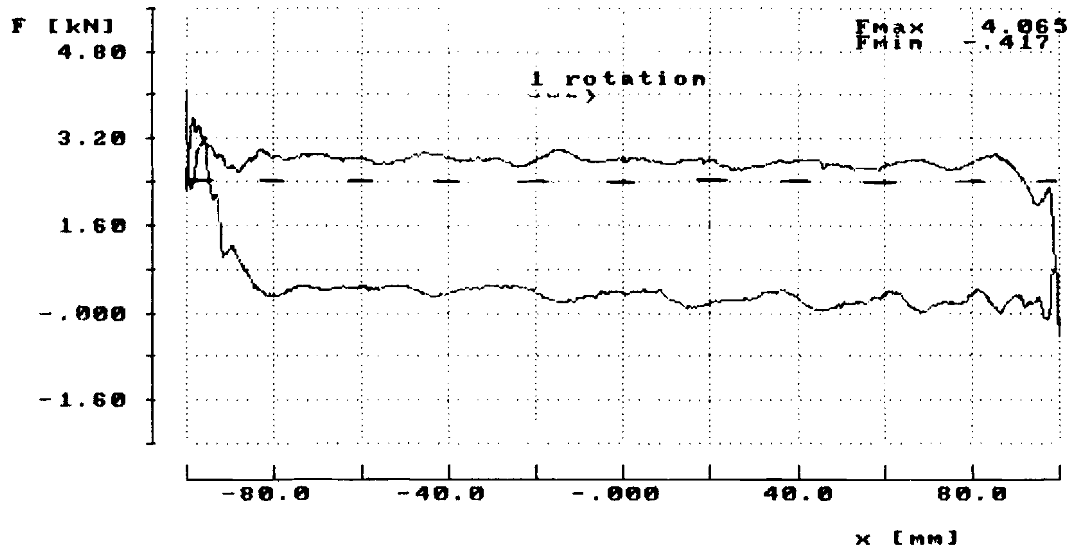
5

filename --> B:P1080223._

Pin [W]:
324.970
Pout[W]:
366.669

Evol :
1.105
Emech :
1.128

head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2



rotationspeed (rps): .700
meanflow (dm3/s) : 1.416 sample frequency (Hz): 1432.777

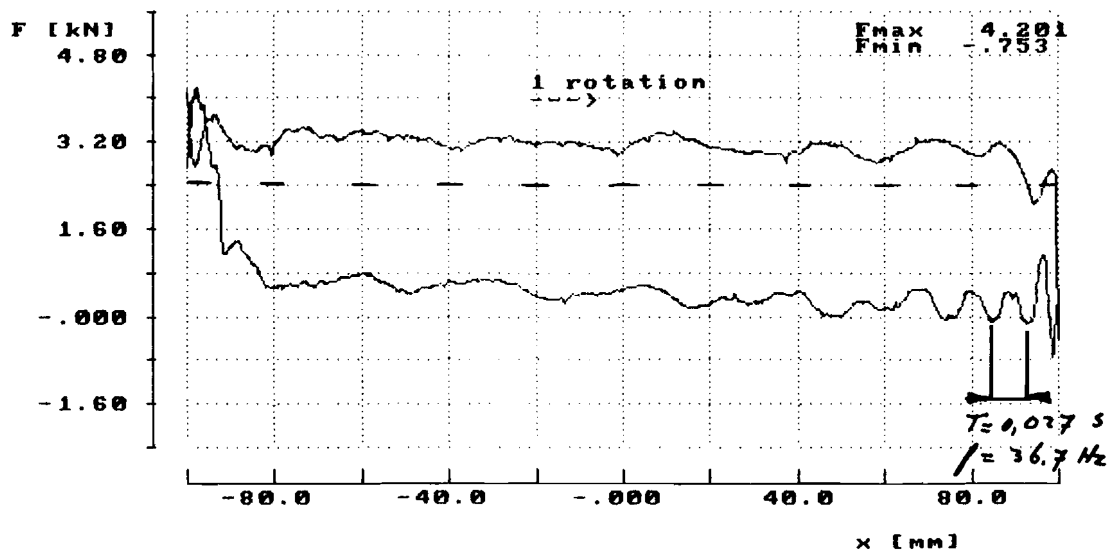
6

filename --> B:P1080222._

Pin [W]:
421.548
Pout[W]:
364.096

Evol :
.941
Emech :
.864

head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2



rotationspeed (rps): .816
meanflow (dm3/s) : 1.406 sample frequency (Hz): 1670.167

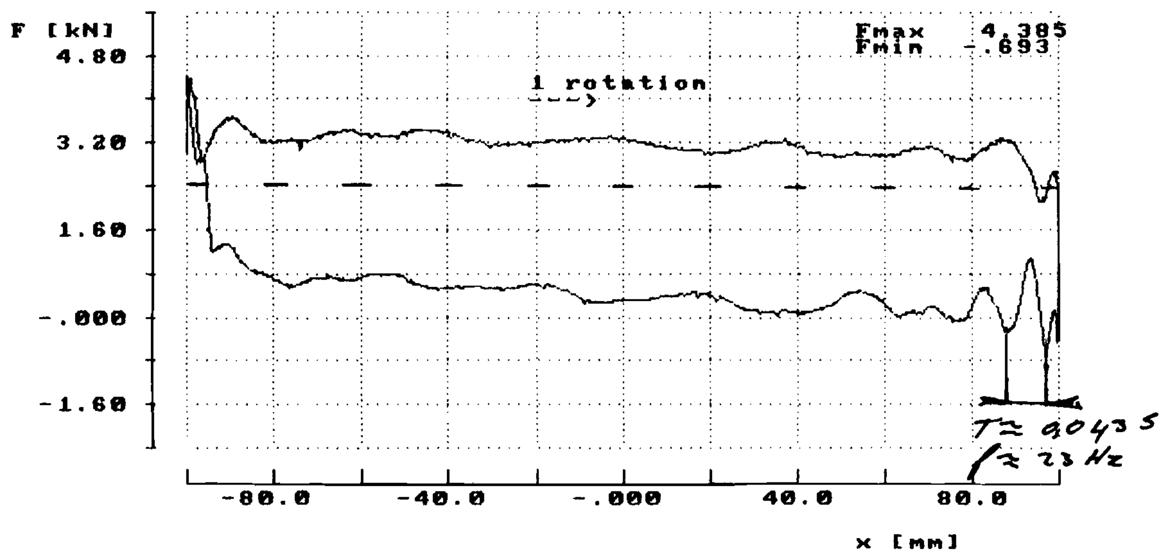
7

filename --> B:P1080221._

Pin [W]:
478.351
Pout[W]:
400.931

Evol :
.939
Emech :
.838

head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2



rotationspeed (rps): .900
meanflow (dm3/s) : 1.548 sample frequency (Hz): 1843.390

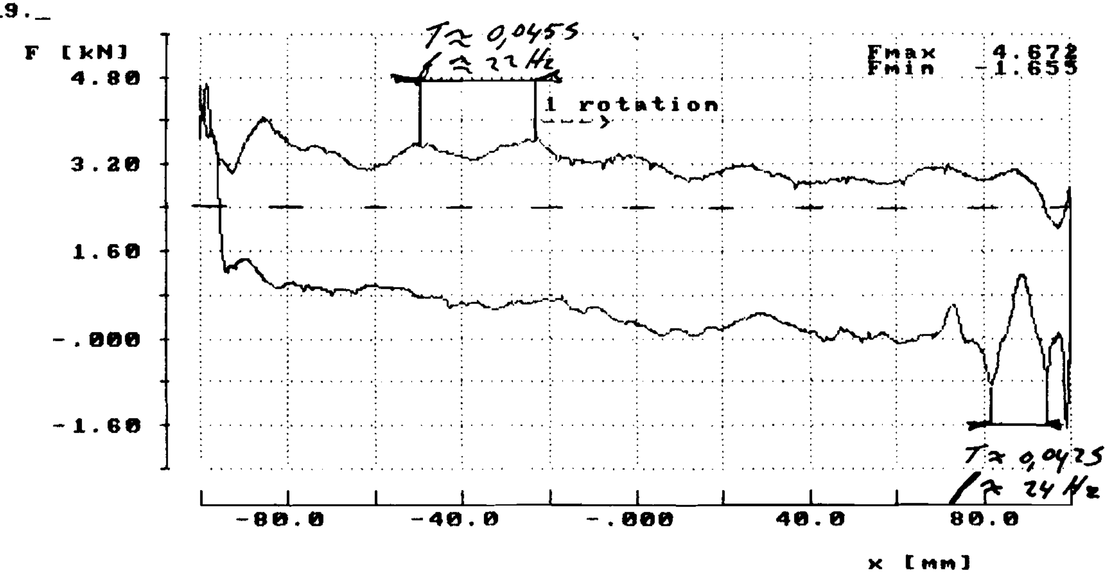
8

filename --> B:P1080219._

Pin [W]:
586.637
Pout[W]:
487.155

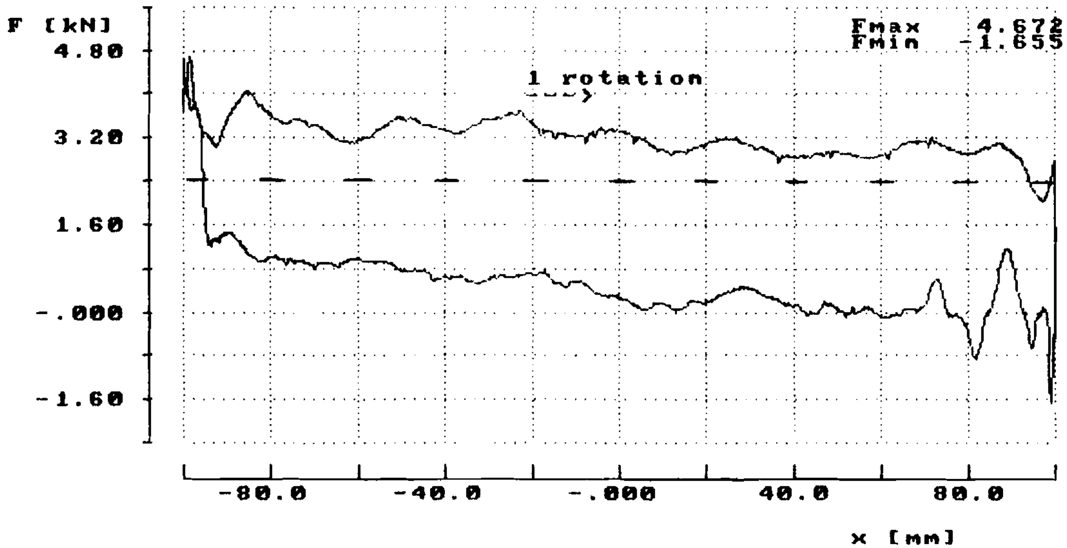
Evol :
1.029
Emech :
.830

head [m] :
26.4
pump [mm] :
100.0
stroke [m]:
.2



rotationspeed (rps): .998
meanflow (dm3/s) : 1.881 sample frequency (Hz): 2043.123

filename --> B:P1080220._



Pin [W]:
586.637
Pout[W]:
487.155

Evol :
.934
Emech :
.830

head [m] :
26.4
pump [mm] :
100.0
stroke [m]:
.2

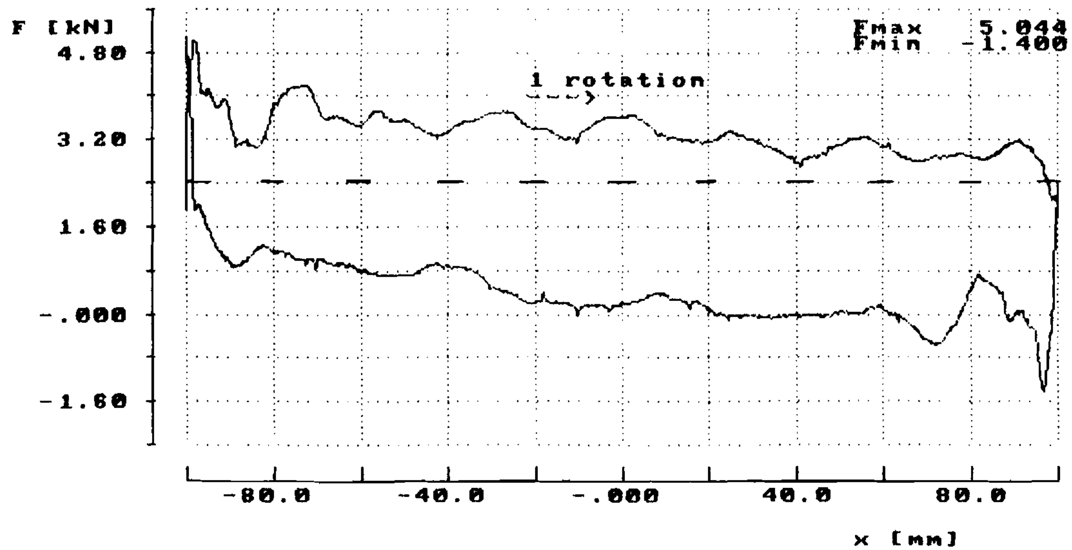
rotationspeed (rps): 1.099
meanflow (dm3/s) : 1.881 sample frequency (Hz): 2251.593

filename --> B:P1080213._

Pin [W]:
699.984
Pout[W]:
548.840

Evol :
.963
Emech :
.784

head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2



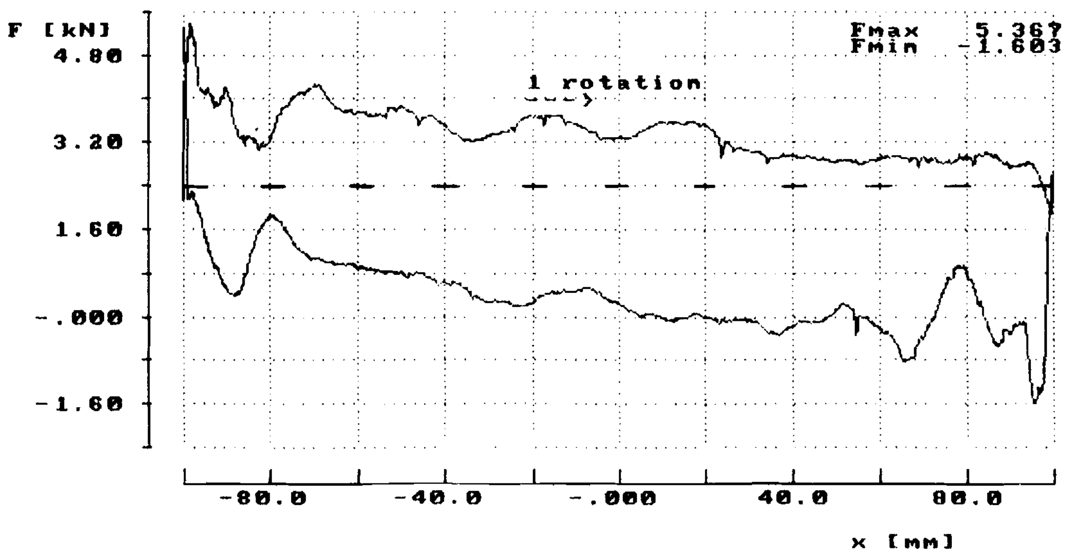
rotationspeed (rps): 1.201
meanflow (dm3/s) : 2.119 sample frequency (Hz): 2459.761

filename --> B:P1080214._

Pin [W]:
774.194
Pout[W]:
585.532

Evol :
.944
Emech :
.756

head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2



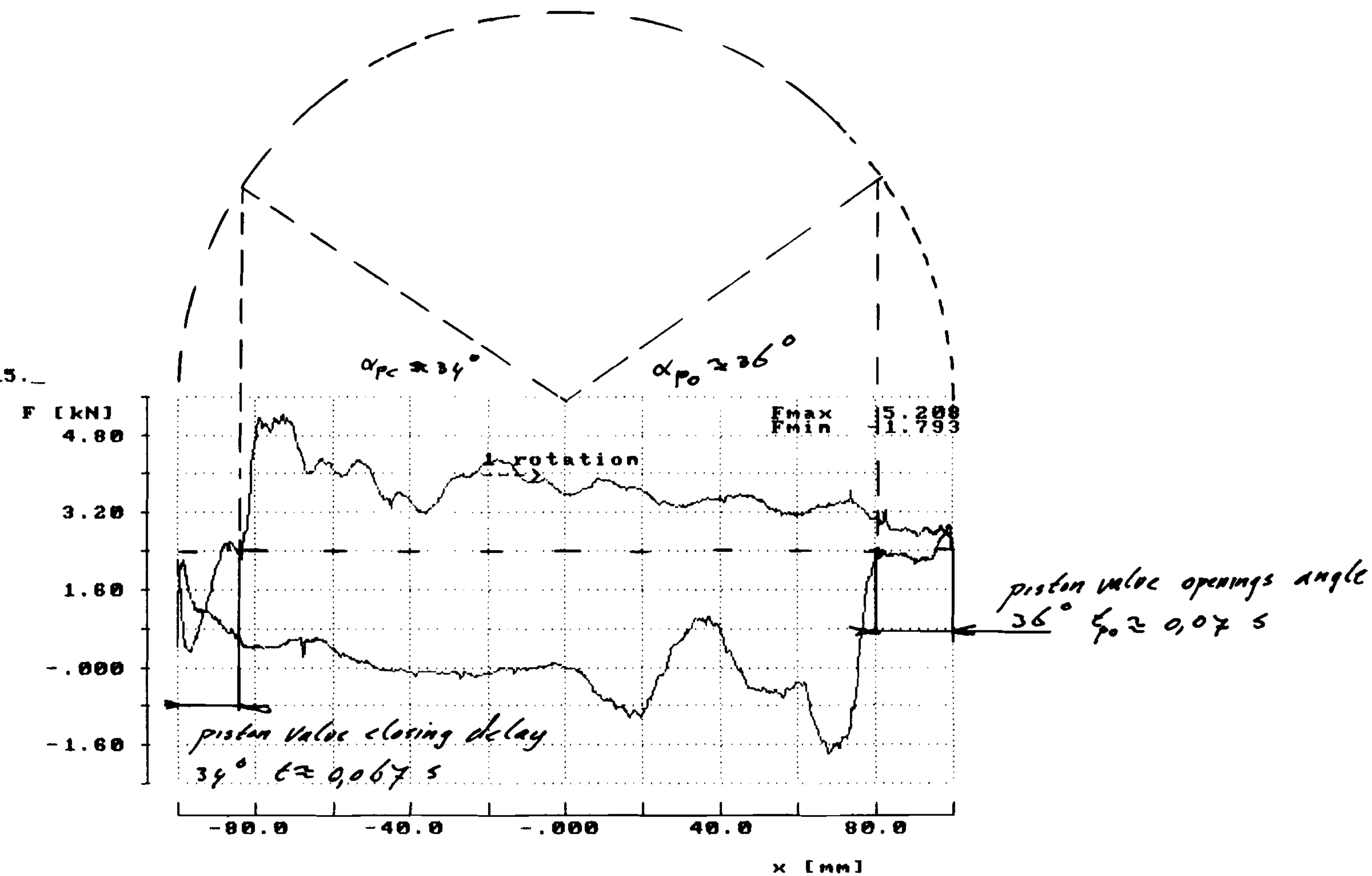
rotationspeed (rps): 1.307
meanflow (dm3/s) : 2.261 sample frequency (Hz): 2676.666

filename --> B:P1080215._

Pin [W]:
894.716
Pout[W]:
625.543

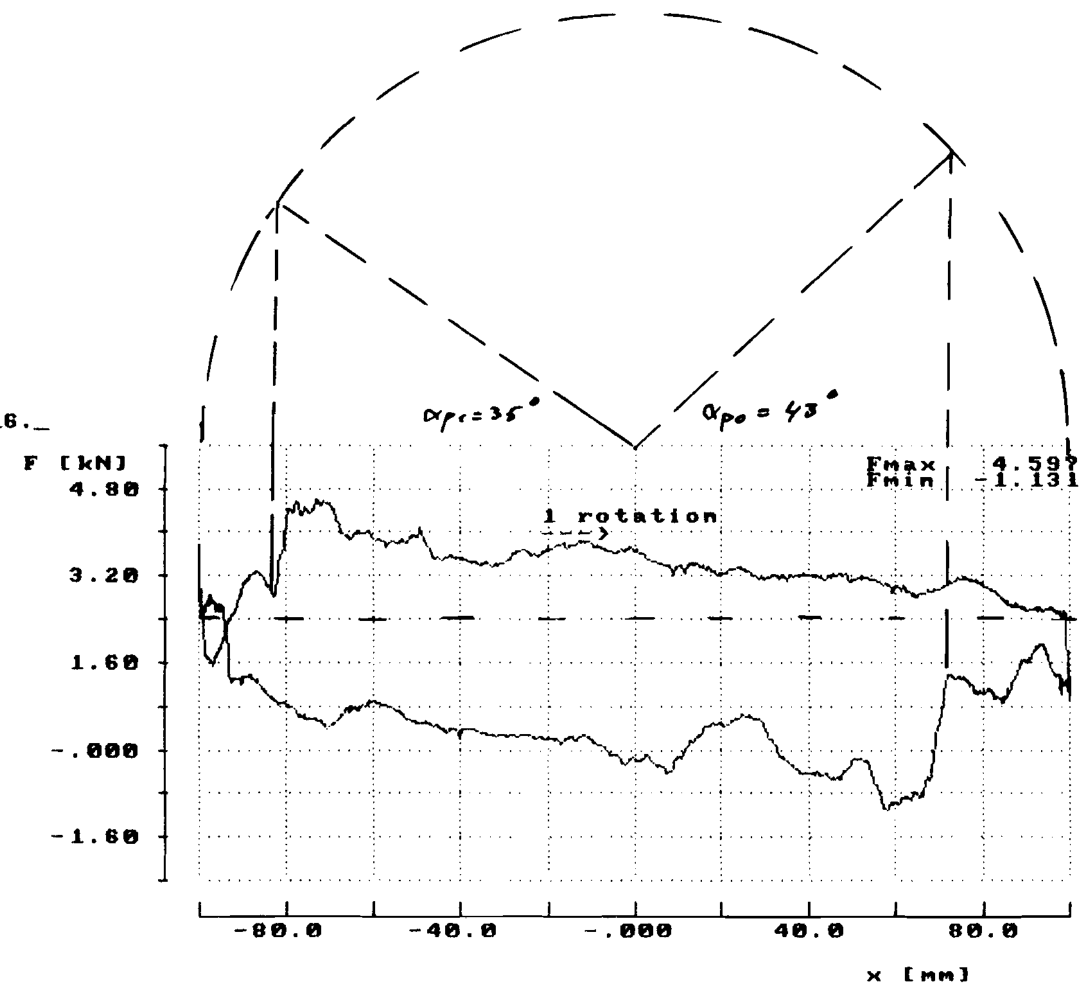
Evol :
.941
Emech :
.699

head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2



rotationspeed (rps): 1.400
meanflow (dm3/s) : 2.415 sample frequency (Hz): 2867.964

filename --> B:P1080216._



Pin [W]:
846.209
Pout[W]:
631.023

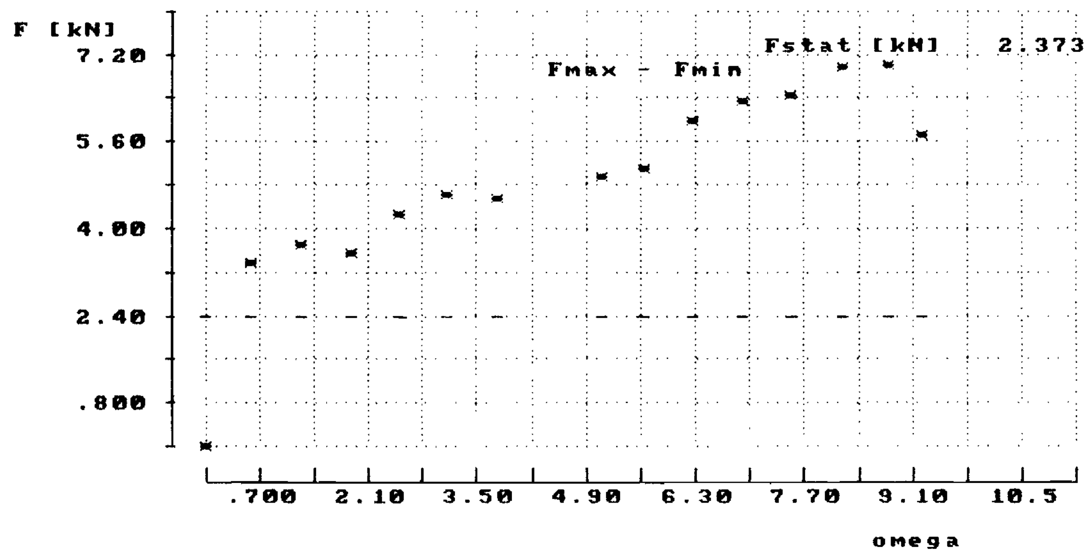
Evol :
.904
Emech :
.746

head [m] :
26.4
pump [mm] :
108.0
stroke [m]:
.2

rotationspeed (rps): 1.471
meanflow (dm3/s) : 2.437 sample frequency (Hz): 3012.567

14

filename --> B:P10802T_

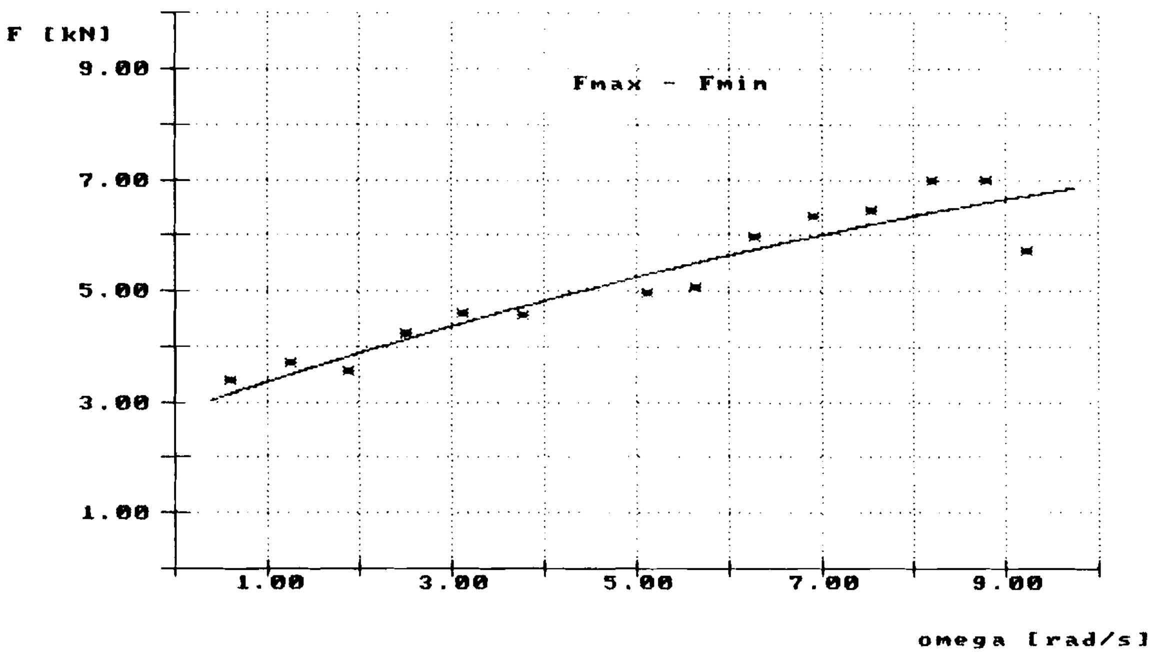


filename --> P1080903_

differences :

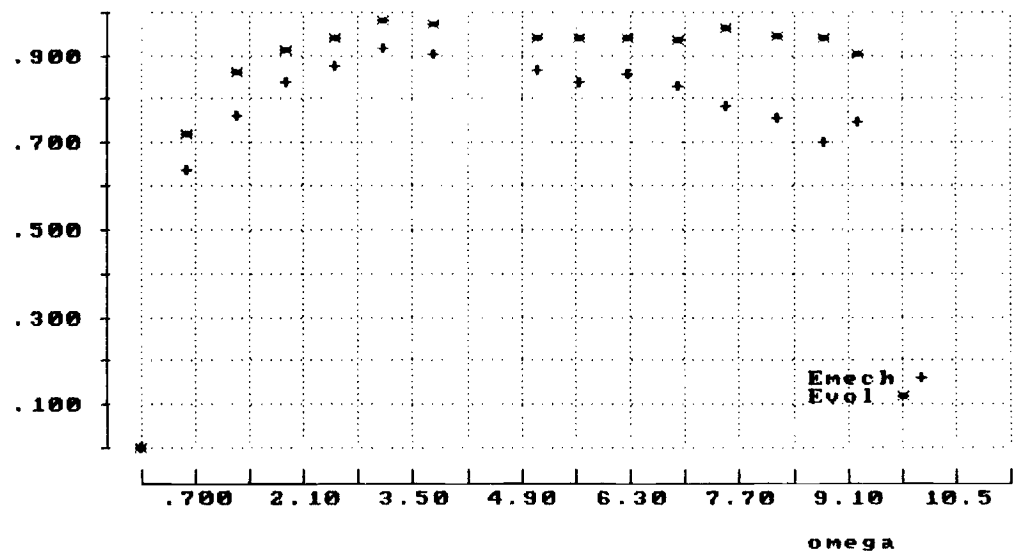
n (rad/s)	%
9.2	17.2
.6	6.9
1.3	5.5
6.3	3.7
6.9	5.5
5.7	8.6
5.1	7.1
1.9	7.8
3.8	3.8
3.1	3.8
2.5	2.4
1.9	7.8

degree
: 2
coefficients
:
-.01553
.56506
2.81776



16

filename --> B:P10802T_

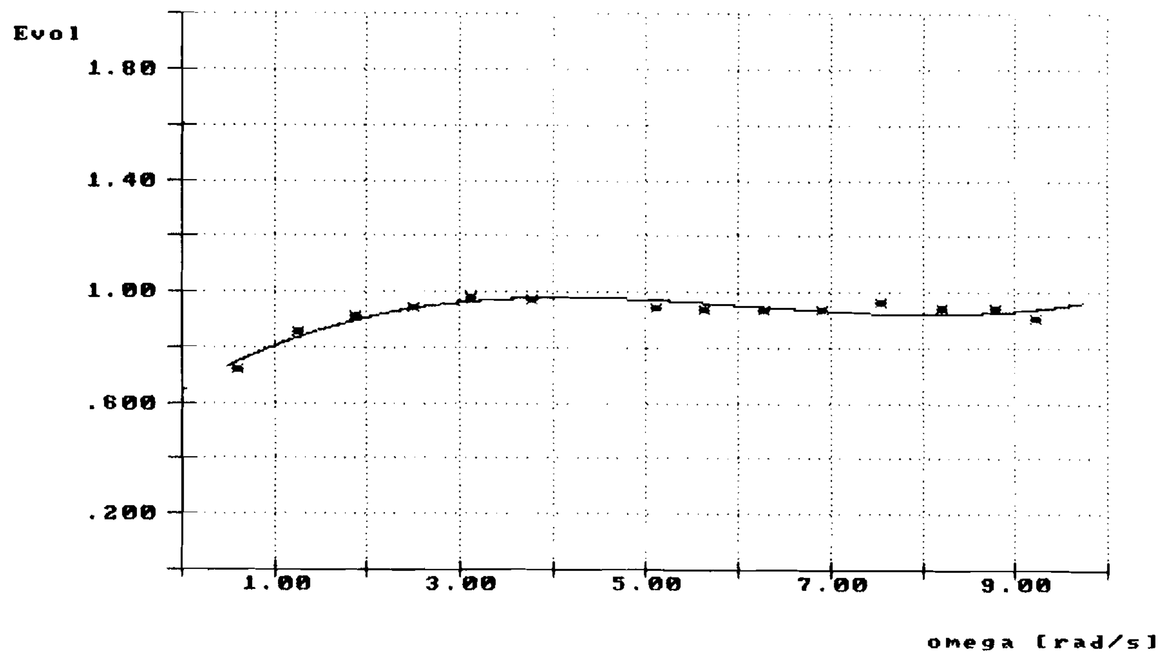


filename --> P1080903_

differences :

n (rad/s)	%
9.2	4.0
.6	4.4
1.3	2.7
6.3	1.0
6.9	.0
5.7	2.3
5.1	3.2
1.9	1.4
3.8	.8
3.1	1.2
2.5	.0
1.9	1.4

degree
: 3
coefficients
:
.00195
-.03579
.19590
.64388

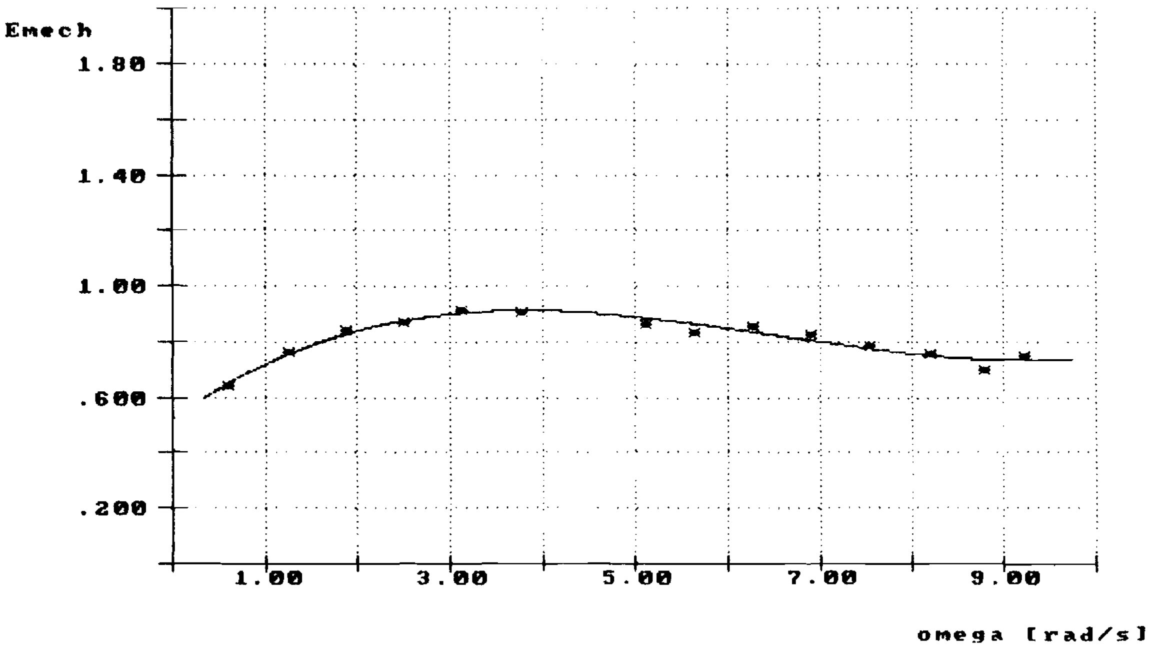


filename --> P1080903_

differences :
n (rad/s) %

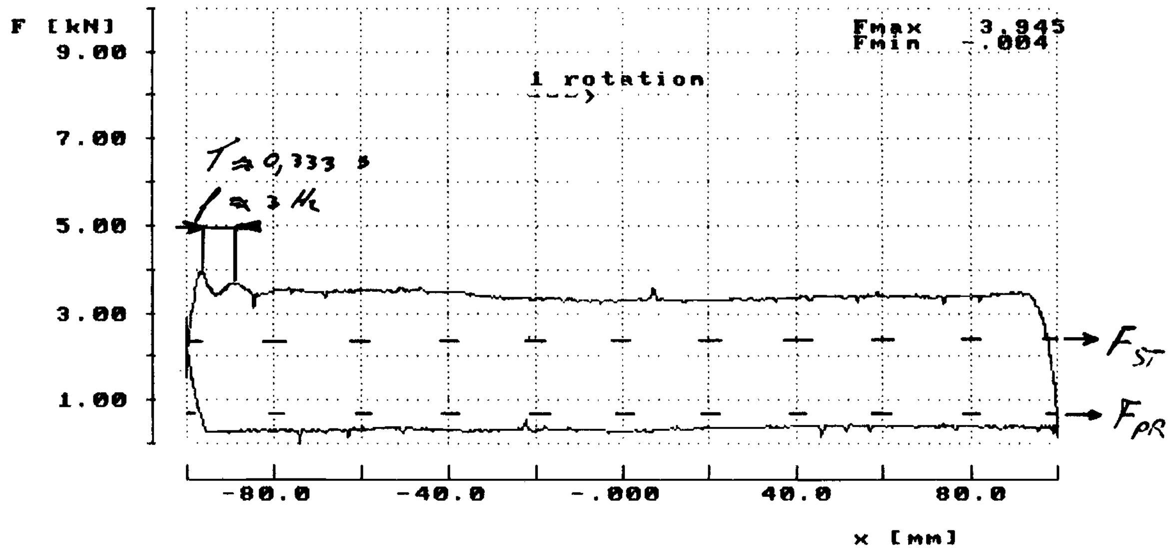
9.2	2.0
.6	2.2
1.3	.8
6.3	2.4
6.9	3.1
5.7	3.3
5.1	2.7
1.9	1.3
3.8	1.0
3.1	1.1
2.5	.4
1.9	1.3

degree
: 3
coefficients
:
.00222
-.04368
.23632
.52445



/

filename --> P1080706._



Pin [W]:
60.201
Pout[W]:
32.353

Evol :
.689
Emech :
.537

head [m] :
26.1
pump [mm] :
108.0
stroke [m]:
.2

rotationspeed (rps): .100
meanflow (dm3/s) : .126 sample frequency (Hz): 204.855

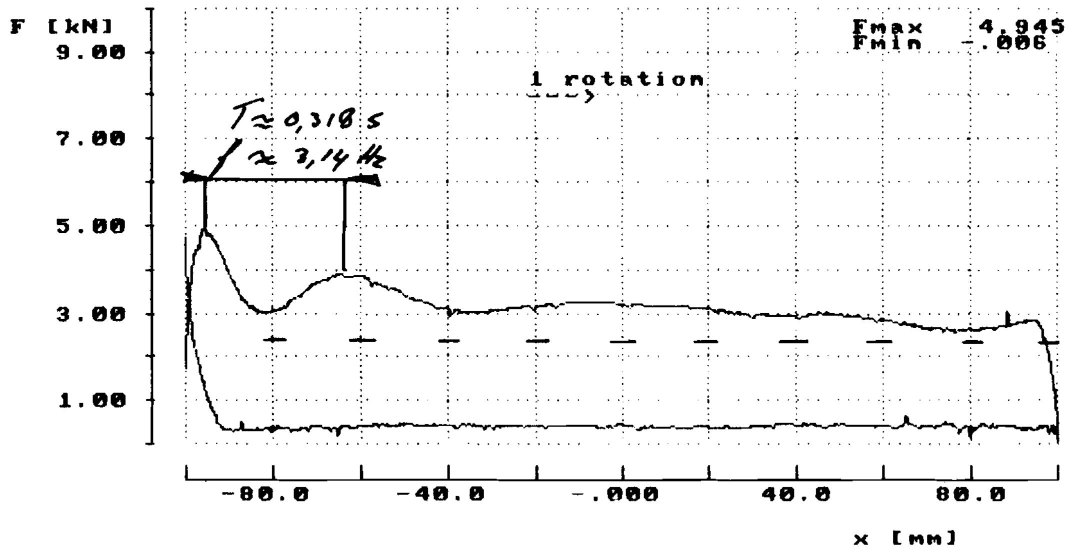
2

filename --> P1080703._

Pin [W]:
160.030
Pout[W]:
141.598

Evol :
1.016
Emech :
.885

head [m] :
26.1
pump [mm] :
108.0
stroke [m]:
.2



rotationspeed (rps): .297
meanflow (dm3/s) : .553 sample frequency (Hz): 608.539

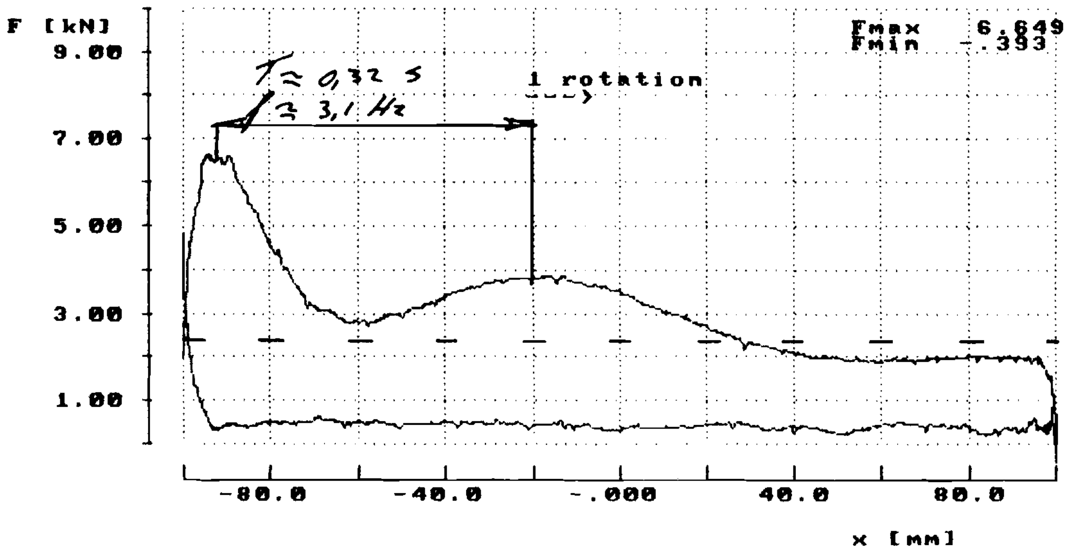
3

filename --> P1080701._

Pin [W]:
261.048
Pout[W]:
236.791

Evol :
1.009
Emech :
.907

head [m] :
26.1
pump [mm] :
100.0
stroke [m]:
.2



rotationspeed (rps): .500
meanflow (dm3/s) : .925 sample frequency (Hz): 1024.273

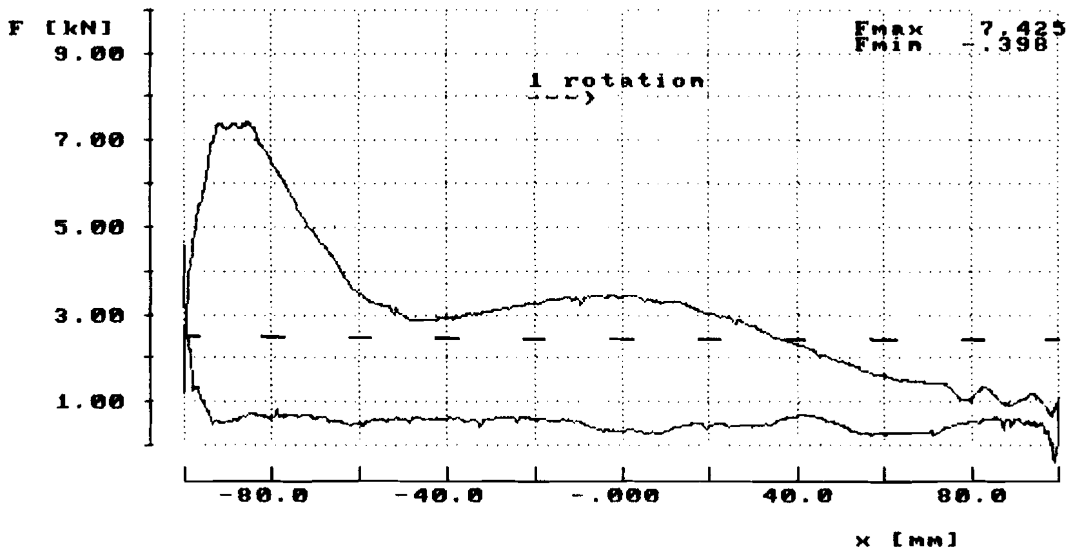
4

filename --> P1080705._

Pin [W]:
311.505
Pout[W]:
271.368

Evol :
.964
Emech :
.871

head [m] :
26.1
pump [mm] :
100.0
stroke [m]:
.2



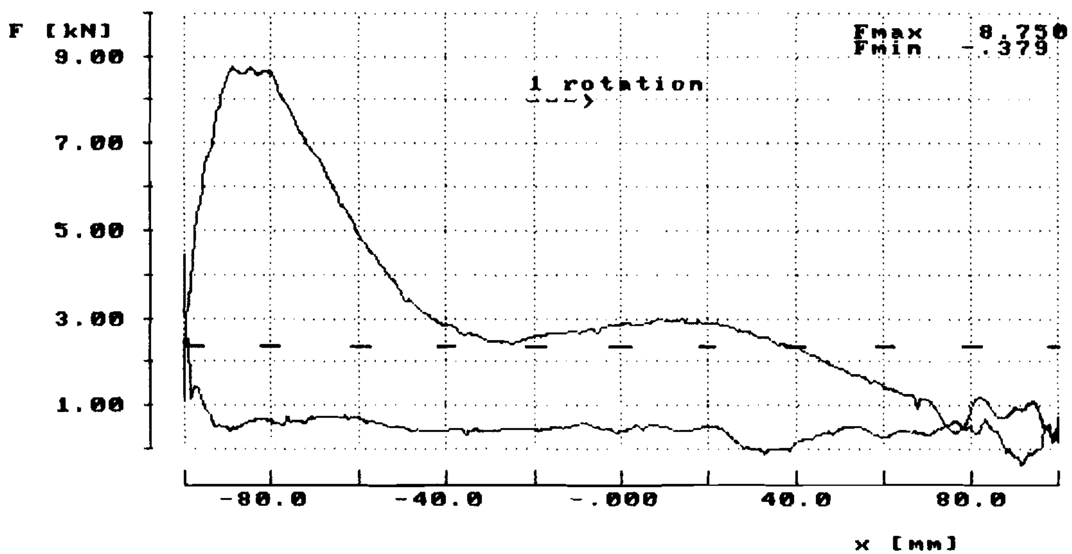
rotationspeed (rps): .600
meanflow (dm3/s) : 1.060 sample frequency (Hz): 1229.127

filename --> P1080702._

Pin [W]:
385.543
Pout[W]:
328.929

Evol :
1.010
Emech :
.853

head [m] :
26.1
pump [mm] :
108.0
stroke [m]:
.2



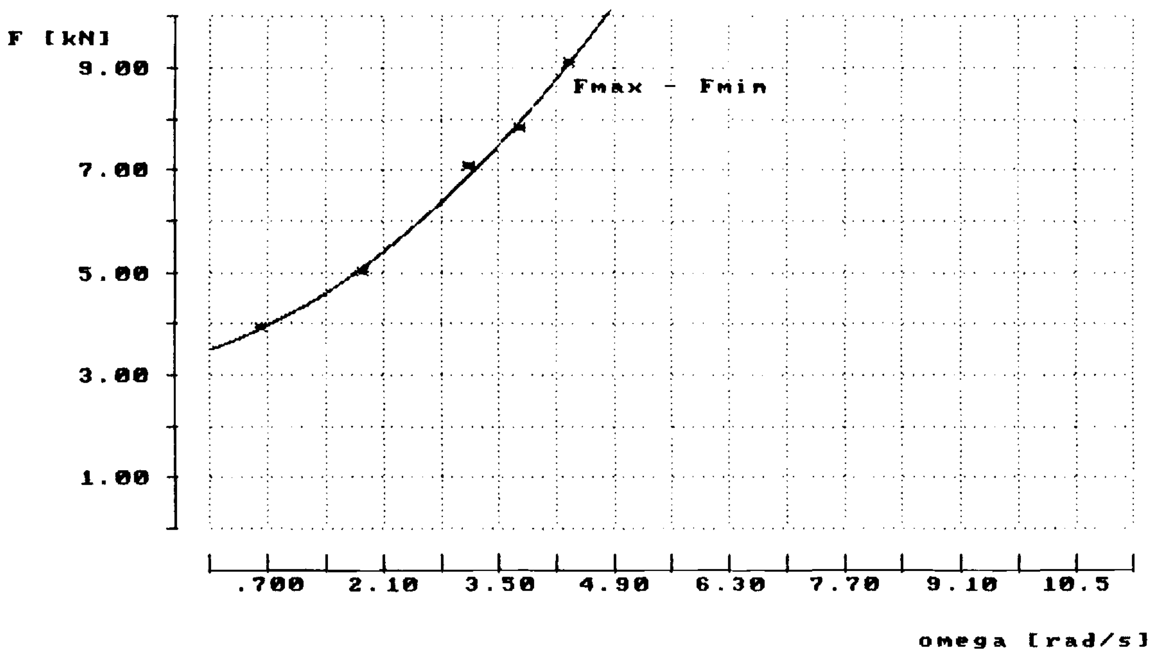
rotationspeed (rps): .694
meanflow (dm3/s) : 1.285 sample frequency (Hz): 1421.932

filename --> B:P10807T_

differences :
n (rad/s) %

.63	.7
1.87	2.0
3.14	2.7
3.77	1.9
4.36	.3

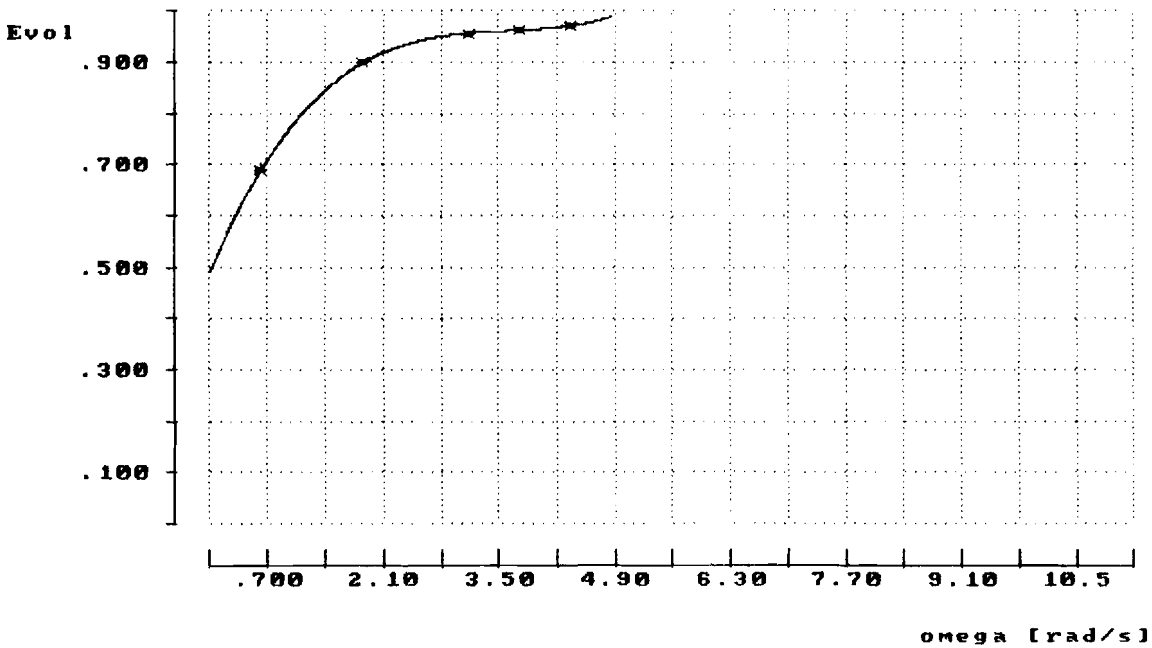
degree
: 2
coefficients
:
.168
.550
3.509



filename --> B:P10807T_

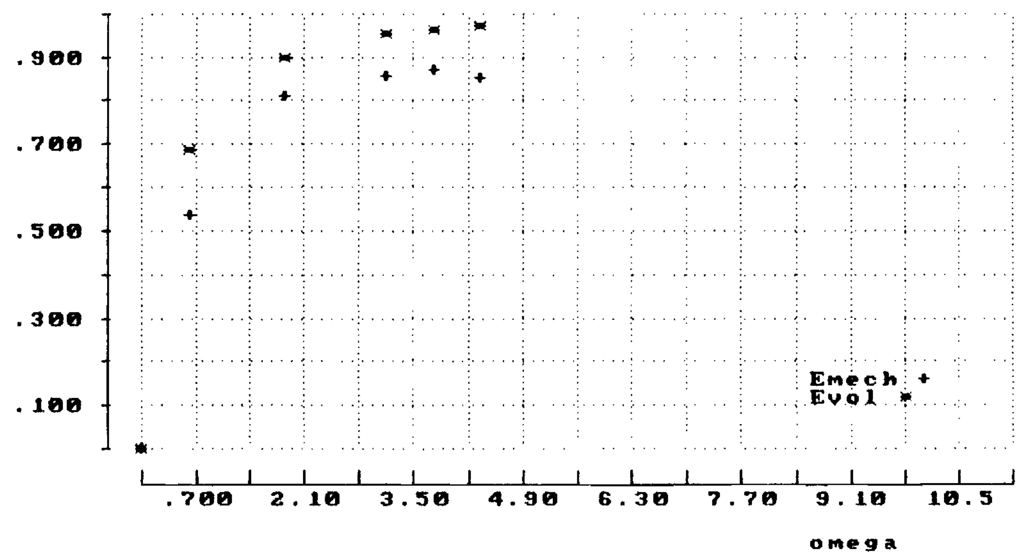
differences :
n (rad/s) %

.63	.0
1.87	.1
3.14	.2
3.77	.2
4.38	.1



degree
: 3
coefficients
:
.010
-.104
.381
.489

filename --> B:P10807T_

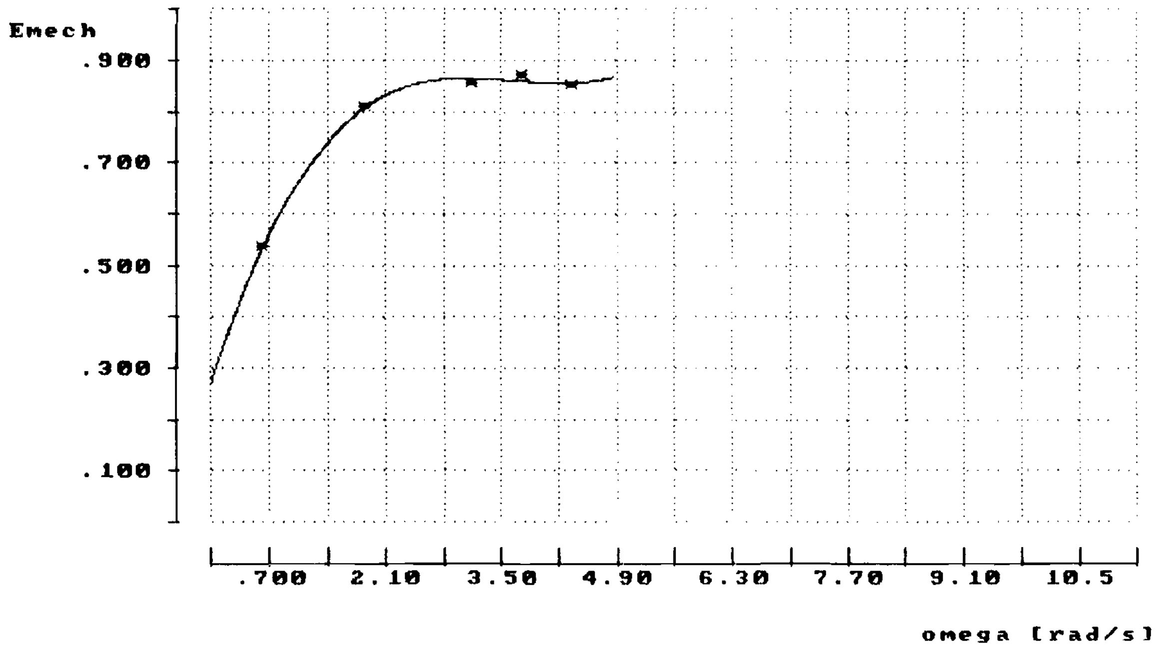


filename --> B:P10807T_

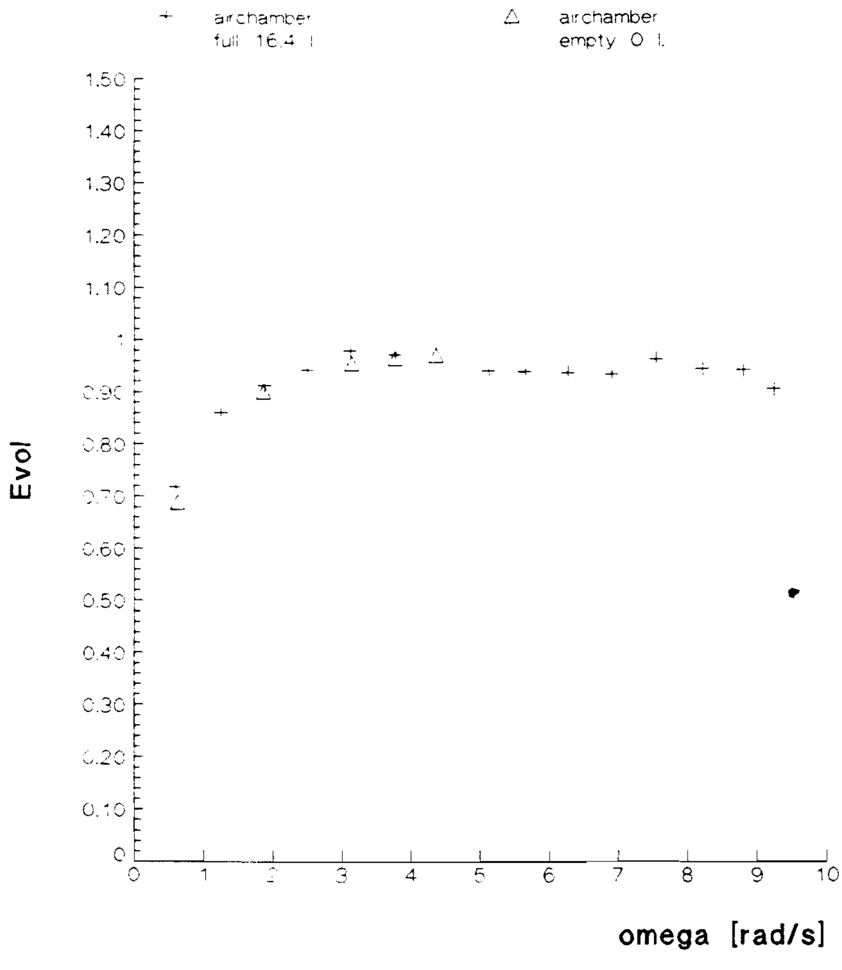
differences :
n (rad/s) %

.63	.1
1.87	.4
3.14	1.2
3.77	1.3
4.36	.4

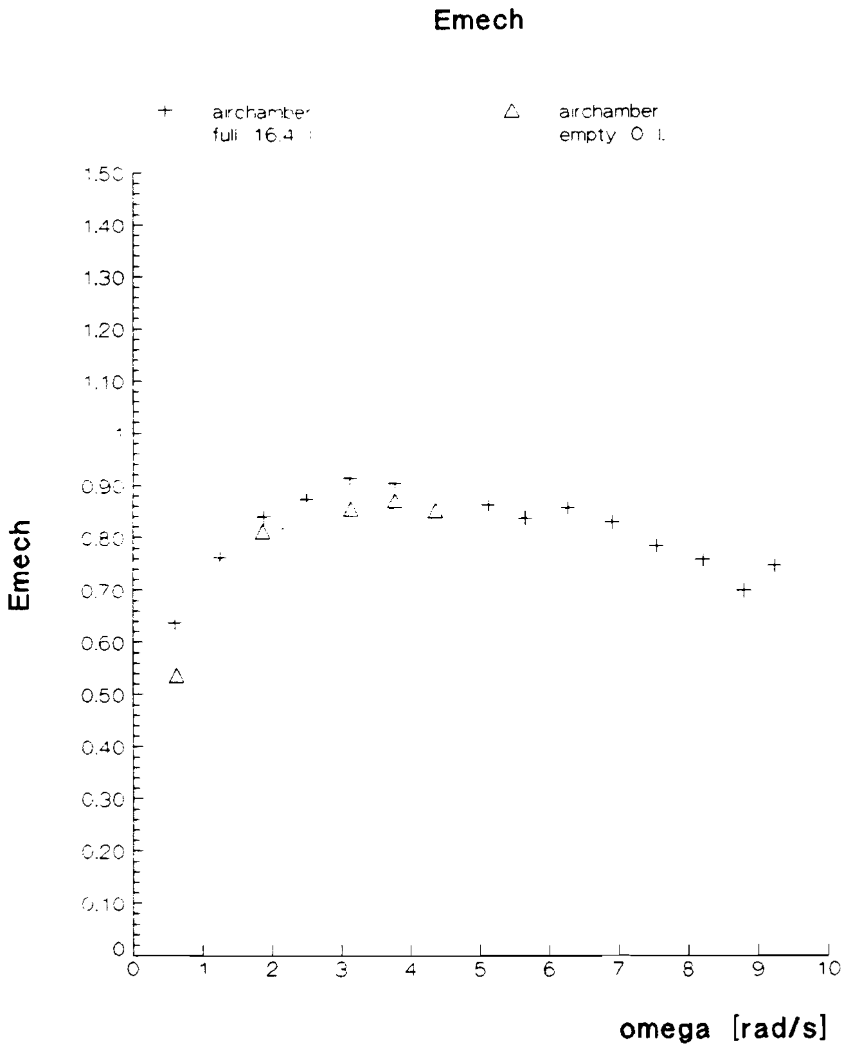
degree
: 3
coefficients
:
.013
-.141
.506
.273

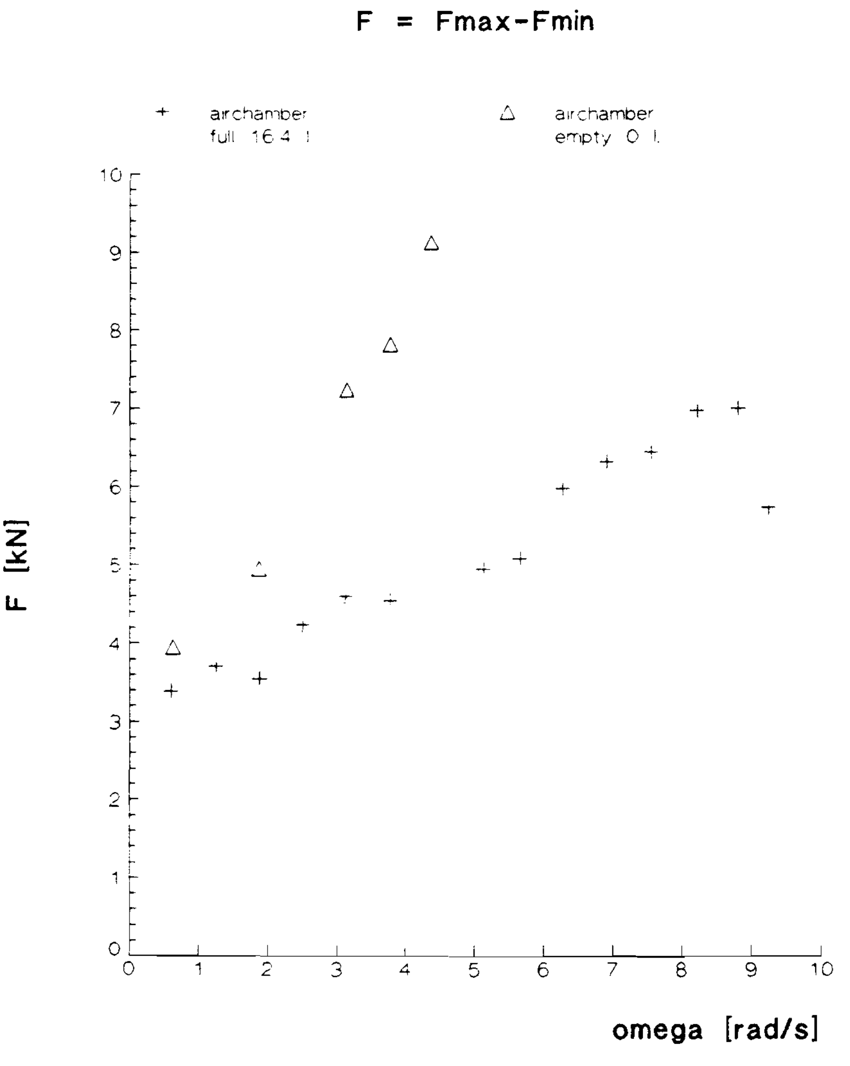


Evol



airchamber full 16.4 l
airchamber empty 0 l.
1.50
1.40
1.30
1.20
1.10
1
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0
Evol
0
1
2
3
4
5
6
7
8
9
10
omega [rad/s]


Emech
airchamber full 16.4
airchamber empty 0
1.50
1.40
1.30
1.20
1.10
1
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0
Emech
0
1
2
3
4
5
6
7
8
9
10
omega [rad/s]


F = Fmax-Fmin
+ airchamber full 16.4 l
△ airchamber empty 0 l.
F [kN]
omega [rad/s]
0
1
2
3
4
5
6
7
8
9
10

ANNEX IV

ANALYSIS OF ERRORS IN MEASURED SIGNALS

Random errors

1. Measured quantities with absolute error

Head:	$H \pm 0.05$	[m]
Stroke:	$s \pm 0.2$	[mm]
Pump diameter:	$D \pm 1$	[mm]
Rotational speed:	$H \pm 0.05$	[m]

2. Signal relative errors

Error in force (F) signal	1% of full-scale output
Error in flow (q) signal	2% of full-scale output
Error in speed (v) signal	1% of full-scale output

3. Hardware relative error

DASH 16 interface 0.01%

The error in calculated quantities is a combination of errors from the measured quantities, signals and hardware.
Two calculated quantities are E_{mech} and E_{vol}. In this case only the relative error has been taken into account. The absolute error can be calculated from the relative error by multiplying the error with the actually calculated or measured quantity.

Relative error: $\frac{\Delta E_{mech}}{|E_{mech}|}$ Absolute error: $\frac{\Delta E_{mech}}{|E_{mech}|} * |E_{mech}|$

Error in E_{mech}:

$$E_{mech} = \frac{\overline{P_{out}}}{\overline{P_{in}}}$$

$$\overline{P_{out}} = \rho g H . \overline{q}$$

$$\overline{P_{in}} = \overline{F.v}$$

First the error in the mean-force, -speed and -flow must be know. After that it is possible to calculate the error in the input/output power.
The speed, flow and force have been sampled into the computer. Each sample has his own error. One measurement exist of 2048 samples. Data in a file on disk is a mean of m measurements. One sample from a measured signal, F (or v, q), is called F_{ij}.

The relative force error is:

$$\frac{\Delta F_{ji}}{|F_{ji}|} = 0.01$$

i = number of measurements, 1 to m

j = sample number, 1 to 2048 per measurement

The means of m measurements reduce the absolute error per sample with a factor $\sqrt{m}$:

$$\overline{F_j} = \overset{m}{\underset{i=1}{\star}} \frac{F_{ij}}{m}$$

$$\Delta\overline{F_j} = \frac{\Delta F_{ij}}{\sqrt{m}}$$

$$\Delta\overline{v_j} = \frac{\Delta v_{ij}}{\sqrt{m}}$$

$$\Delta\overline{q_j} = \frac{\Delta q_{ij}}{\sqrt{m}}$$

The relative error:

$$\frac{\Delta\overline{F_j}}{|\overline{F_j}|} = \frac{\Delta F_{ji}}{\sqrt{m}\,|F_{ji}|}$$

$$\frac{\Delta\overline{v_j}}{|\overline{v_j}|} = \frac{\Delta v_{ji}}{\sqrt{m}\,|v_{ji}|}$$

$$\frac{\Delta\overline{q_j}}{|\overline{q_j}|} = \frac{\Delta q_{ji}}{\sqrt{m}\,|q_{ji}|}$$

The result of this calculation is an average sample $\overline{F_j}$, $\overline{v_j}$ or $\overline{q_j}$ with a relative error which is lower as the relative error of the rough signal.

The mean input power per sample is: $\overline{P_{in\,j}} = \overline{F_j} * \overline{v_j}$.
The total average input power over 2048 samples is:

$$\overline{P_{in}} = \overset{2048}{\underset{j=1}{\star}} \frac{1}{2048} \left[\overline{F_j} * \overline{v_j}\right] = \overline{F * v}.$$

The relative error:

$$\frac{\Delta P_{in}}{|P_{in}|} = \frac{\Delta F}{|F|} + \frac{\Delta v}{|v|}$$

$$\frac{\Delta E_{mech}}{|E_{mech}|} = \frac{\Delta P_{in}}{|P_{in}|} + \frac{\Delta H}{|H|} + \frac{\Delta \bar{q}}{|q|} = \frac{\Delta F}{|F|} + \frac{\Delta v}{|v|} + \frac{\Delta q}{|q|} + \frac{\Delta H}{|H|}$$

$$= \frac{0.01}{\sqrt{m}} + \frac{0.01}{\sqrt{m}} + \frac{0.02}{\sqrt{m}} + \frac{0.05}{H} = 4\left[\frac{0.01}{\sqrt{m}}\right] + \frac{0.05}{H}$$

Error in E_{vol}:

$$E_{vol}: \quad \frac{\bar{q}}{n \triangleright_s} = \frac{\bar{q}}{[D/2]^2 s.n.\pi}$$

$$\frac{\Delta E_{vol}}{|E_{vol}|} = \frac{2\Delta D}{|D|} + \frac{\Delta s}{|s|} + \frac{\Delta n}{|n|} + \frac{\Delta \bar{q}}{|q|}$$

$$= \frac{2}{|D|} + \frac{0.2}{|s|} + \frac{0.001}{n} + \frac{0.02}{\sqrt{m}}$$

In the configurations as described in chapter [3] the relative errors are:

<u>configuration 02/07</u>

$$\frac{\Delta E_{mech}}{|E_{mech}|} = 0.01$$

$$\frac{\Delta E_{vol}}{|E_{vol}|} = 0.026$$