

**TECHNICAL**

**REPORT**

**1990**



**BY : FRANS BRUGHUIS**

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# **TECHNICAL REPORT 1990**

**of the Diever 450**

**by: Frans Brughuis**

**October 1990**



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**FOREWORD**

This technical report is the result of four years of research. It is meant for people of the WOT to develop their knowledge about waterpumping windmills (= windpumps) and especially about the Diever 450 windmill. It is also meant for people in developing countries who have the idea to built the Diever 450. To understand the theory and conceptions which are used in the report the author assumes that the reader has sufficient basic knowledge of wind energy. If this is not the case the author advises to read first the WOT-publication 'wind energy for the third world' (lit.1).

The report reflects the development of the design and the results of the tests on the prototype.

The author is grateful to the people who helped to design the Diever 450, especially to A. de Roest, A. Schaap, C. Vos, S. Vreeland, F. Van Oostrum, J. Andringa, G. Vlogman, B. de Jong, G. Wijbenga and R. van leeuwen.

Frans Brughuis

may 1990

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LIST OF SYMBOLS

symbol	description	unit
$A_{hs}$	side area head	$m^2$
$A_p$	piston area	$m^2$
$A_{pr}$	area of the pumprod	$m^2$
$A_{pri}$	area of the pumprod iron	$m^2$
$A_{proj}$	projected area	$m^2$
$A_r$	rotor area	$m^2$
$A_{rm}$	area of the rising main	$m^2$
$A_{rs}$	side area rotor (= 7,5% of $A_r$ )	$m^2$
B	number of blades	
c	corde	m
$C_d$	drag coefficient	
$C_l$	lift coefficient	
$C_p$	power coefficient	
$C_Q$	torque coefficient	
$C_{Qstart}$	starting torque coefficient	
$D_r$	rotor diameter	m
F	force	N
$\bar{F}$	admissible force	N
$F_{peak}$	peak force in the pumprod	N
$F_{pr}$	pumprod force	N
H	waterlifting head	m
l	blade length	m
$l_k$	buckling length	m
P	power	W
$P_{out}$	power output	W
$P_r$	mechanical power of the rotor	W
$P_{wind}$	power input	W
Q	torque	Nm
$Q_{start}$	starting torque	Nm
r	local radius	m
$R_r$	rotor radius	m
$R_c$	crank length	m
$R_K, R_L,$	reaction forces in	
$R_M, R_N$	K, L, M and N	N
s	stroke length	m

$v$	windspeed	m/s
$v_d$	design windspeed	m/s
$v_{max}$	maximum windspeed	m/s
$v_r$	rated windspeed	m/s
$v_{start}$	starting windspeed	m/s
$v_{tip}$	tipspeed	m/s
$\alpha$	angle of attack	
$\beta$	blade angle	
$\gamma$	angle between actual position of main vane and its rest position	
$\delta$	angle of yaw (between rotor axis and wind direction)	
$\epsilon$	angle between hinge axis and vertical axis	
$\phi$	angle between rotor plane and relative flow speed	
$\lambda$	tipspeed ratio	
$\lambda_d$	design tipspeed ratio	
$\lambda_r$	local speed ratio at radius $r$	
$\eta_{hydr}$	hydraulic efficiency of the pump installation	
$\eta_{inst}$	efficiency of the pump installation	
$\eta_{mech}$	mechanical efficiency of the pump	
$\eta_{tot}$	total efficiency of the windpump	
$\eta_{tr}$	efficiency of the transmission	
$\eta_{vol}$	volumetric efficiency of the pump	
$\Omega$	rotor angular speed	rad/s
$\rho_a$	density of air	kg/m <sup>3</sup>
$\rho_c$	density of concrete	kg/m <sup>3</sup>
$\rho_w$	density of water	kg/m <sup>3</sup>
$\sigma$	stress	N/mm <sup>2</sup>
$\bar{\sigma}$	admissible stress	N/mm <sup>2</sup>
$\sigma_e$	equivalent stress	N/mm <sup>2</sup>
$\sigma_{min}$	minimum stress	N/mm <sup>2</sup>
$\sigma_{max}$	maximum stress	N/mm <sup>2</sup>
$\sigma_v$	surface stress	N/mm <sup>2</sup>
$\tau$	shear stress	N/mm <sup>2</sup>
$\omega$	buckling factor	

## CHAPTER 1 INTRODUCTION

In 1979 the WOT designed the 12PU500 windmill. This windmill is built in India, Indonesia, Bolivia, China, Tanzania and other countries.

After seven years of experiences, in 1986, it was clear that the 12PU500 design could be improved to get more output and a longer life-time.

Therefore the WOT decided to redesign the windmill which resulted in a new windmill, the 18PU450, also called the Diever 450. Diever is the surname of our oldest and most loyal member.

### 1.1 The 12PU500 windmill

The 12PU500 windmill is a waterpumping windmill. It has an horizontal-axis rotor with 12 blades and a diameter of five meters. The tip-speed-ratio  $\lambda$  (= tip-speed of the rotorblades divided by the wind-speed, see lit. 1) is two. The tower is a welded construction of angle-irons and at the top a pipe of 4", the towerpipe. The tower has a height of six meters. The tail of the head construction carries a windvane which turns the head around the towerpipe in order to keep the rotor perpendicular to the wind. The safety system is half-automatic. In case of a severe storm it will unlock automatically the head from the tail after which the head and rotor turns out of the wind. After the storm the rotor must be

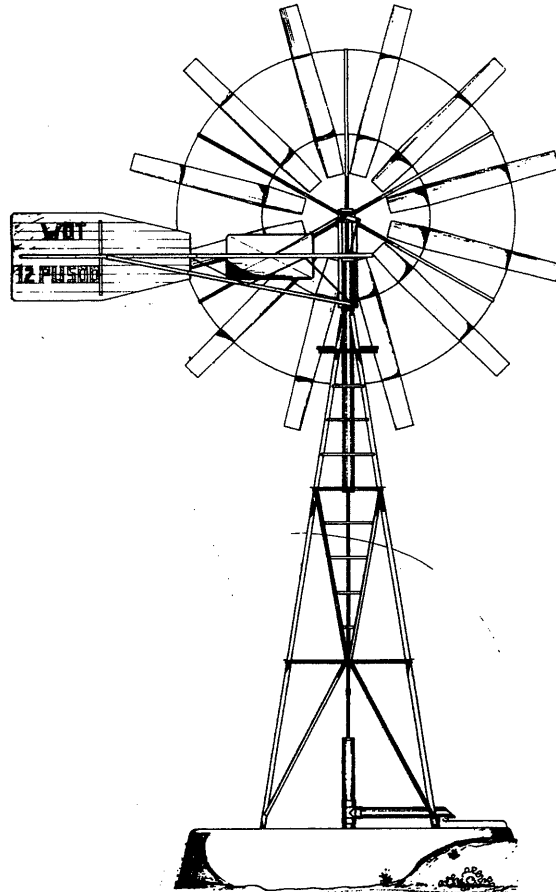


figure 1.1: the 12PU500 windmill

put perpendicular to the wind by hand.

The pump is a single-acting piston pump which consists of a piston and two valves, one valve in the piston (pistonvalve) and one lower valve (footvalve), see lit. 1. The pump has airchambers to smooth the flow and to reduce the shock forces in the pumprod.

The total weight of the windmill is 400 kg and the material costs in the Netherlands are about US\$ 600,-.

For more information about the 12PU500 see lit.2 and 3.

### 1.2 The evaluation of the 12PU500 windmill

In 1986 the WOT evaluated the 12PU500 with help of reports of T. Meyer, Rakish and Majithia from India and J. Keuper from Indonesia and with help of the experiences on the testfield of the WOT. Especially the evaluation report of 155 installed 12PU500 windmills by mr. Rakish is very detailed and accurate and therefore helpful.

The conclusions of the evaluation (from mr. Rakish) were:

- Feasibility studies are very important before starting to introduce windmills.
- The quality of the iron profiles is often bad in developing countries. Pipes aren't circular, angle-irons aren't straight, the strength of the iron materials is small, etc.
- The axis of the rotor isn't horizontal but a little bit sloping (70% of the windmills).
- The blade supports (100% of the windmills) and the blade tips (30%) are cracked.
- There is too much or to little play between the head and the towerpipe (70%).
- Sometimes high windspeeds lift the head and rotor from the towerpipe.
- The safety system is wrong constructed or installed (80%), the teeth of the toothed handle wear out too much.
- The transmission: the crank is welded obliquely the crankpin is bolted obliquely to the crank the crank bearing and the crosshead bearing have too much

play

the wooden crosshead swells because of rainwater and sticks inside the towerpipe

the crosshead wears out because the towerpipe is unround or has a rough inner wall

the crank is not removable

the crankholes are eccentric.

- The pump: the airchambers leak often by leaking welds or washers

the washers dry up and start to leak

the bronze bushes for guiding the pumprod wear out

the wooden piston swells in the water and sticks inside the pumpcylinder

the piston wears out too fast

bad axial alignment of the pumpcylinder and the rising main.

Other conclusions of the evaluation:

- The tower is difficult to transport.
- The tower is too low.
- The pumprod bents and rubs against the rising main.
- The safety system must be full-automatic. That means that the rotor turns back in the wind after the storm.
- Nylon for the bearings and sesame-wood for the cross-head is difficult to obtain.
- The air escapes slowly out of the airchambers. when the airchambers are full of water the shock forces in the pump rod increase much.
- The yaw bearing (head-towerpipe) is iron on iron. It wears out when it has no frequent lubrication.
- The windmill is too expensive for poor farmers with less than 1,25 ha. land.
- There is no interest of the local people when there isn't sufficient guidance and participation.

### 1.3 The requirement list

With help of the results of the evaluation a new list of requirements is made:

General: - long-life, for replaceable parts a minimum life of two years, for the rest minimum of fifteen years  
 - the whole windmill transportable on a roofrack of a cross country car like landrover.

Materials: - an efficient use  
 - easily available  
 - not too expensive.

Manufacturing: - possible in a simple workshop ( electric welding appliance, drill machine, a simple lathe and hand tools)  
 - the dimensional accuracy of the design not too high.

Rotor: - a lower tipspeed ratio  
 - not too heavy so that it is possible to pull it up by hand (not heavier than the rotor of the 12PU500)  
 - stronger blade tips and supports  
 - high power-coefficient  $C_p$   
 - high starting torque (starting windspeed  $v_{start}$  low).

Safety system: - limiting the axial forces on the rotor  
 - limiting the rotation speed of the rotor  
 - full-automatic  
 - 100% dependable.

Head: - avoiding that the head lifts from the tower  
 - the yaw bearing not iron on iron.

Transmission: - avoiding high shock forces in the pumprod  
 - no wooden cross-head in the towerpipe  
 - an alternative for nylon bearings  
 - a crank which is strong enough and easy to make the crankpin parallel to the rotor shaft)  
 - the construction strong enough with a fatigue load.

Pump: - simple construction (no airchambers)  
 - the piston not made of wood  
 - no guiding of the pumprod  
 - the construction strong enough with a fatigue load  
 - pumpcylinder and rising main easily to align

- high efficiency.

Tower: - higher than 6 meters

- construction strong enough for a windspeed of 12 m/s and the rotor perpendicular in the wind and for a windspeed of 40 m/s and the rotor out of the wind
- possible to install by hand.

The redesign of the 12PU500 is done by a group of ten people, see foreword. The windmill design was separated in five parts, namely:

- the rotor
- the safety system and head construction
- the transmission
- the pump
- the tower

(see next chapters)



## CHAPTER 2. THE ROTOR

### 2.1. The rotor dimensions

The code 12PU500 means that the rotor has a diameter of 500 cm and 12 blades and is coupled to a pump unit.

The blades of the 12PU500 windmill are made of steel sheet of 1 mm thick and have a length of 2 m. One of the conclusions of the evaluation was that the blades are too long. At storms the tips and the inner part can collapse and crack. To avoid this we can make a third ring to support the blades but this will make the construction too heavy and more expensive. A better solution is to choose the length of the blades shorter. The standard measurements of steel sheet are 1x2 m. We chose a new blade length of 1 m so that the blades can be cut out of the steel sheet efficiently. With the same construction of the rings and spokes the rotor diameter became smaller, namely 4,5 m (450 rotor). A shorter length of the blades has the advantage that a smaller sheet roller can be used to make the bent blade profile. The disadvantage is the loss of power because of the 'hole' in the center of the rotor.

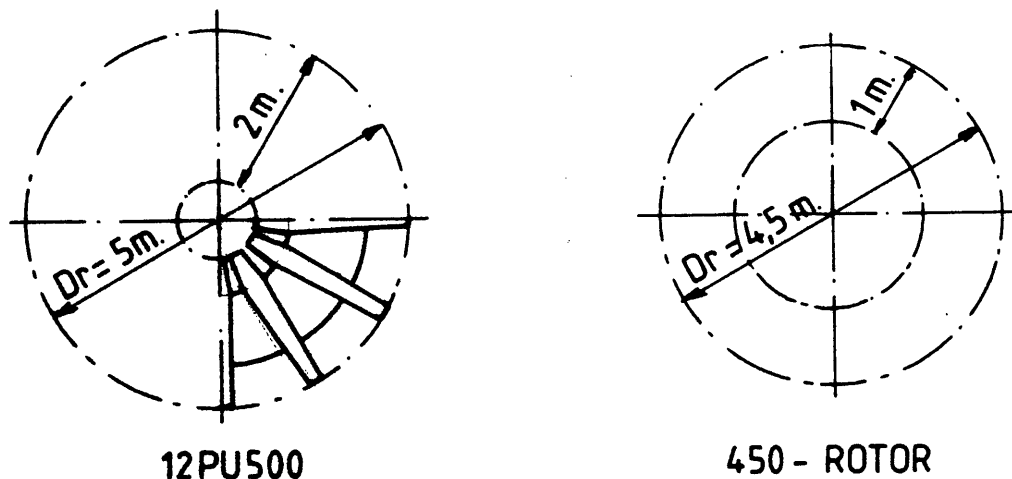


figure 2.1: the 12PU500 and 450 rotor

## 2.2. The choice of the design tip speed ratio

The design tip speed ratio ( $\lambda_d$ ) is the tip speed ratio at the design windspeed. At this windspeed the overall efficiency of the windpump is maximum. The design tip speed ratio of the 12PU500 is two. For the 450-rotor we chose a lower design tip speed ratio, namely:

$$\lambda_d = 1.$$

We wanted to have a pump without airchambers. But these pumps have high peakforces in the pumprod at high rotation speeds. We thought that the peakforces are lower when we choose a lower design tip speed ratio. The conclusion of appendix 2 is that a lower design tip speed ratio does not result in lower peakforces for the windspeeds of 9 m/s (fatigue load) and 12 m/s (maximum 'static' load). The peakforces are more or less equal for  $\lambda_d = 1$  and  $\lambda_d = 2$ .

The advantages of a lower design tip speed ratio are:

- less wear of the piston and the pump cylinder
- lower gyroscopic moment of the rotor

The design windspeed of the 12PU500 is 3 m/s. We took the same design windspeed for the new design, so:

$$v_d = 3 \text{ m/s}$$

## 2.3. The blades

The blades are made of steel sheet of 1 mm. The sheets are bent as in figure 2.2. with  $f/c = 0,1$ . From table 2.1 of lit.4 we find the  $C_d/C_l$  ratio = 0,02.

The number of blades (B) must be a multiple of 6 because of the 6 spokes: B = 6, 12, 18 or 24.

To have a high starting torque the solidity (= area of all the

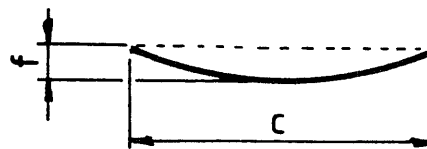


figure 2.2: the blade profile

blades divided by the rotor area) must be high too (lit.4). Therefore it is better to have 18 or 24 blades in stead of 6 or 12. A rotor of 24 blades would be very heavy, so we chose 18 blades:

$$\left. \begin{array}{l} B= 18 \\ D_r= 450 \text{ cm} \end{array} \right\} \underline{\text{18PU450 rotor}}$$

To design the blade dimensions we need the following data:

- the rotor radius ( $R_r$ )
- number of blades ( $B$ )
- design tip speed ratio ( $\lambda_d$ )
- lift coefficient ( $C_l$ ), see table 2.1, lit.4
- corresponding angle of attack ( $\alpha$ )

and 4 formulas, see lit.4:

$$1. \lambda_r = \lambda_d * r / R_r \quad (\text{formula 2.1})$$

$$2. \phi = \sqrt[2]{\frac{1}{3}} * \arctan 1 / \lambda_r \quad (\text{formula 2.2})$$

$$3. \text{corde } c = \frac{8 * \pi * r}{B * C_l} * (1 - \cos \phi) \quad (\text{formula 2.3})$$

$$4. \beta = \phi - \alpha \quad (\text{formula 2.4})$$

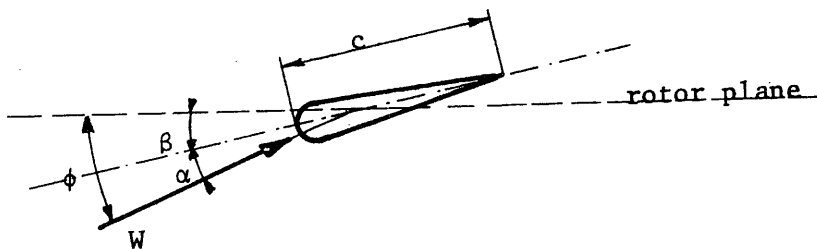


figure 2.3: blade setting  $\beta$

For the 18PU450:

$$R_r = 2,25 \text{ m}, C_l = 1,25, \lambda_d = 1, B = 18 \text{ and } \alpha = 3^\circ$$

The corde ( $c$ ) from  $r = 1,25$  till  $r = R_r = 2,25$  is  $0,34 - 0,35$  m. We chose  $c$  larger,  $c = 0,39$  m, because we want a high solidity compensating the hole in the center. A high solidity gives a high starting torque. The angle  $\beta$  for the support on the inner ring is  $38^\circ$  and for the support on the outer ring  $30^\circ$ .

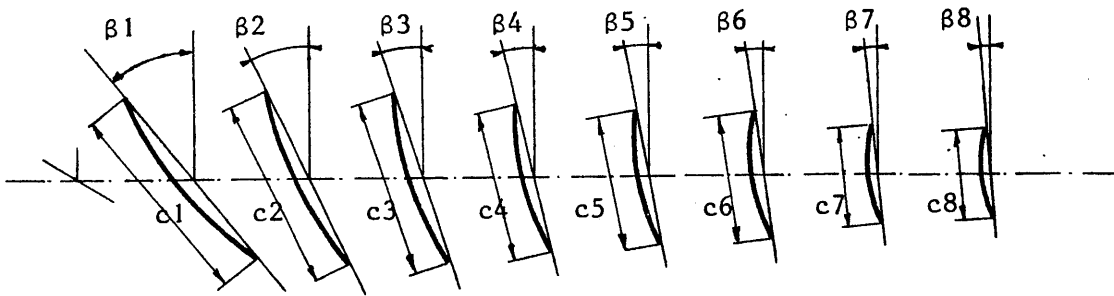
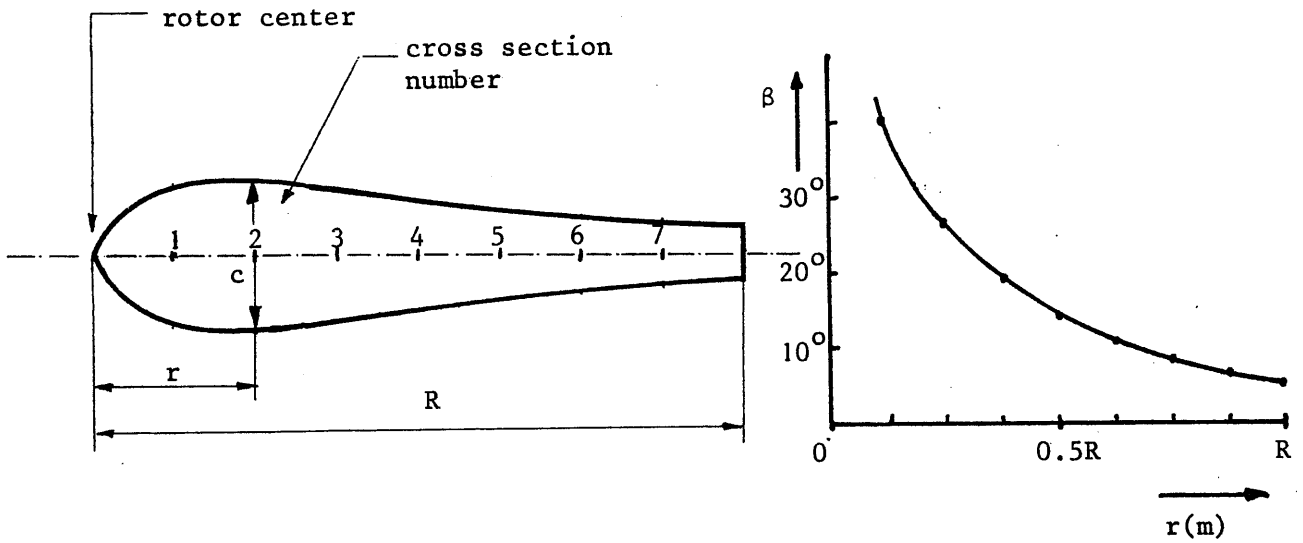


figure 2.4: blade form, twist and cross sections

position	$r$ in m	$\lambda_r$	$\phi$ in $^\circ$	$\beta$ in $^\circ$	$c$ in m
1	0,28	0,125	55,2	52,2	0,13
2	0,56	0,25	50,6	47,6	0,23
3	0,84	0,375	46,3	43,6	0,29
4	1,13	0,5	42,1	39,3	0,33
5	1,41	0,625	38,7	35,7	0,35
6	1,69	0,75	35,4	32,4	0,35
7	1,97	0,875	32,5	29,5	0,34
8	2,25	1	30	27	0,34
support innerring support outerring	1,25  1,90	0,56  0,84	40,6  33,2	37,6  30,2	0,34  0,35

The blade supports of the 12PU500 are made of steel sheet of 1 and 2 mm. The manufacturing of these supports requires much labour. The evaluation showed us that the supports can crack. Therefore we chose flat iron 30x6 mm for the supports of the 18PU450, see drawing nr. 2. This construction is easier to make and stronger. The disadvantage is that it is a little bit heavier.

#### 2.4. The power and torque coefficient

The mechanical power which is converted by the rotor from the windpower is:

$$P_r = C_p \cdot \frac{1}{2} \cdot \rho_a \cdot v^3 \cdot A_r \quad (\text{formula 2.5})$$

The power coefficient  $C_p$  of the 12PU500 is measured in a windtunnel:  $C_p = 0,32$ . The  $C_p$ -value of the 18PU450 is not measured in a windtunnel but with lit.4 we can predict it:

$$\left. \begin{array}{l} C_d/C_l = 0,02 \\ \lambda_d = 1 \\ B = 18 \end{array} \right\} C_{p,th} (= \text{theoretical } C_p\text{-value}) = 0,39$$

When we calculate the losses of the hole in the center of the rotor then the maximum power coefficient is (see lit. 16):

$$C_{p,max} = C_{p,th} \cdot (2 \cdot R_r \cdot 1 - 1^2) / R_r^2 = 0,27$$

The torque ( $Q$ ) characteristic of the rotor and the load is very important. A piston pump has an almost constant torque which results in a relatively high starting torque ( $Q_{start}$ ). Therefore it is important that the rotor has a high starting torque too.

The torque is given by:

$$Q = C_Q \cdot \frac{1}{2} \cdot \rho_a \cdot v^2 \cdot A_r \cdot R_r \quad (\text{formula 2.6})$$

$$\text{The torque coefficient } C_Q = C_p / \lambda \quad (\text{formula 2.7})$$

The starting torque coefficient is determined by the empiric relation:  $C_{Qstart} = 0,5/\lambda^2$  (formula 2.8)

The 12PU500 ( $\lambda=2$ ):  $C_{Qstart} = 0,5/2^2 = 0,125$

The 18PU450 ( $\lambda=1$ ):  $C_{Qstart} = 0,5/1^2 = 0,5$

From experiences on rotors with  $\lambda=1$  it appeared that this value of 0,5 is too high. According to lit. 16 the starting torque coefficient is:

$$C_{Qstart} = 0,75 * B * (R - \frac{1}{2} * l) * C_l * c * l / (\pi * R_r^3) = 0,28$$

(with  $C_l = 1,1$  for  $\alpha = 90^\circ - \beta \approx 54^\circ$ )

The starting windspeed ( $v_{start}$ ) of the 12PU500 is more or less 2,5 m/s. The starting torque at this windspeed is;

$$12PU500: Q_{start} = C_{Qstart} * \frac{1}{2} * \rho_a * v_{start}^2 * A_r * R_r =$$

$$0,125 * \frac{1}{2} * 1,2 * 2,5^2 * 18,8 * 2,5 = 21,2 \text{ Nm}$$

$$18PU450: Q_{start} = 0,28 * \frac{1}{2} * 1,2 * 2,5^2 * 11 * 2,25 = 26,0 \text{ Nm}$$

The 18PU450 has a higher starting torque.

## 2.5. Measurements of the windspeed-rotationspeed relation

The 18PU450 prototype on the testfield of the WOT is equipped with an anemometer beside the rotor and a rotation speed meter on the rotorshaft. The two meters are connected to a computer which registers the data. The anemometer is a cup-anemometer with a reed-contact on the shaft. The registered cycle time is a measure for the windspeed. The anemometer is calibrated with another anemometer, an Aeolian Kinetics Wind Prospector 4000. The computer registers once every minute the cycle time of the anemometer and of the rotor. A computer program calculates the windspeed, the rotation speed of the rotor and the tipspeed ratio. It calculates also the average tipspeed ratio for

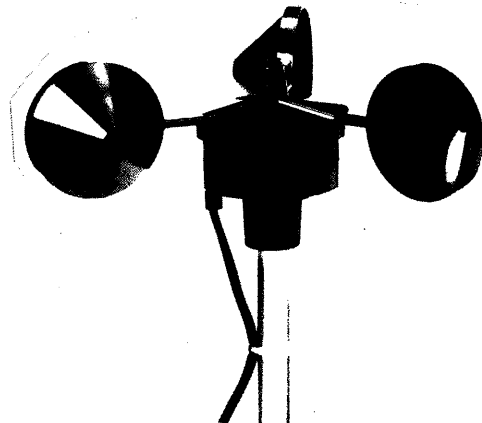


figure 2.5: cup-anemometer

intervals of windspeed. measurements are done with and without load. The load is a 4" pump with  $D_p = 105$  mm and  $R_c = 120$  mm. The waterlifting head is 10,5 m. The average tipspeed ratio at  $v = 3$  m/s is 1,0 and at  $v = 9$  m/s 1,6, see fig. 2.6. The average tipspeed ratio without load is 1,7. The rotor stood perpendicular in the wind during the measurements (the prototype has the hysteresis safety system, see par. 3.2). The measurements aren't accurate because the windspeed is fluctuating very much. For more accurate measurements we have to use a windtunnel with constant windspeeds.

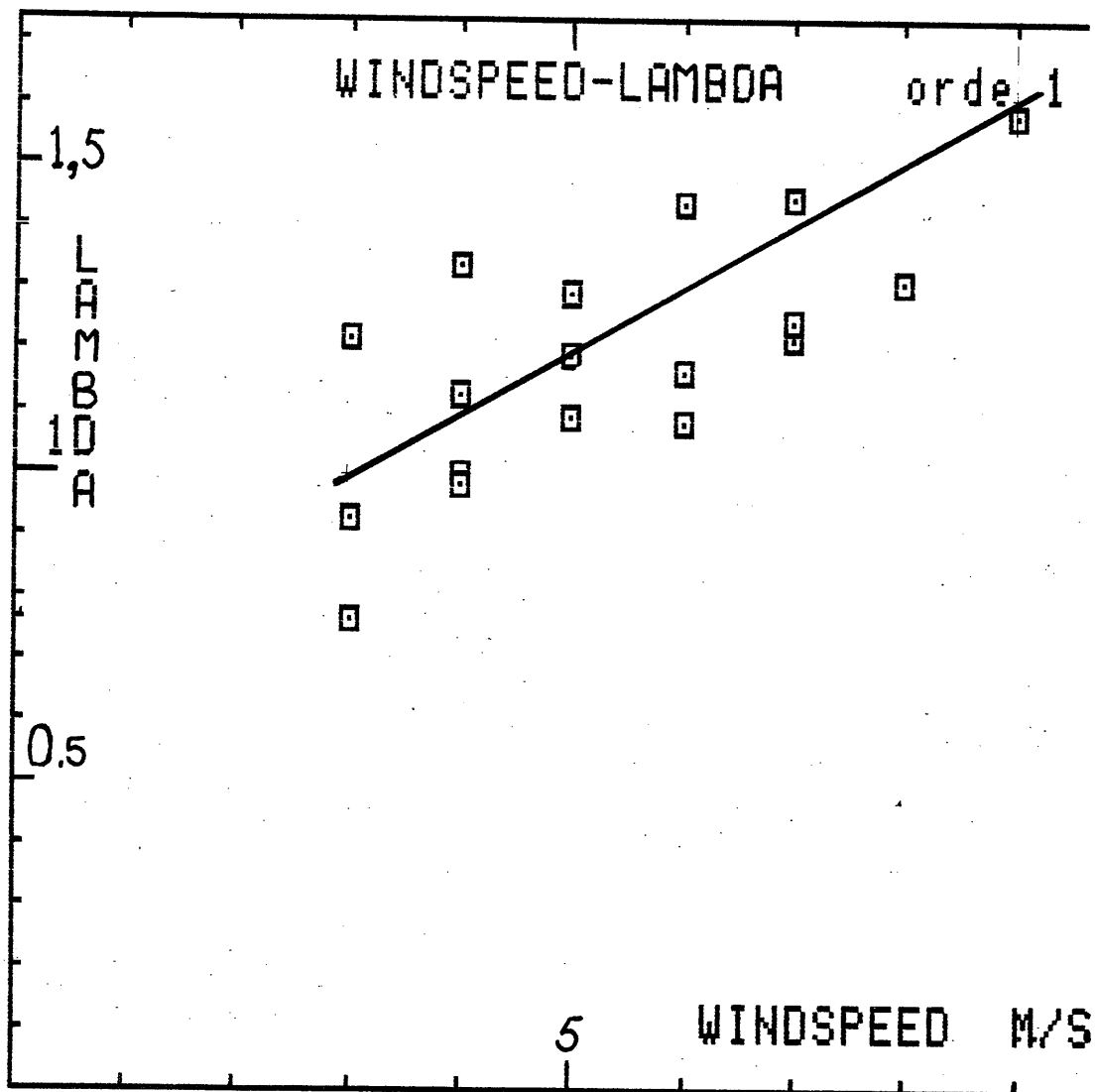


figure 2.6: tipspeed ratio as function of the windspeed with load

## CHAPTER 3. THE SAFETY SYSTEM AND THE HEAD CONSTRUCTION

### 3.1. General

The safety system has to limit the axial windforces on the rotor and the rotation speed of the rotor.

The 12PU500 has a half-automatic safety system. When the windspeed is too high the rotor turns out of the wind. After the hard winds the rotor must be put in the wind again by hand.

The 18PU450 has a full-automatic system, without necessary human interference. Before designing the system all kind of existed systems for windpumps were evaluated, see lit.6.

### 3.2. The hysteresis system

The first choice was a completely new system, the so-called hysteresis system, see fig.3.1.

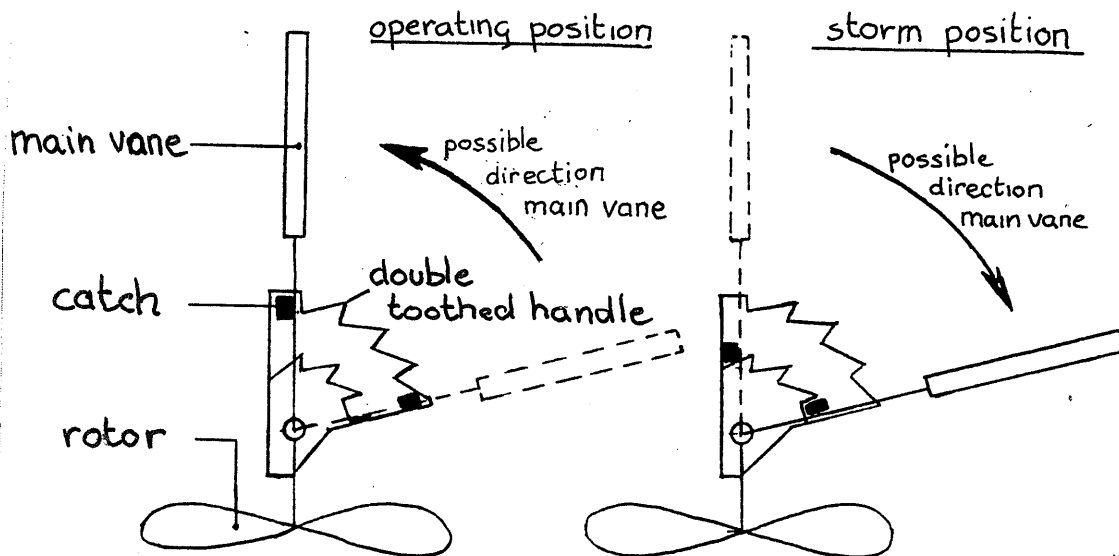


figure 3.1: the safety mechanism with a double toothed handle

This mechanism with a double toothed handle has a comparable working as the half-automatic system of the 12PU500. Only this mechanism has a second toothed handle which takes care that the rotor turns in the wind again. In the normal position the catch is in the toothed handle A. The catch is the extension of the arm of the help vane as in fig.3.2 shown. When the



windspeed becomes too high the windpressure on the help vane pushes the help vane backwards. The catch falls in the toothed handle B. The head with the rotor is unlocked from the tail and will turn out of the wind. This turning starts because of variations in the wind direction and then continues because the windforce on the rotor is eccentric to the towerpipe axis and causes a torque. When the windspeed decreases the help vane falls down in its normal position by its weight. The catch is in toothed handle A again. Because of variations in the wind direction the rotor will turn in the wind again, tooth after tooth.

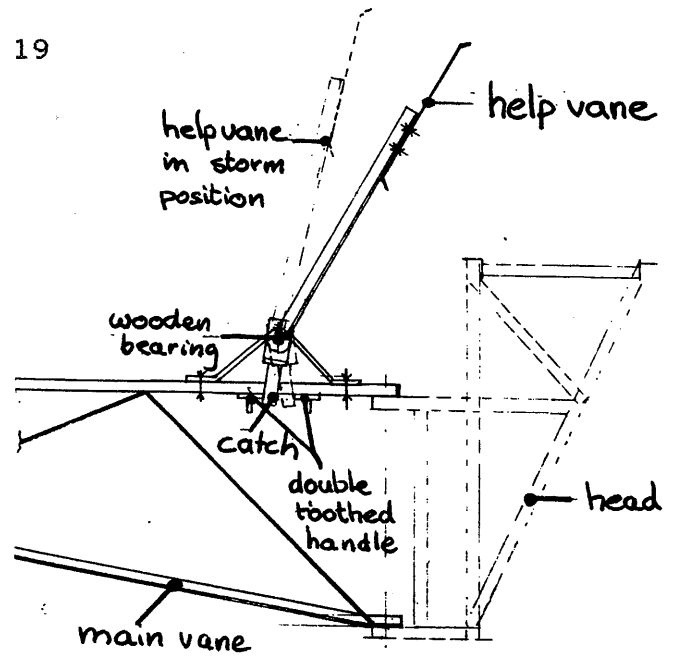


figure 3.2: the double toothed handle with the help vane

The help vane works concerning a hysteresis. The relation between the windspeed and the angle of the arm and the horizontal ( $\delta$ ) is given in fig.3.3. At  $v_{\max}$  (12 m/s) the help vane is blown backwards and the rotor starts to turn out of the wind. At  $v_1$  (more or less 7,5 m/s) the helpvane falls forwards in its normal position and the rotor starts to turn in the wind again.

The graph of fig.3.3 shows an hysteresis loop.

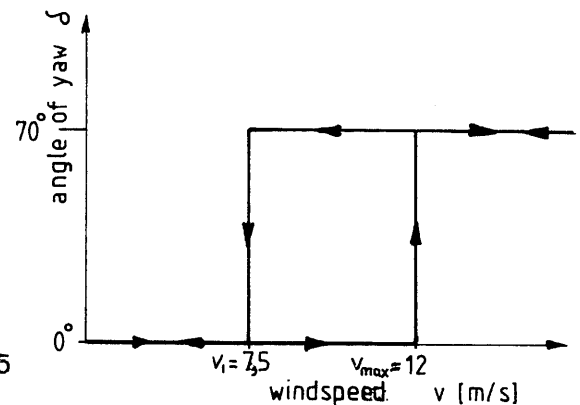


figure 3.3: relation between the windspeed  $v$  and angle  $\delta$

The 18PU450 prototype is equipped by the hysteresis system. Till now the system has done its duty, but there appeared some problems:

- The time that the rotor needed for turning in the wind again is sometimes more than one day, especially when the

windspeed decreased lower than 4-5 m/s. This causes a loss in the output.

- Sometimes the rotor didn't turn out of the wind directly after the catch fell in toothed handle B but reacted just after 4-5 seconds. During this time the rotation speed can increase too much and damage the pump.
- When the rotor was turning out of the wind the shock of the catch against the end of the toothed handle was rather heavy sometimes.

Other disadvantages of the hysteresis system are:

- The design depends on variations of wind direction. In areas where the wind direction is rather constant the system possibly may not function well.
- The construction of the help vane has a bearing which never may have too much friction.
- The manufacturing of the double toothed handle requires much labour.

These points make clear that the hysteresis system isn't dependable for 100% and can cause output losses. We chose another system, namely the well-known inclined hinged vane safety system.

### 3.3. The inclined hinged vane system

This system has a tail which doesn't hinge in an horizontal plane but an inclined plane, see fig.3.4.

When the windspeed increases the thrust on the side vane and on the rotor by the wind increases too. The thrust causes a higher moment which turns the rotor out of the wind. The tail vane will not turn so far because the wind thrusts the tail vane in the wind direction. This position of the tail vane is not its lowest position, so its weight will give a moment around the s-axis of the hinge. The tail vane will make an angle ( $\alpha$ ) with the wind direction. The force caused by the wind thrust on the tail vane ( $F_v$ ) will give a moment around the z-axis of the towerpipe. This moment will stop the rotor from



perpendicular to the wind direction. This means a loss of power.

- The wooden yaw bearing of the Diever 450 has more friction than ball-bearings or roller-bearings. This means an uncertain factor for the behaviour of the system.

The advantages of the system:

- Simple construction
- Not sensitive for failure
- Full-automatic
- Applied on many other windmills.

After it was clear that the hysteresis system isn't the ideal system we made a new investigation to other safety systems. The conclusion was that the inclined hinged vane system was a good alternative. The system can be partly adjusted by varying the side vane area ( $A_{rs}$ ) and arm length ( $R_a$ ). The angle of the hinge ( $\epsilon$ ) on the prototype should be variable too. The influence of the wooden yawing bearing could only be found out by trying on a prototype.

To predict the behaviour of the system (relation between the windspeed and the angle  $\delta$ ) we can use the next formulas:

Forces:

$$\begin{aligned} \text{thrust on rotor} & : F_{rt} = C_t * \frac{1}{2} * \rho_a * (v * \cos \delta)^2 * A_r \\ \text{side force on rotor} & : F_{rs} = C_f * \frac{1}{2} * \rho_a * (v * \sin \delta)^2 * A_{rs} \\ \text{wind normal force on tail vane} & : F_v = 2,6 * \alpha * \frac{1}{2} * \rho_a * (1-a)^2 * v^2 * A_v \\ \text{weight normal force on tailvane} & : F_{vg} = G * \sin \epsilon * \sin \tau \\ \text{wind normal force on side vane} & : F_a = C_{H(90^\circ - \delta - \xi)} * \frac{1}{2} * \rho_a * v^2 * A_a * \cos \xi \\ & \text{(formulas 3.1-3.5)} \end{aligned}$$

Moments:

$$\text{around s-axis: } F_v * R_v = F_{vg} * R_g \quad \text{(formula 3.6)}$$

$$\text{around z-axis: } F_{rt} * e + F_{rs} * f + F_a * R_a = F_v * (h * \cos \gamma + R_v * \cos \epsilon) \quad \text{(formula 3.7)}$$

The angles:

$$\sin \alpha = \sin \delta * \cos \gamma - \cos \delta * \cos \epsilon * \sin \gamma \quad \text{(formula 3.8)}$$

$$\text{for small angles of } \alpha: \alpha \text{ (in rad)} \approx \sin \alpha \quad \text{(formula 3.9)}$$

The two moment balance equations around the z-axis and the s-axis can be combined in one formula:

$$C_t \cdot \cos^2(\delta - \delta_0) \cdot \frac{A_r \cdot e}{A_v \cdot R_v} + C_f \cdot \sin^2(\delta - \delta_0) \cdot \frac{A_{rs} \cdot f}{A_v \cdot R_v} + C_H(90^\circ - (\delta - \delta_0) - \xi) \cdot \cos \xi \cdot \frac{A_a \cdot R_a}{A_v \cdot R_v} = 2,6 \cdot F \cdot \frac{T}{\sqrt{(1+T^2)}} \cdot (1-a)^2 \cdot \left\{ \frac{h}{R_v \cdot \sqrt{(1+T^2)}} + \cos \epsilon \right\} \quad (\text{formula 3.10})$$

with:

$$F = \frac{G \cdot R_0 \cdot \sin \epsilon}{2,6 \cdot \frac{1}{2} \cdot \rho_a \cdot (1-a)^2 \cdot v^2 \cdot A_v \cdot R_v} \quad (\text{formula 3.11})$$

and:

$$T = \frac{\sin \delta}{F + \cos \delta \cdot \cos \epsilon} \quad (\text{formula 3.12})$$

The solution of these equations should be the angle  $\delta$  as a function of the windspeed  $v$ :

$$\delta = \delta(v) \quad (\text{formula 3.13})$$

In order to find this function we need to know a survey of parameters. For the Diever 450 these parameters are:

<u>rotor</u>	<u>value</u>	<u>unit</u>
$D_r$ = rotor diameter	4,5	m
$A_r$ = rotor area	15,9	m <sup>2</sup>
$e$ = rotor eccentricity	0	m
$A_{rs}$ = rotor side area = $0,075 \times A_r$	1,2	m <sup>2</sup>
$f$ = distance rotor plane to z-axis	0,8	m
<u>side vane</u>		
$A_a$ = side vane area	0,42	m <sup>2</sup>
$R_a$ = distance aerodynamic center of the side vane to the z-axis	3	m
$\xi$ = side vane angle	0°	degree
<u>main vane</u>		
$A_v$ = main vane area	2,75	m <sup>2</sup>
$R_v$ = distance aerodynamic center of the main vane to the s-axis	3,37	m
$\delta_0$ = preset angle of the main vane	0°	degree
$h$ = see fig. 3.4	0,35	m

	<u>value</u>	<u>unit</u>
$\epsilon$ = angle of inclination of the s-axis	10°	degree
G= main vane weight	550	N
$R_g$ = distance gravity center to the s-axis	2,45	m

aerodynamic

$\rho_a$ = air density	1,2	kg/m <sup>3</sup>
$C_f$ = rotor side force coefficient	$\frac{8}{9}$	
$C_{\parallel}$ = normal force coefficient	see fig. 3.5	
a= wake factor	see fig. 3.6	

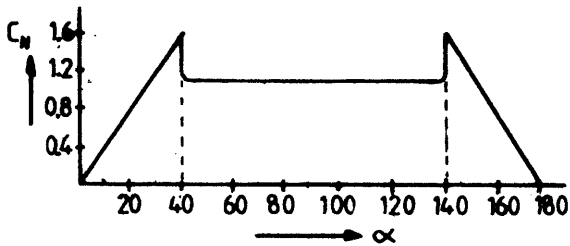


figure 3.5: normal force coefficient

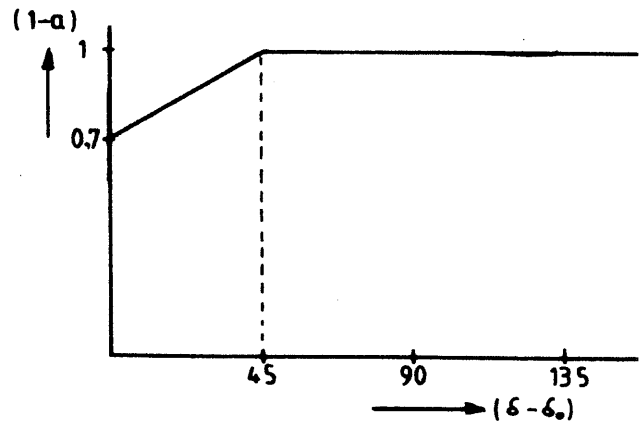


figure 3.6: the wake factor a

Now the theoretical  $\delta$ -v curve for the behaviour of the safety system can be calculated, see fig. 3.7.

In fig. 3.7 we assume that the friction of the wooden yaw bearing is negligible. This is not true. The wooden bearing has a friction that causes a counteracting moment around the z-axis ( $M_f$ ), with a value of more or less 40 Nm.

When we take this value of  $M_f = 40$  Nm and calculate  $\delta(v)$  for an increasing and a decreasing windspeed then we get the curves of figure 3.8.

For more information about inclined hinged vane systems see lit. 5 and 8.

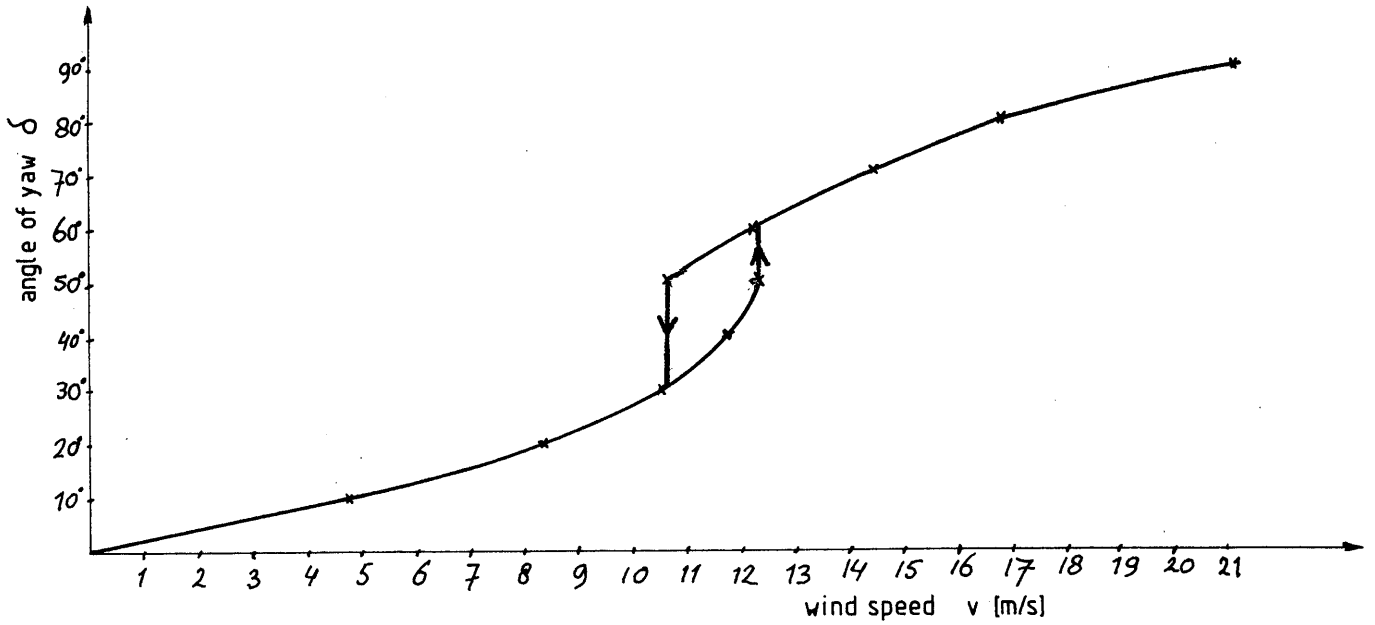


figure 3.7:  $\delta$ - $v$  curve without friction of the yaw bearing

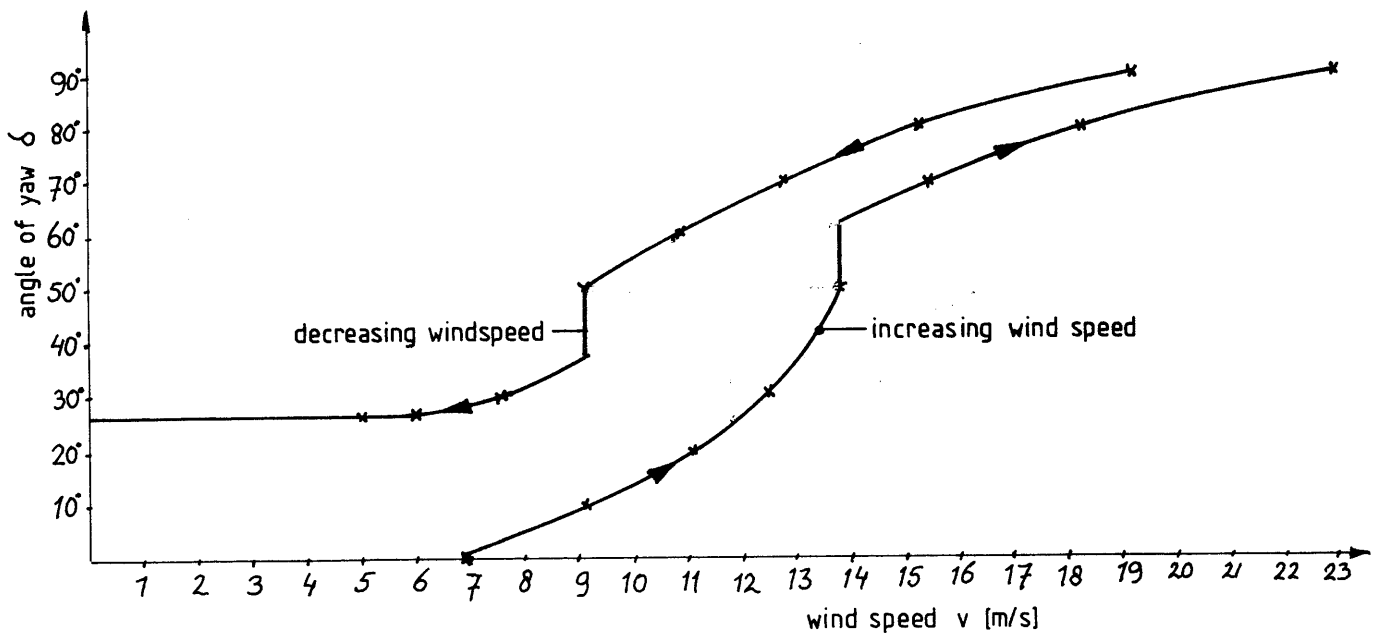


figure 3.8:  $\delta$ - $v$  curves for increasing and decreasing windspeed

### 3.4. The strength calculations of the safety system

For the Diever 450 we chose the inclined hinged vane system. The dimensions are given in par. 3.3 and drawing nr.3. The two hinges of the main vane are wooden bearings. The admissible surface pressure for wood is 2 N/mm<sup>2</sup> for constant load and 5 N/mm<sup>2</sup> for peakloads.

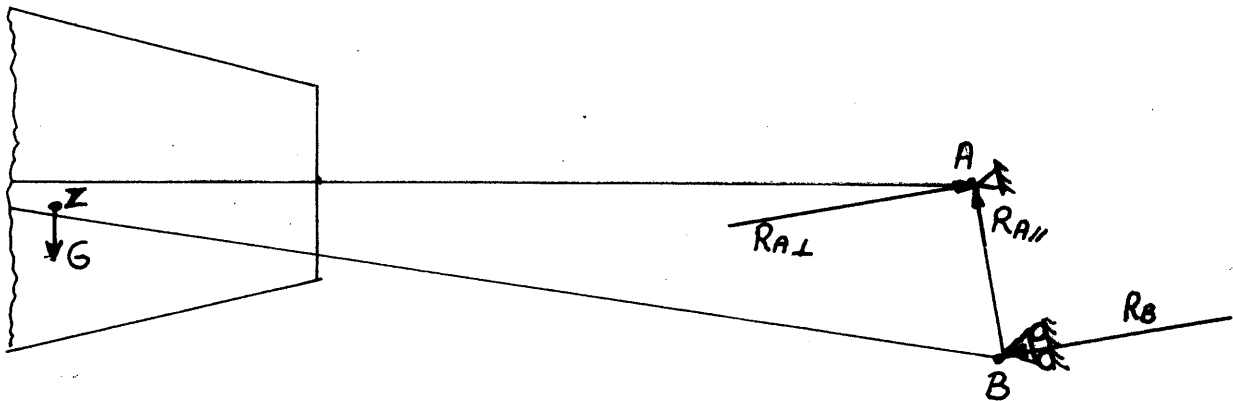


figure 3.9: reaction forces on the hinges

$$\left. \begin{array}{l} \Sigma V = 0 \\ \Sigma H = 0 \\ \Sigma M_{\text{around A}} = 0 \end{array} \right\} \begin{array}{l} R_A = 3200 \text{ N} \\ R_A = 560 \text{ N} \\ R_B = 3040 \text{ N} \end{array}$$

The bearing A is most critical. The surface pressure:

in the axial direction:  $\sigma_v = 0,55 \text{ N/mm}^2$

in the radial direction:  $\sigma_r = 1,11 \text{ N/mm}^2$

The barforces in the main vane construction can be calculated by the Cremona-method, see fig. 3.10.

The barforces are given in the next table:

bar nr.	profile	tensile	pressure	$\sigma_t$	$\sigma_b$
1	L40x40x4		3150		21,6
2	L40x40x4		2600		26,7
3	L40x40x4		2350		24,1
4	L40x40x4	2400		3,9	
5	L40x40x4	3000		4,9	
6	1½"	600		1,3	
7	L30x30x3	250		1,4	
8	L30x30x3		400		8,5
9	L30x30x3	300		1,7	

The forces in [N], the stresses in [N/mm<sup>2</sup>].



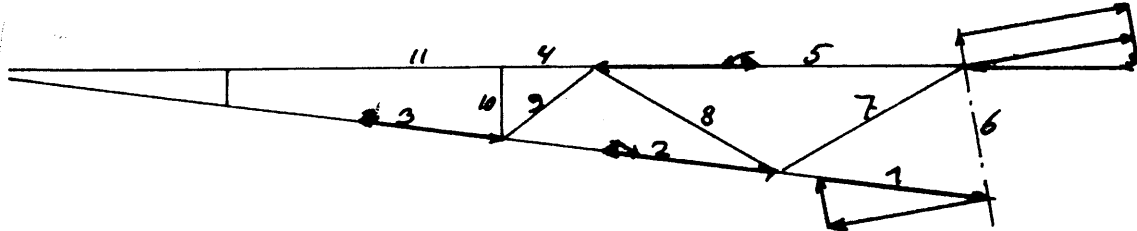


figure 3.10: barforces calculated by Cremona-method

The admissible stress is  $160 \text{ N/mm}^2$ . The stresses in the bars are much lower, so the construction is strong enough. We could make the construction lighter but these calculations are only based on the load of the weight. Loads which are not included in the calculations are:

- torsion caused by turbulences in the wind. These turbulences can cause different windpressures on the upperpart and on the lower part of the main vane. That will give a torsion on the construction.
- shock against the bumper. When the rotor turns out of the wind till the farthest position the main vane hits the bumper. The bumper avoids that the rotor hits the main vane. When we assume that the rotor turns out of the wind with an angular speed of  $0,63 \text{ rad/s}$  and hits the bumper, we can calculate the bending stress on the construction just where it hits the bumper:  $\sigma = 155 \text{ N/mm}^2$  (the admissible stress is  $160 \text{ N/mm}^2$ ).

These points make clear that we cannot make the construction lighter.

The forces on the side vane are:

- the weight of the vane and its arm construction (resp.  $100 \text{ N}$  and  $140 \text{ N}$ )
- the wind force on the vane (maximum  $60 \text{ N}$ )

The bars ADM and CD are made of  $\frac{3}{4}$ " gaspipe, bar BD of  $\frac{1}{2}$ ".

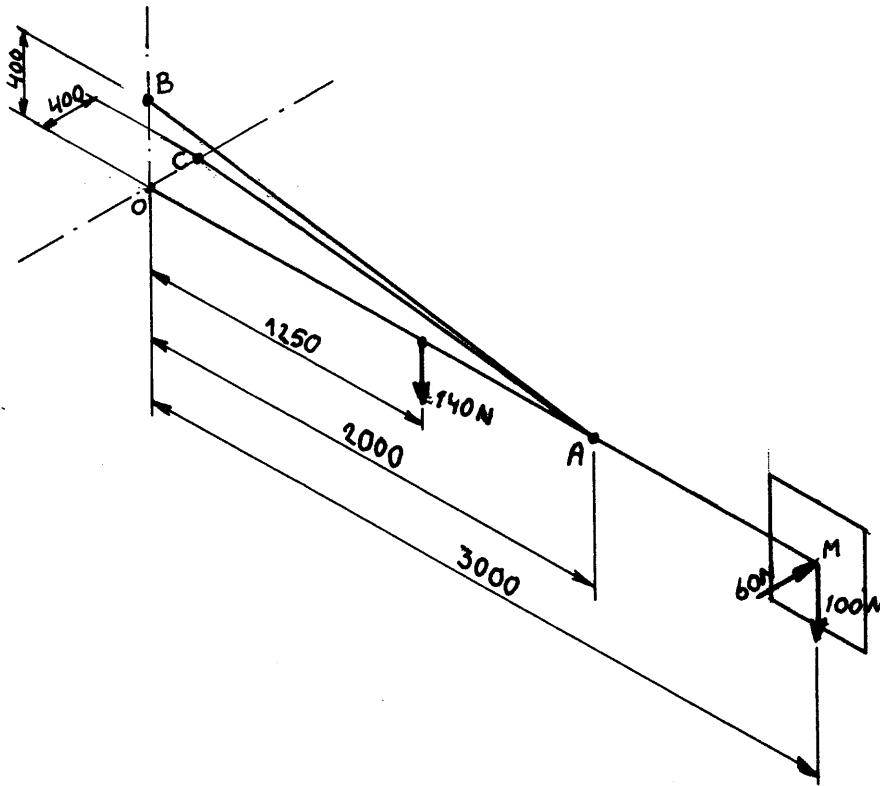


figure 3.11: forces on the side vane

The reaction forces in the connections A, B and C are calculated and given in fig. 3.11. The bar forces are:

bar AD:  $F_{AD} = -750$  N (pressure)

bar BD:  $F_{BD} = +1220$  N (tensile)

bar CD:  $F_{CD} = -460$  N (pressure)

For  $\frac{3}{4}$ " gaspipe the admissible pressure force with a buckle length of 2 m is:  $\bar{F} = 3100$  N

The bending moment next to D:  $M_D = 121$  Nm. For  $\frac{3}{4}$ " gaspipe:  
 $\sigma = M/W = 109$  N/mm<sup>2</sup>.

We can conclude that the arm construction is strong enough.



fig. 4.2 is a mechanism of four bars. At a constant angular speed of the rotor the upward movement of the piston takes more time than downward ( $202^\circ$  of  $360^\circ$  rotation upward and  $158^\circ$  downward).

In appendix 2 the position of the piston ( $s$ ) as function of the time ( $t$ ) is calculated and given in graph nr. 1. By numeric differentiating we get the speed of the piston ( $v_p$ ) as function of  $t$  (graph nr. 2) and secondly numeric differentiating we get the acceleration of the piston ( $a_p$ ) as function of  $t$  (graph nr. 3). From the graph nr. 3 we see that the acceleration of the piston in its lowest position is:

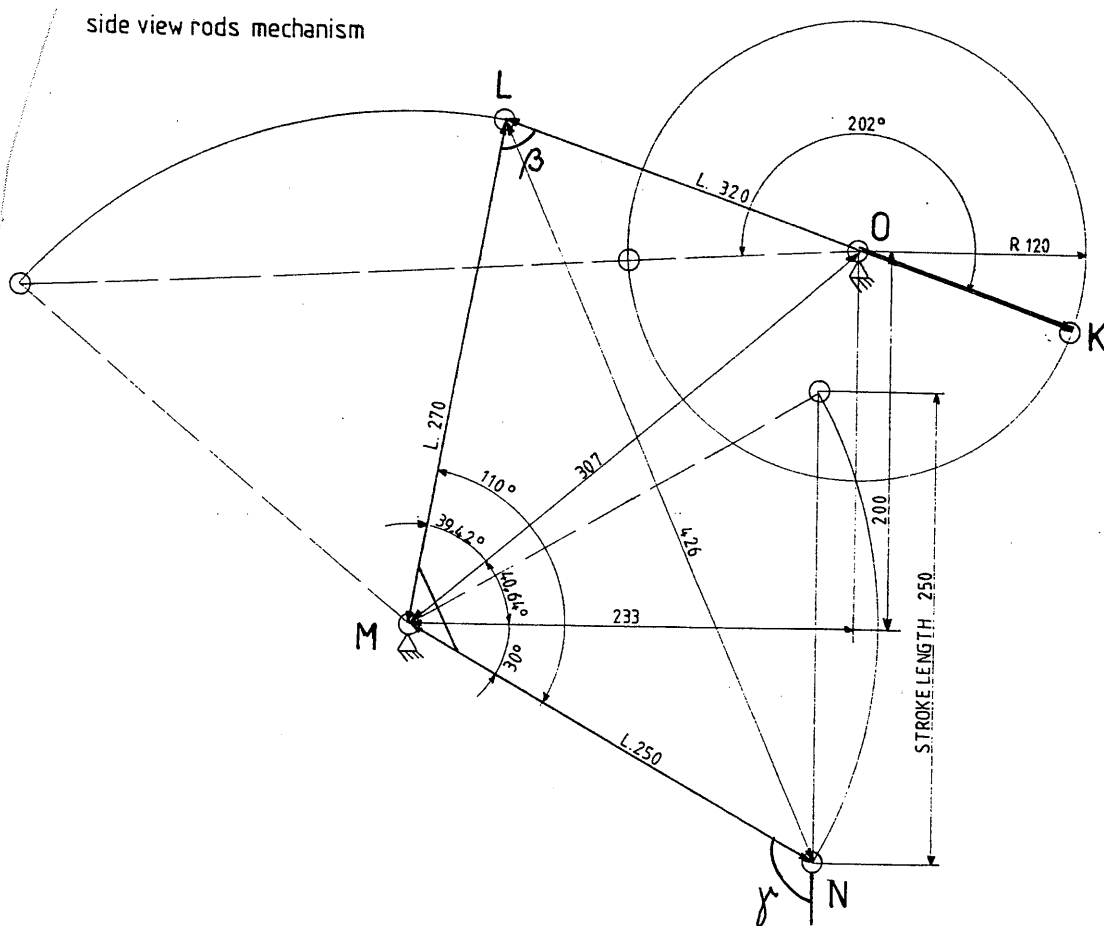


figure 4.2: four bars mechanism

$$a_p = 2,4 \text{ m/s}^2 \text{ for } \Omega = 2\pi \text{ rad/s and } s = 250 \text{ mm}$$

With the same values of the angular speed and stroke length the transmission of the 12PU500 gives:

$$a_p = 4,7 \text{ m/s}^2!$$

The  $a_p$  with the transmission of the Diever 450 is 51% of the  $a_p$  with the transmission of the 12PU500 and a crank length of 120

mm and 76% with a crank length of 60 mm.

#### 4.2 The construction and the strength

The construction of the transmission of the Diever 450 is given in drawing nr.4. The crankpin is an iron shaft of  $\phi 30$  mm. Flat irons of 30x6 mm are welded between the crankpin and the rotorshaft. The crank length is 120 mm and is not variable. A construction of a crank with a variable crank length is given in appendix 6. From the crank a bar of 1" gaspipe (the connecting rod) is connected to a tumbler construction, 'the elbow', which is made of two iron sheets of 4mm. The pumprod is connected at the other side of the elbow.

All the bearing bushes are made of wood. The admissible surface stress ( $\sigma_v$ ) is 5 N/mm<sup>2</sup> for peak load. The projected area ( $A_{proj}$ ) of the bearings L, M and N is 27\*70= 1890 mm<sup>2</sup>, of K is 30\*70= 2100 mm<sup>2</sup>. The admissible force on the bearings L, M and N:  $\bar{F} = 5 \cdot 1890 = 9450$  N.

The admissible force on the bearings in K:  $\bar{F} = 5 \cdot 30 \cdot 70 = 10500$  N

The peak force in the pumprod ( $F_{peak}$ ) appears when the piston passes its lowest position. With the piston in its lowest position and the crank length of 120 mm the angle  $\beta = 81^\circ$  and  $\gamma = 120^\circ$  (see fig. 4.2). The reaction forces in the bearings are:

in the crank bearing K:  $R_K = 0,81 \cdot F_{peak}$

in bearing L :  $R_L = 0,81 \cdot F_{peak}$

in bearing M :  $R_M = 1,07 \cdot F_{peak}$

in bearing N :  $R_N = F_{peak}$

The reaction force in M is the highest. If  $R_M = F = 9450$  N then:

$\rightarrow \bar{F}_{peak} = 8830$  N

The pump makes a lot of strokes, possibly more than 10 million. It means that the load (the pumprod forces) is a fatigue load. The admissible stresses for the iron parts with a fatigue load are lower than with a static load. Therefore we have to calculate the fatigue strength of the iron parts.

The fatigue strength of the crank:

The admissible stress is:

$$\bar{\sigma}_e = \sqrt{(\sigma^2 + \tau^2)} = 105 \text{ N/mm}^2$$

(for  $\sigma_{\min}/\sigma_{\max} = 0$ , see lit.11)

$$\sigma = M/W = R_k * 44 / (\pi/16 * 30^3)$$

$$\tau = R_k/A = R_k / (\pi/4 * 30^2)$$

$$\rightarrow \bar{R}_k = 8400 \text{ N} \rightarrow \bar{F}_{\text{peak}} = 10370 \text{ N}$$

The connecting rod is loaded by a pressure force during the peak force in the pumprod:

$$F = 0,81 * F_{\text{peak}}$$

The buckle length is:  $l_k = 320 \text{ mm}$

$$\rightarrow \bar{F} = 30520 \text{ N} \rightarrow \bar{F}_{\text{peak}} = 37680 \text{ N}$$

The strength of the rotorshaft bearings:

The admissible reaction force in the bearing next to the crank is:

$$\bar{R} = \bar{\sigma}_v * A_{\text{proj}} = 5 * 50 * 70 = 17500 \text{ N}$$

$$F_{\text{peak}} \approx 0,89 * R$$

$$\rightarrow \bar{F}_{\text{peak}} = 15630 \text{ N}$$

The conclusion of these strength calculations is that for the transmission the admissible pumprod force is:

$$\bar{F}_{\text{pr}} = \bar{F}_{\text{peak}} = 8830 \text{ N}$$

In stead of wooden bearings we can use ball-bearings when they are available. In appendix 5 there is the drawing of the transmission with ball-bearings.

## CHAPTER 5. THE PUMP

### 5.1. General

The Diever 450 is coupled to a single-acting piston pump, as the 12PU500. The piston pump has a piston which moves up- and downwards (reciprocating) in a cylinder (pump cylinder). The pump has two valves, the piston has a valve (piston valve) and a second valve at the bottom of the pump (foot valve), see lit. 1.

### 5.2. The pumprod forces

The pump of the 12PU500 has airchambers. The function of airchambers is to smooth the pulsating flow of the pump and to reduce the dynamic forces. But we experienced that the airchambers were loosing their air slowly. There are four possibilities for solving this problem:

- a flexible wall separating the air from the water (for example a rubber hose)
- an airpump filling the airchamber
- airchambers with a snuffle valve
- without airchambers and the pumprod forces lower than the admissible forces of the construction of the pump, pumprod and transmission.

Without airchambers the pump construction is more simple. But it means also that the design windspeed is limited. A high design windspeed means a large swept volume and causes high pumprod forces (peakforces).

The peak forces in the pumprod appear just after the piston has passed its lowest position. The peak forces consist of different forces (see appendix 2):

$$F_{\text{peak}} = F_{\text{stat}} + F_a + F_s + F_v + F_{v|}$$

$F_{\text{stat}}$  = force caused by the static pressure

$F_a$  = force caused by the acceleration of the water, piston and pumprod

$F_s$  = force caused by the shock of the piston against the water column at the moment that the piston valve closes

$F_v$  = force caused by the friction of the piston and the cylinder

$F_{vl}$  = force caused by the conductor resistance in the pump and rising main (see lit. 9)

With the transmission of the Diever 450 the acceleration of the piston in its lowest position ( $a_p$ ) is 51% of the  $a_p$  with the transmission of the 12PU500 at the same rotation speed, see chapter 4 (for  $R_c = 120$  mm). Therefore the acceleration force  $F_a$  is much smaller.

The shock force  $F_s$  appears when the piston valve closes and the piston bumps against the standing water column. For the Diever 450  $F_s$  is smaller than for the 12PU500 because the speed of the piston ( $v_p$ ) of the Diever 450 at the moment of bumping is lower (71% of  $v_p$  of the 12PU500) at the same rotation speed.

It may be clear that it isn't easy to calculate  $F_{peak}$  this way. Especially the shockforce is difficult to determine. The C.W.D. did a lot of research on this matter. They made a program for the calculation of the pumprod forces of their pumps. They have found also another simple way to calculate it by using the next formula (lit. 10):

$$F_{peak} = k \cdot \rho_v \cdot H \cdot A_p \cdot (g + \Omega^2 \cdot R_c \cdot A_p / A_{rn}) \quad (\text{formula 5.1})$$

$k$  is an overshoot factor.

To make the formula more accurate we have to bring in  $A_{pr}$ .

$$F_{peak} = k \cdot \rho_v \cdot H \cdot (A_p - A_{pr}) \cdot \{g + \Omega^2 \cdot R_c \cdot (A_p - A_{pr}) / (A_{rn} - A_{pr})\} \quad (\text{formula 5.2})$$

In this report I will use this formula. With my measurement results I will calculate  $k$  too, see par. 4.3. The measurements are done with two pumps on the pump test rig and on the Diever 450 on testfield of the WOT. The efficiency of the pump installation is determined by the indicator diagram of the



pump, see par. 5.6.

### 5.3. The rotation speed

Because of the reciprocating piston the system experiences a lot of fluctuating load cycles and fatigue symptoms can appear. The admissible stresses in materials under a fatigue load is much lower than under a static load. For the fatigue strength calculations of the pump I take the rated windspeed of  $v = 9$  m/s and for the static strength the maximum windspeed  $v = 12$  m/s, for both cases the rotor perpendicular in the wind. The tipspeed ratio  $\lambda$  of the Diever 450 is 1 for  $v_d = 3$  m/s. For higher windspeeds the tipspeed ratio is higher, for  $v = 9$  m/s and  $v = 12$  m/s the tipspeed ratio  $\lambda \approx 1,6$ .

$$\lambda = \Omega \cdot R_r / v = \pi \cdot n \cdot D_r / v$$

for  $v = 9$  m/s:  $n = 60$  r.p.m.

for  $v = 12$  m/s:  $n = 80$  r.p.m.

### 5.4. The pump dimensions

To determine the optimal swept volume of the pump I use the next formula (lit. 4):

$$P_{\text{rotor}} = P_{\text{pump}} / \eta_{\text{tot}}$$

$$\frac{1}{2} \cdot C_p \cdot \rho_a \cdot v^3 \cdot \frac{1}{4} \cdot \pi \cdot D_r^2 = \rho_v \cdot g \cdot H \cdot \Phi_{\text{eff}} / \eta_{\text{tot}} \quad (\text{formula 5.3}), \text{ by which:}$$

$$\Phi_{\text{eff}} = \eta_{\text{vol}} \cdot V_s \cdot n = \eta_{\text{vol}} \cdot V_s \cdot \lambda \cdot v / \pi D_r \quad (\text{formula 5.4})$$

Formula 5.3 and 5.4 together:

$$V_s = \frac{\rho_a \cdot \pi^2 \cdot C_p \cdot \eta_{\text{tot}} \cdot v^2 \cdot D_r^3}{8 \cdot \rho_v \cdot g \cdot H \cdot \eta_{\text{vol}} \cdot \lambda} \quad (\text{formula 5.5})$$

For  $v$  we take the design windspeed  $v_d = 3$  m/s.

The other values are:

$$C_p = 0,27 \quad ; \quad \eta_{\text{tot}} = 0,67 \quad ; \quad \rho_a = 1,2 \text{ kg/m}^3 \quad ; \quad \rho_v = 1000 \text{ kg/m}^3 \quad ; \\ g = 9,8 \text{ m/s}^2 \quad ; \quad D_r = 4,5 \text{ m} \quad ; \quad \lambda = 1 \quad ; \quad \eta_{\text{vol}} = 0,9$$

These values in formula 5 give:

$$V_s = A_p \cdot s = 24,8/H \text{ [lit]} \quad (\text{formula 5.6})$$

When  $V_s$  is known and the stroke length  $s$  is chosen the piston area  $A_p$  can be calculated:

$$A_p = V_s / s \quad (\text{formula 5.7})$$

From formula 5.2 and 5.3 it is clear that to reduce  $F_{\text{peak}}$  you must choose  $s$  as long as possible so that  $A_p$  is as small as possible. For the Diever 450 this is 250 mm.

To choose the pump cylinder it depends on what is available. In the past the WOT used iron gaspipes of 4", 5" and 6". But the iron cylinder caused trouble, because it rusts. The rust is like sandpaper for the piston. The life-time of the piston was very short (few months). Alternatives are stainless steel, bronze, brass or p.v.c. Experiences with stainless steel, bronze and brass makes clear that these materials are suitable for the use as pumpcylinder but they are difficult to obtain, especially brass cylinders. Stainless steel cylinders are often used in the food-processing industry. It is possible to cast bronze cylinders and to turn out on a big lathe. We choose p.v.c. because p.v.c. pipes are more available in developing countries. In the next table some p.v.c. pipes are chosen as pump cylinders. It gives the optimal waterlifting head calculated by formula 5.6 at  $s = 250$  mm. It gives also the maximum admissible pressure  $p_{\text{max}}$  of the pipes.

Table 5.1: p.v.c. pipes as pump cylinders

pipe size in inch	outerxinner size in mm	optimal head in m	$P_{\text{max}}$ in bar
8"	200x190,2	3,5	6
6"	160x150,6	5,6	7,5
5"	125x117,6	10,1	7,5
4"	110x101,6	12,2	10
3½"	90x81,4	19,0	12,5
3"	75x67,8	27,6	12,5
2"	63x53,6	44,3	16

For the 8", 6", 5" and 4" pump it is possible to take a pipe with a thinner wall, but for these pipes the admissible

waterlifting heads are smaller. In practice we found that p.v.c. wore out when the water is sandy. Therefore it is better to choose pipes with a thicker wall, like we did in table 5.1.

### 5.5. The strength calculation of the pumps

The admissible pumprod forces depend on the admissible pressure of the p.v.c. pipe ( $\bar{F}_{pr} = P_{max} * (A_p - A_{pr})$ ) and on the admissible load of the other parts of the pump like the piston and the pumprod. Hereby we take the fatigue and the static load. For the fatigue load I used lit. 11 and 12. The load is a repeated load ( $R = \sigma_{min} / \sigma_{max} = 0$ ). The safety factor is 1,2 for the welds and 1,5 for the other parts.

The results of the calculations are put in table 5.2:

Table 5.2: strength calculations

pump in inch	rising main in inch	fatigue load $\bar{F}_{pr}$ (n=60) in kN.	static load $\bar{F}_{pr}$ (n=80) in kN.
8"	4"	10,9	18,8
6"	3"	8,3	10,8
5"	3"	7,9 <sup>*</sup>	12,4
4"	2"	7,7 <sup>*</sup>	11,8
3½"	2"	6,0 <sup>*</sup>	9,0
3"	2"	4,0 <sup>*</sup>	7,2
2"	1½"	3,0 <sup>*</sup>	5,7

<sup>\*</sup>These admissible values are determined by  $P_{max}$  of the p.v.c. pipe.

### 5.6. Tests of p.v.c. pumps

Two pumps with p.v.c. pump cylinders are used for the tests, a 6" pump and a 4" pump (see drawings nr. 5A and 5C). The pumps are tested on the Diever 450 windmill and on a pump test rig.

The waterlifting head of the Diever 450 is 10,5 m, of the test rig 11,5 m (see appendix 4 and 5).

#### 5.6.1. The aim of the tests

The aim of the tests is to determine:

1. the pumprod forces and the overshoot factor of formula 5.2.
2. the volumetric efficiency of the pump
3. the indicator diagram of the pump (force-position diagram).  
With this the total efficiency of the pump installation can be calculated.
4. the strength and the durability of the pump.

##### ad 1. The pumprod forces

The pumprod forces of both pumps are measured on the test rig, with 2" and 3" rising mains. On the Diever 450 the pumprod forces of both pumps are measured, hereby only with 2" rising mains. The peak force in the pumprod ( $F_{peak}$ ) is measured for different rotation speeds. The pumprod has a force reader, which is a shaft of  $\phi 16$  mm with strain gauges glued on both sides. An oscilloscope registered the forces on the vertical scale and the time on the horizontal scale. Hereby the peak forces and the rotation speeds could be determined.

##### ad 2. The volumetric efficiency

The volumetric efficiency is checked regularly by a flowmeter and a stroke counter.

$$\eta_{vol} = \frac{\text{water output per stroke}}{V_s} \times 100\% \quad (\text{formula 5.8})$$

##### ad 3. The indicator diagram

On the test rig a position reader is installed which registered the position of the piston. An oscilloscope registered the pumprod force on the vertical scale with the force reader and the position of the piston on the horizontal scale. Hereby the indicator diagram is determined. To determine the surface of the indicator diagram you get the

amount of energy input of the pump during one stroke (=  $E_{in}$ ).

$$E_{in} = \frac{V_{eff} * P_{stat}}{\eta_{vol} * \eta_{mech} * \eta_{hydr}} = V_{eff} * P_{stat} / \eta_{inst} \quad (\text{formula 5.9})$$

$V_{eff}$  = effective water output per stroke measured by the flow meter and the stroke counter

$$P_{stat} = \text{static pressure} = \rho_w * g * H$$

With formula 5.8 and 5.9 we can calculate the total efficiency of the pump installation  $\eta_{inst}$  and the product  $\eta_{mech} * \eta_{hydr}$ .

The hydraulic efficiency  $\eta_{hydr}$  separated and therefore the mechanical efficiency of the pump  $\eta_{mech}$  cannot be determined easily because the water flow and the conductor resistance in the pump and rising mains aren't constant.

#### ad 4. The strength and durability

A life test of the 4" pump is done on the Diever 450 and is still going on. The life test of the 6" pump is done on the test rig and has finished after 4,43 million strokes.

The wear of the piston and foot valve is checked several times.

#### 5.6.2. The test equipment

The measuring erection of the pump test rig is given in figure 5.1. An electromotor of 3 kW, 1430 r.p.m., drive the pump by way of a gear of three teeth belts and the Diever 450 transmission.

The crank was in the beginning variable in length like the 12PU500 but this construction wasn't strong enough. Therefore the construction changed in a crank with a fixed cranklength, see drawing nr. 4.

The transmission is identic to the one of the Diever 450, see appendix 2. The drive is built on a tower of 12 meters high. Under the tower there is a water tank of 1 meter deep in where the pump is placed. From the pump rising mains conduct the water upwards till a barrel which stands on the platform, 11,5 m higher than the waterlevel in the water tank. Through return pipe the water streams back in the water tank. A desaeration

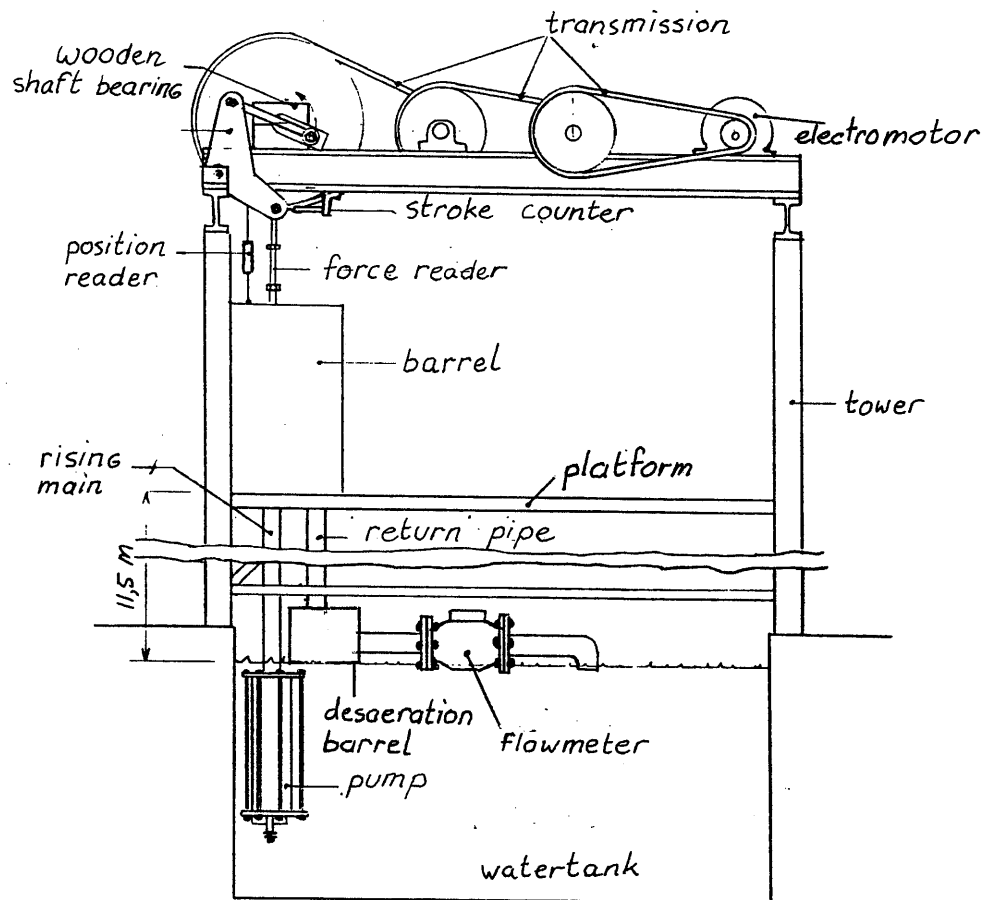


figure 5.1: the pump test rig

barrel prevents that air is going with the water trough the flowmeter. Air can cause a wrong registration of the water flow.

The force reader is placed between the transmission and the pumprod. The position reader is placed parallel to the pumprod and connected between the transmission and the tower. The stroke counter consists of an inductive reader which gives a pulse when the transmission moves close by it and a counter which counts the pulses.

On the Diever 450 the force reader was also coupled between the transmission and the pumprod. A flowmeter is placed in the return pipe. For the stroke counter we used a km-counter of a bicycle. This is cheap but it has a very short life-time.

### 5.6.3. The results

1. The overshoot factor  $k$ :

the 6" pump on the test rig :  $1,5 < k < 2,1$

the 6" pump on the Diever 450:  $1,3 < k < 1,7$

the 4" pump on the test rig :  $1,5 < k < 2,0$

the 4" pump on the Diever 450:  $1,4 < k < 2,0$

Remarks:

A higher valve lift caused a bigger  $F_{peak}$  with 2" rising mains and didn't show any obvious difference of  $F_{peak}$  with 3" rising mains. The average  $k$ -value on the Diever 450 is lower than on the test rig.

2. The volumetric efficiency:

the 6" pump:  $82\% < \eta_{vol} < 107\%$

the 4" pump:  $92\% < \eta_{vol} < 99\%$

Remarks:

The low value of 82% was caused by a leaking foot valve. The high value of 107% (more than 100%!) was caused by the inertia-effect: the kinetic energy of the accelerated water column is converted into an extra delivery.

A higher rotation speed gave a higher  $\eta_{vol}$ .

3. The indicator diagram:

the 6" pump:  $62\% < \eta_{inst} < 83\%$

the 4" pump:  $53\% < \eta_{inst} < 56\%$

Remarks:

A lower  $\eta_{vol}$  caused by a leaking foot valve gave a higher  $\eta_{inst}$ .

A higher valve lift of the foot valve only caused a higher  $\eta_{inst}$  for the 6" pump but not for the 4" pump.

4. The life tests:

The 6" pump on the test rig: The wear of the wall thickness of the p.v.c cylinder was 0,2 till 0,5 mm after 3,37 million strokes. Therefore it is wise to choose a p.v.c.pipe with a thick wall. The wear of the piston cup was negligible. The volumetric efficiency of the pump varied during the test from 82% till 107% with an average value of 98%.

The 4" pump on the Diever 450: The pump is placed on the 24th of may in 1988 and has made more or less 2,5 million strokes till now (may 1990). Nothing has broken yet. The wear of the lip thickness of the leather piston cup is about 0,2-2 mm.

### 5.7. The choice of the p.v.c. pipe as pump cylinder

In par. 5.5 we found the admissible loads for different pumps with p.v.c. cylinders and in par. 5.4 the optimal waterlifting head with  $R_c = 120$  mm. In par. 5.6 we found the overshoot factor  $k$  for the 4" pump (with  $R_c = 120$  mm) between 1,4 and 2,0 and for the 6" pump (with  $R_c = 60$  mm) between 1,3 and 2,1. These values are a little bit lower than the values of the C.W.D. (lit.10) because of the four bars mechanism. Another point is the big fluctuation in the  $k$ -values. That's why it isn't possible to predict the pumpforces accurately. For safety we choose the value:  $k = 2,0$  for  $R_c = 120$  mm. Now we can calculate the maximum admissible waterlifting heads ( $H_{max}$ ) of the pumps with formula 5.2:

Table 5.3: maximum admissible waterlifting heads

pump in inch	Outerxinner diameter in mm	risingmain in inch	pumprod in inch	$H_{max}$ in m
8"	200x190,2	4"	$\frac{3}{4}$ "	7,5
6"	160x150,6	3"	$\frac{1}{2}$ "	7,5
5"	125x117,6	3"	$\frac{1}{2}$ "	18,4
4"	110x101,6	2"	$\frac{1}{2}$ "	16,9
$3\frac{1}{2}$ "	90x81,4	2"	$\frac{1}{2}$ "	27,9
3"	75x67,8	2"	$\frac{1}{2}$ "	34,2
2"	63x53,6	$1\frac{1}{2}$ "	$\frac{1}{2}$ "	50



Table 5.4: Recommendations for choosing the pumpcylinder

waterlifting head	pump diameter in inch	rising main in inch
from 0 till 5 m	8"	4"
from 5 till 7 m	6"	3"
from 7 till 12 m	5"	3"
from 12 till 16 m	4"	2"
from 16 till 25 m	3½"	2"
from 25 till 34 m	3"	2"
from 34 till 50 m	2"	1½"

The design windspeed as functions of the waterlifting head for table 5.4 can be calculated with formula 5.5 and the data in par. 5.4:

$$v_d \approx 9,51 * \sqrt{\{(A_p - A_{pr}) * H\}}$$

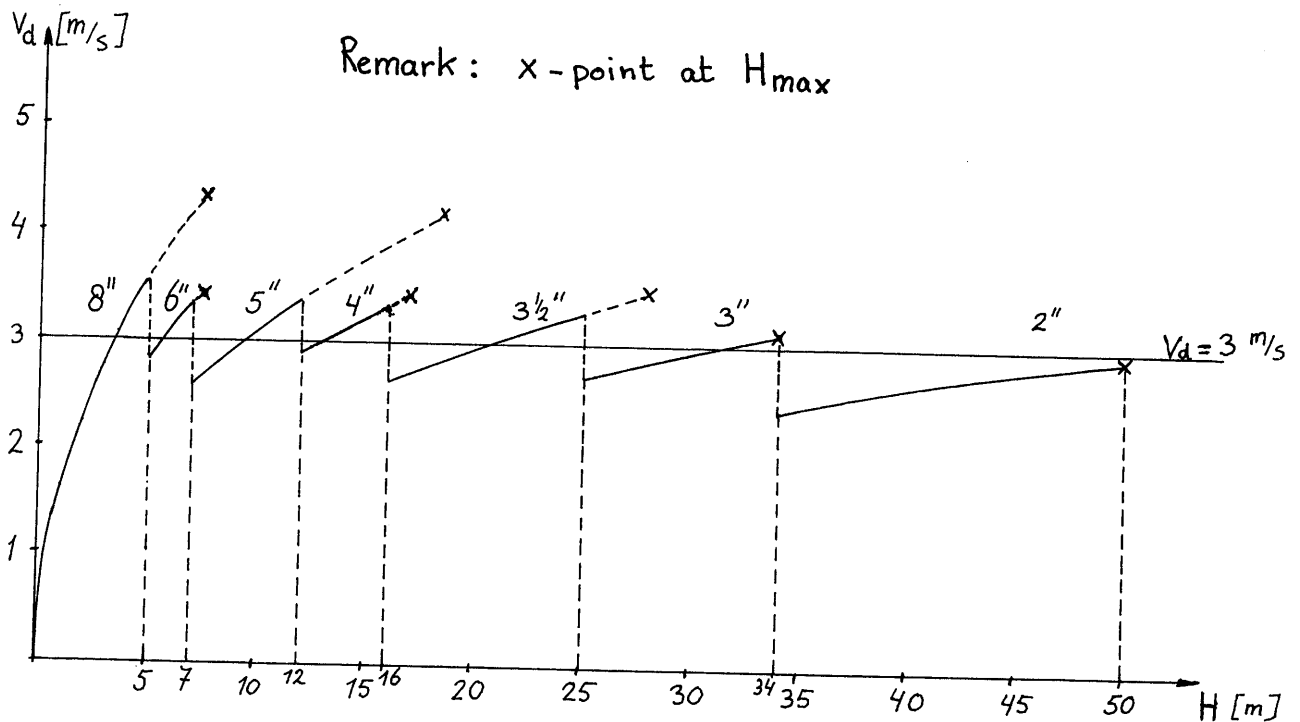


figure 5.2: the design windspeed as functions of the waterlifting head

## CHAPTER 6. THE TOWER

### 6.1. General

The evaluation of the 12PU500 in par. 1.2 has learned us that the tower of 6 m high is too low and that the tower is difficult to transport. For the Diever 450 we chose a tower with a height of 10 meters. The tower is a frame consisting of angle irons and is welded in 10 parts which are connected together with bolts. The welded parts are transportable all together on a roofrack of a landrover.

The construction has four legs which are made of  $\angle 50 \times 50 \times 5$ , the horizontals and diagonals of  $\angle 30 \times 30 \times 3$ . The towerpipe is made of 4" gaspipe (see drawings nr. 6 and 6A). At one side there are stairs till a height of 6 meters (drawing nr. 6B). It continues at two opposite sides of the tower till 9 meters. We chose for the last 3 meters two stairs at opposite sides to stay away from the turning rotor. From the stairs you can step on the seat which is connected to the head (see drawing nr. 6C). On this seat it is easy and safe to lubricate the shaftbearings and the bearings of the transmission or to do other maintenance work. This is safer then standing on a platform which is connected to the tower.

Aerodynamic forces, gravity forces and pumprod forces act on the tower. These are calculated for two situations: for maximum operating conditions and for storm conditions.

In the calculations the following conditions are assumed:

- Survival windspeed of 40 m/s.
- At the windspeed of 12 m/s it is possible that the rotor temporarily faces the wind perpendicular.
- The influence of rain, snow and glazed frost is neglected.
- The stresses in the legs will be maximal when the wind attacks the tower in a diagonal way. This is explained in fig. 6.1.

Assuming the tower to hinge on foundation blocks B and D during diagonal attack, the total wind force is divided among

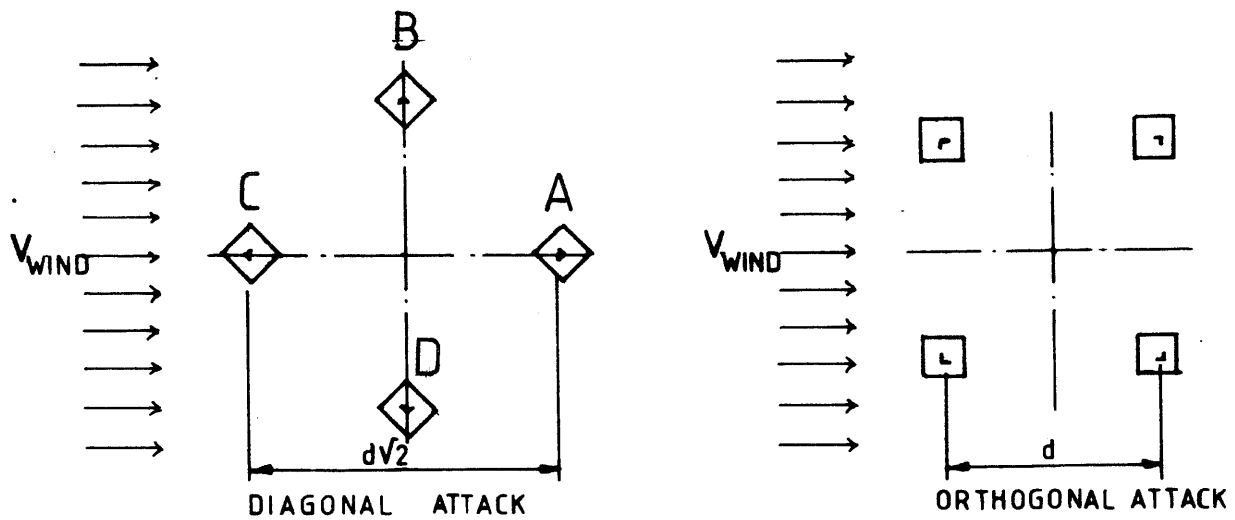


figure 6.1: top view on the tower

legs A and C, loading A to buckle and C to tensile forces. The vertical load is divided over all four legs in both situations. But the horizontal load (wind load) and the moments on the tower top cause a barforce in leg A (compression) and C (tensile) under diagonal attack which is  $\sqrt{2}$  times higher than in leg C and D (compression) and A and B (tensile) under orthogonal attack. Also the projected area of the tower under diagonal attack is bigger than under orthogonal attack. Therefore in the following calculations only the diagonal attack of the wind on the tower is taken into account.

Calculations on the tower are divided in the following parts:

Forces on the tower top (6.2)

1. at operating conditions ( $v = 12$  m/s)
2. at storm conditions ( $v = 40$  m/s)

Forces on the tower construction (6.3)

1. at operating conditions
2. at storm conditions

Stresses in the towerlegs (6.4)

1. buckling
2. tensile

Foundation (6.5)

Forces on the tower during hoisting (6.6)

## 6.2 Forces on the tower top

### 6.2.1. At operating conditions ( $v= 12$ m/s)

If we have seen in chapter 3 at  $v= 12$  m/s the rotor turns out the wind. But because of fluctuating windspeed and wind direction it is possible that the rotor temporarily faces the wind perpendicular at  $v= 12$  m/s. Therefore the next conditions are assumed:

- $v= 12$  m/s
- the rotor is turning at full speed ( $n= 80$  r.p.m.)
- the main vane is parallel to the wind direction
- Gyroscopic effects of the rotor cause a moment on the tower

<u>Data:</u>	<u>Value:</u>	<u>Unit:</u>
$v$ windspeed	12	m/s
$C_T$ rotor trust coefficient	0,89	--
$C_D$ drag force coefficient	1,2	--
$d_{rx}$ distance c.o.g. (= center of gravity) rotor to y-axis	0,8	m
$d_{rz}$ distance c.o.g. rotor to tower top	0,48	m
$d_{vx}$ distance c.o.g. main vane to y-axis	2,7	m
$d_{ax}$ distance c.o.g. side vane to y-axis	0,37	m
$d_{ay}$ distance c.o.g. side vane to x-axis	2	m
$d_{hx}$ distance c.o.g. head to y-axis	0	
$d_{hy}$ distance c.o.g. head to x-axis	0	
$F_{pr \max}$ maximum pumprod force, see below	11200	N
$m_r$ mass rotor	206	kg
$m_h$ mass head	50	kg
$m_v$ mass main vane	56	kg
$m_a$ mass side vane	13	kg
$m_{tr}$ mass transmission	8	kg
$M_{gyr}$ maximum gyroscopic moment of the rotor, see below	1540	Nm
$R_r$ rotor radius	2,25	m
$\rho_a$ air density	1,2	kg/m <sup>3</sup>

To calculate  $F_{pr \max}$  we use the table in par. 5.7. When we take

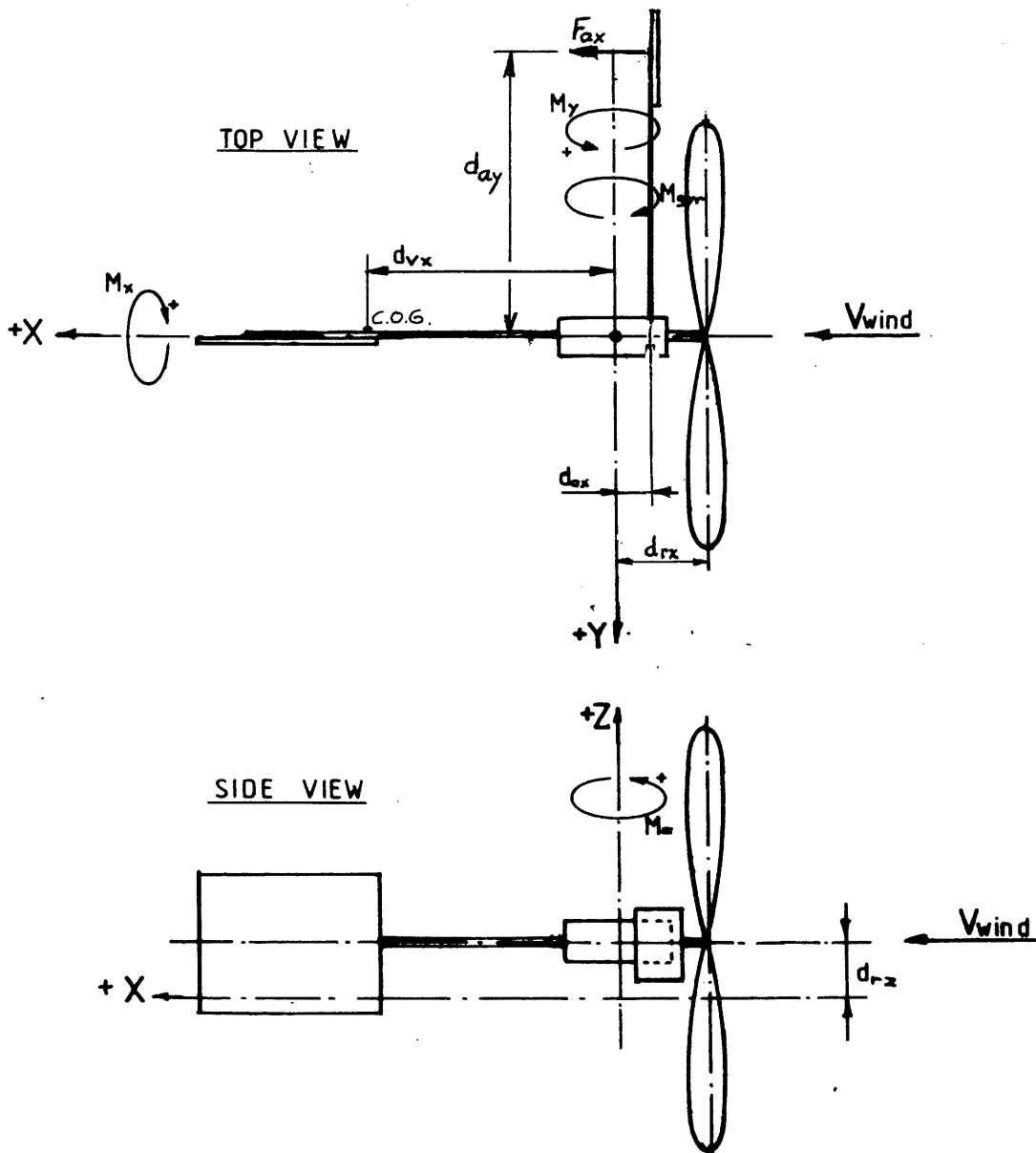


figure 6.2: situation in operating conditions

for  $k=2,0$  and  $H$  the upper limit of the chosen interval for each pump size we can calculate the pumprod force with formula 5.2. The 4" pump with  $H=16$  m has the highest force. Therefore we take this pump and waterlifting head for the calculations here.

The gyroscopic moment  $M_{gyr} = J \cdot \Omega \cdot \Omega_{yav}$ :

$J$  = moment of inertia of the rotor = 291 kgm<sup>2</sup>

$\Omega$  = angular speed of the rotor =  $80/60 \cdot 2\pi = 8.4$  rad/s

$\Omega_{yav}$  = angular speed of the head = maximum of 0.63 rad/s (this is a value measured by the CWD on the CWD5000 which is comparable to the Diever 450)

The forces and moments on the tower top:

$F_x = C_T * \frac{1}{2} * \rho_a * v^2 * \pi * R^2 + F_{ax} =$	1267	N
$F_{ax} = C_D * \frac{1}{2} * \rho_a * v^2 * A_a =$	44	N
$F_z = -(m_h + m_{tr} + m_r + m_v + m_a) * g - F_{pr \max} =$	-14463	N
$M_x = m_a * d_{ay} * g$	255	Nm
$M_y = (m_v * d_{vx} - m_a * d_{ax} - m_r * d_{rx}) * g + (F_x - F_{ax}) * d_{rz} +$ $M_{gyr} =$	1947	Nm
$M_z = \text{friction in the yaw bearing (is neglected)}$	0	Nm

6.2.2. At storm conditions (v= 40 m/s)

In storm conditions it is assumed that;

- the rotor is not turning
- the rotorplane and both vanes are parallel to the wind direction

<u>Data:</u>	<u>Value:</u>	<u>Unit:</u>
v windspeed	40	m/s
A <sub>hs</sub> side area head	0,28	m <sup>2</sup>
A <sub>rs</sub> side area rotor	1,2	m <sup>2</sup>
d <sub>ry</sub> distance c.o.g. rotor to x-axis	0,8	m
d <sub>vx</sub> distance c.o.g. main vane to y-axis	2,46	m
d <sub>vy</sub> distance c.o.g. main vane to x-axis	0,24	m
d <sub>vz</sub> distance c.o.g. main vane to x-axis	0,43	m
d <sub>ax</sub> distance c.o.g. side vane to y-axis	2	m
d <sub>ay</sub> distance c.o.g. side vane to x-axis	0,37	m
d <sub>avx</sub> distance aerodynamic center to y-axis	3,4	m
m <sub>p+pr</sub> mass of piston + pumprod	37	kg

Calculations and results:

$F_{h,s} = \text{sideways force on head} =$ $C_D * \frac{1}{2} * \rho_a * v^2 * A_{hs}$	322	N
$F_{r,s} = \text{sideways force on rotor} =$ $C_D * \frac{1}{2} * \rho_a * v^2 * A_{rs}$	1382	N

As the sum of moments around z-axis = 0 we find;

$$F_{v,y} * d_{avx} - F_{r,s} * d_{ry} = 0$$

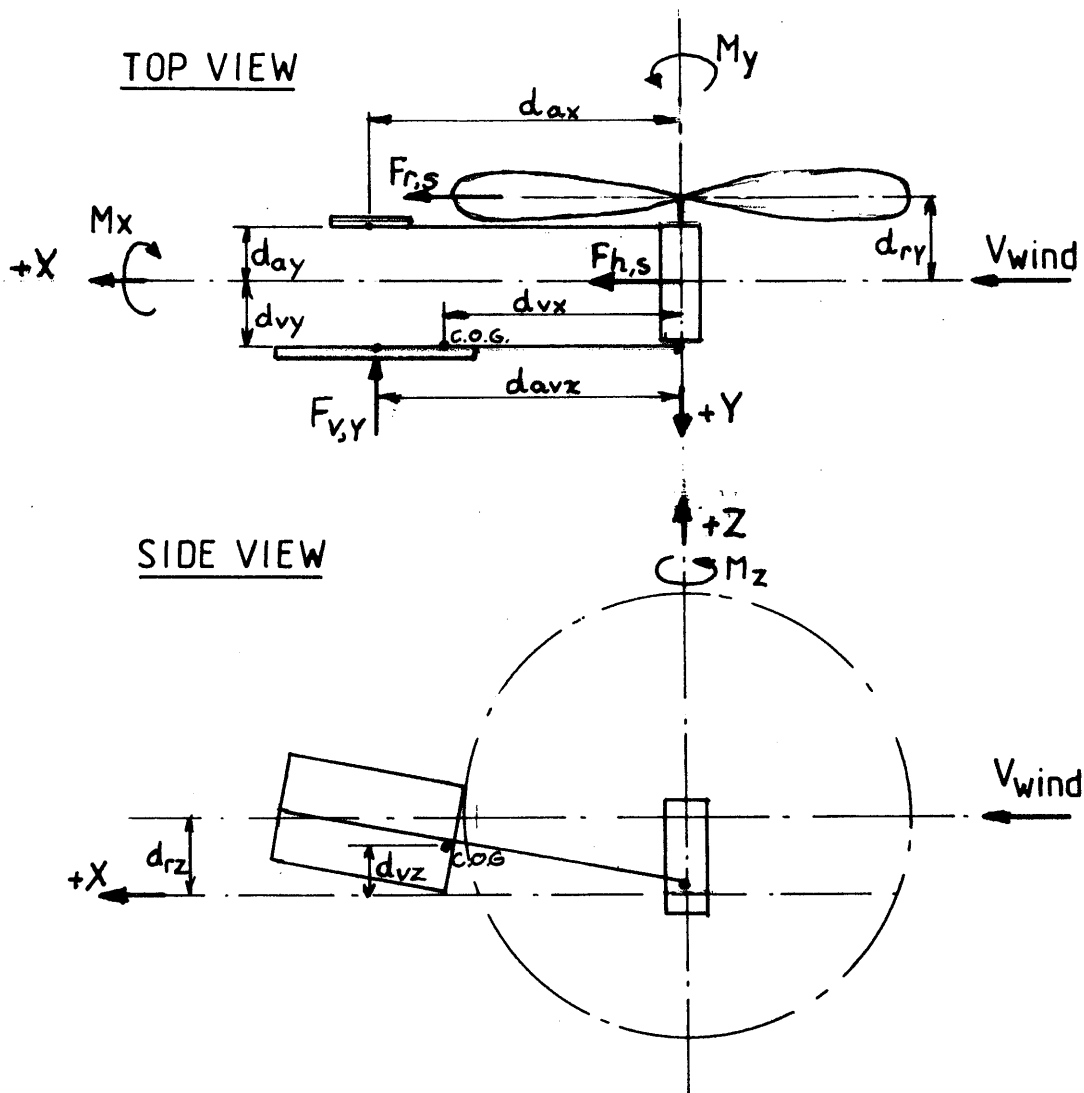


figure 6.3: situation in storm conditions

$F_{v,y}$  force on main vane in y-direction 325 N

The forces and moments on the tower top:

$F_x = F_{h,s} + F_{r,s} =$	1704	N
$F_y = -F_{v,y} =$	-325	N
$F_z = -(m_h + m_{tr} + m_r + m_v + m_a + m_{p+pr}) * g =$	-3626	N
$M_x = (-m_v * d_{vy} + m_r * d_{ry} + m_a * d_{ay}) * g + F_{v,y} * d_{vz} =$	1724	Nm
$M_y = (m_v * d_{vx} + m_a * d_{ax}) * g + F_{r,s} * d_{rz} =$	1811	Nm
$M_z =$ friction in the yaw bearing (is neglected)	0	Nm

### 6.3. Forces on the tower construction

First the load is calculated for the operating and storm conditions and the reaction forces in the supporting points. With these results the barforces in the legs can be calculated as followed:

The barforce of a leg is equal to the vertical reaction force in the supporting point of the leg divided by the cosines of the angle between the leg and the vertical, for example:

$$F_{leg\ AE} = F_{VA} / \cos 12^\circ.$$

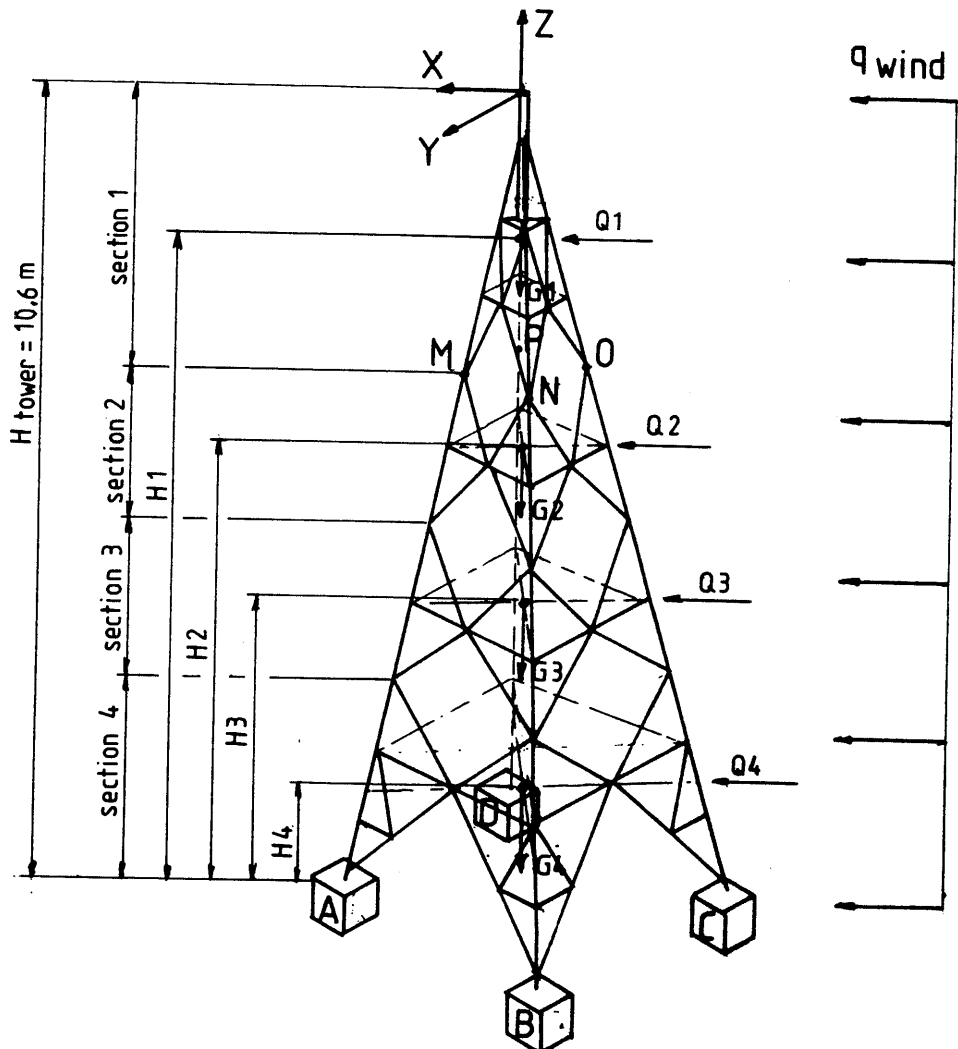


figure 6.4: diagonal attack of the wind on the tower construction

The following simplifications are made:



- the tower is split up in four sections, see fig. 6.4
- all the legs are exposed to the wind (no wind shadow)
- the rising main ends 2,5 m below the tower top
- the projected length of the horizontals is the real length ( $l_h$ ) multiplied by  $\frac{1}{2}\sqrt{2}$ , the projected area of the horizontals is  $\frac{1}{2}\sqrt{2} \cdot l_h \cdot t$  ( $t$ = width of the profile)
- the total projected length of the diagonals ( $l_d$ ) is equal to  $2 \cdot 4 \cdot \text{height}$  of the section, the projected area of the diagonals is the length multiplied by  $t \cdot \frac{1}{2} \cdot (\sqrt{2} + \frac{1}{2}\sqrt{2}) = 1,06 \cdot t$
- the point of impacts (=p.o.i.) of the section is in the middle

### 6.3.1. At operating conditions ( $v= 12$ m/s)

Forces and stresses on the tower are caused by:

- forces and moments on the tower top, see par. 6.2.1
- the wind load on the tower construction
- the tower weight
- the weight of the pump and rising main

<u>Data:</u>	<u>Value:</u>	<u>Unit:</u>
$A_{proj1}$ projected area section 1	1,64	m <sup>2</sup>
$A_{proj2}$ projected area section 2	1,20	m <sup>2</sup>
$A_{proj3}$ projected area section 3	1,26	m <sup>2</sup>
$A_{proj4}$ projected area section 4	2,24	m <sup>2</sup>
$C_D$ drag coefficient: for angle irons	1,6	--
for rising main and towerpipe	1,2	--
$H_1$ height p.o.i. of section 1	8,5	m
$H_2$ height p.o.i. of section 2	6	m
$H_3$ height p.o.i. of section 3	4	m
$H_4$ height p.o.i. of section 4	1,5	m
$m_1$ mass of section 1	107	kg
$m_2$ mass of section 2	67	kg
$m_3$ mass of section 3	69	kg
$m_4$ mass of section 4	119	kg
$m_t$ mass of tower	362	kg

$m_{pu+rm}$  mass pump + rising main 140 kg

Forces on the tower:

The tower experiences the forces and moments on the tower top calculated in par. 6.2.1, and:

	<u>Value:</u>	<u>Unit:</u>
$Q_1 =$ wind load on section 1= $C_D * \frac{1}{2} * \rho_a * v^2 * A_1$	227	N
$Q_2$ wind load on section 2	166	N
$Q_3$ wind load on section 3	174	N
$Q_4$ wind load on section 4	310	N
$G_1 =$ weight of section 1 = $-(m_1 + m_{pu+rm}) * g$	-2421	N
$G_2 =$ weight of section 2 = $-m_2 * g$	-660	N
$G_3 =$ weight of section 3	-680	N
$G_4 =$ weight of section 4	-1170	N

Calculations and results:

First the reaction forces in the supporting points M, N, O and P of section 1 are calculated and then in A, B, C and D. Only the vertical reaction forces are calculated because these are necessary for the calculations of the barforces in the legs.

In M, N, O and P:

$F_{VM}$  = vertical reaction force in M =

$$\frac{1}{4} * (-F_2 + G_1) + (M_y + F_x * 3,6 + Q_1 * 1,8) / 1,36 = 9307 \text{ N}$$

$F_{VN}$  = vertical reaction force in N =

$$\frac{1}{4} * (-F_2 + G_1) - (M_x - F_y * 3,6) / 1,36 = 4033 \text{ N}$$

$F_{VO}$  = vertical reaction force in O =

$$\frac{1}{4} * (-F_2 + G_1) - (M_y + F_x * 3,6 + Q_1 * 1,8) / 1,36 = -865 \text{ N}$$

$F_{VP}$  = vertical reaction force in P =

$$\frac{1}{4} * (-F_2 + G_1) + (M_x - F_y * 3,6) / 1,36 = 4409 \text{ N}$$

In A, B, C and D:

$F_{VA}$  = vertical reaction force in A =

$$\frac{1}{4} * (-F_2 + G_1 + G_2 + G_3 + G_4) + (M_y + F_x * 10,6 + Q_1 * 8,5 + Q_2 * 6 + Q_3 * 4 + Q_4 * 1,5) / 4,2 = 4849 + 4634 = 9483 \text{ N}$$

$F_{vB}$  = vertical reaction force in B =  
 $\frac{1}{4} * (-F_z + G_1 + G_2 + G_3 + G_4) - (M_x - F_y * 10,6) / 4,2 = 4849 - 61 =$   
 4788 N

$F_{vC}$  = vertical reaction force in C =  
 4849 - 4634 = 215 N

$F_{vD}$  = vertical reaction force in D =  
 4849 + 61 = 4910 N

Conclusion:

The maximum compression and tensile loads occur respectively on legs AE and OS. These loads will be compared with loads under storm conditions, see next paragraph.

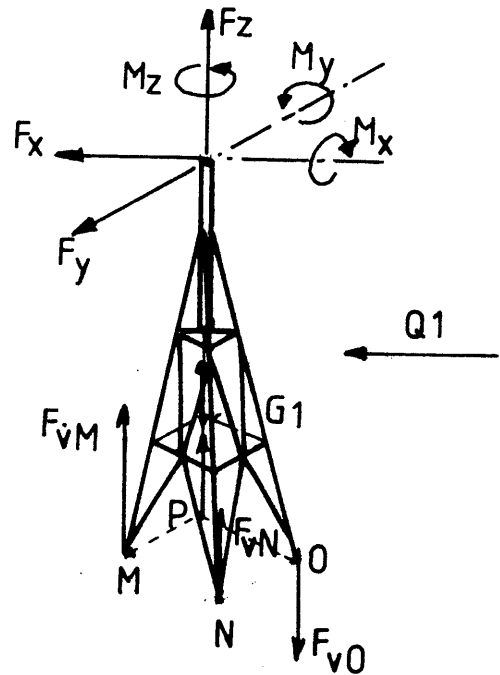


figure 6.5: load and reaction forces on section 1

6.3.2. At storm conditions (v= 40 m/s)

Forces and stresses on the tower are caused by:

- forces and moments on the tower top, see par 6.2.2.
- the wind load on the tower
- the tower weight
- the weight of pump and rising main, both filled with water

Data:

		<u>Value:</u>	<u>Unit:</u>
v	windspeed	40	m/s
$m_v$	mass of the water column in pump and rising main	31	kg

Forces on the tower:

The tower experiences the forces and moments on the tower top and:

$Q_1$	wind load on section 1	2520	N
$Q_2$	wind load on section 2	1850	N
$Q_3$	wind load on section 3	1940	N
$Q_4$	wind load on section 4	3450	N

$G_1$	weight of section 1 = $-(m_1 + m_{pu+rm} + m_w) * g = -2724$	N
$G_2$	weight of section 2	-660 N
$G_3$	weight of section 3	-680 N
$G_4$	weight of section 4	-1170 N

#### Calculations and results:

The vertical reaction forces in M, N, O and P:

$$F_{vM} = 1588 + 9178 = 10766 \text{ N}$$

$$F_{vN} = 1588 - 2128 = -540 \text{ N}$$

$$F_{vO} = 1588 - 9178 = -7590 \text{ N}$$

$$F_{vP} = 1588 + 2128 = 3716 \text{ N}$$

In A, B, C and D:

$$F_{vA} = 2215 + 15554 = 17769 \text{ N}$$

$$F_{vB} = 2215 - 1231 = 984 \text{ N}$$

$$F_{vC} = 2215 - 15554 = -13339 \text{ N}$$

$$F_{vD} = 2215 + 1231 = 3446 \text{ N}$$

#### Conclusions:

Maximum loads occur on legs AE (compression) and CG (tensile). These loads are used for the stress calculations. The storm conditions are decisive for the tower construction and also for the foundation block dimensions.

#### 6.4. Stresses in the towerlegs

As already given in par. 6.2 the barforces in the legs are:

$$F_{\text{bar}} = F_{\text{reaction}} / \cos 12^\circ$$

This means that the maximum compression force is:

$$F_{\text{bar}} = 17769 / 0,955 = 18606 \text{ N}$$

The maximum tensile force is:  $F_{\text{bar}} = 13339 / 0,955 = 13967 \text{ N}$

The compression force is decisive for the strength of the legs because of buckling. Therefore the maximum buckling stress is calculated:

<u>Data:</u>	<u>Value:</u>	<u>Unit:</u>
$l_b$ buckling length	1000	mm

$i_{min}$	minimum radius of gyration L50x50x5	9,7	mm
A	cross-section area L50x50x5	480	mm <sup>2</sup>
$F_{bar}$	barforce (maximum compression)	18606	N
$A_{bolt}$	stress area of M10 bolt	74	mm <sup>2</sup>

The connections of the legs consists of three bolts M10

#### Calculations and results:

$\lambda$	slenderness ratio= $l_b/i_{min}$	103	--
$\omega$	buckling coefficient (see table in lit. 13)	2,12	--
$\sigma_{buckle}$	buckling stress= $\omega * F_{bar} / A$	82	N/mm <sup>2</sup>
$\tau_{bolt}$	shear stress in bolt M10= $F_{bar} / (3 * A_{bolt}) =$	83,5	N/mm <sup>2</sup>

#### Conclusion:

As the maximum admissible stress is 160 N/mm<sup>2</sup> and the calculated stress is 82 N/mm<sup>2</sup> it is obvious that the legs are strong enough.

The admissible shear stress for bolts is:  $\bar{\tau} = 0,7 * 160 = 112$  N/mm<sup>2</sup>. The calculated shear stress is smaller.

#### 6.5. The foundation

The calculated maximum reaction force in point C is decisive for the dimensions of the foundation blocks. The blocks must be heavy enough to overcome the tensile forces.

<u>Data:</u>		<u>Value:</u>	<u>Unit:</u>
$H_b$	height of block	0,9	m
$W_b$	width of block	0,9	m
$L_b$	length of block	0,9	m
$\rho_c$	density of concrete	2100	kg/m <sup>3</sup>
$F_{vC}$	vertical reaction force in C	13327	N

#### Calculations and results:

$G_b$	block weight= $H_b * W_b * L_b * \rho_c * g$	15003	N
-------	--	-------	---

#### Conclusion:

The block is heavy enough to take the maximum tensile force

### 6.6. Forces on the tower during hoisting

The installation of the windpump can be done by two methods. The first method is the method of the 12PU500, explained in appendix 6 and lit. 3. Only the tower of the Diever 450 is higher. Therefore the poles must be higher (about 6 m). The other method is as followed: First the whole windpump is assembled in the horizontal position. two legs are connected to the foundation with each a bolt M16, see drawing nr. 6E. This bolt is the hinge when the windmill is hoisted vertically. The load during hoisting is caused by the weight of the tower and head with rotor, transmission and vanes. Windpressure is not taken in account. The tensile force in the steel cable causes compression forces in the tower. It is assumed that the cable support yoke has a height of 5,8 m (see fig. 6.6 and drawing nr. 7).

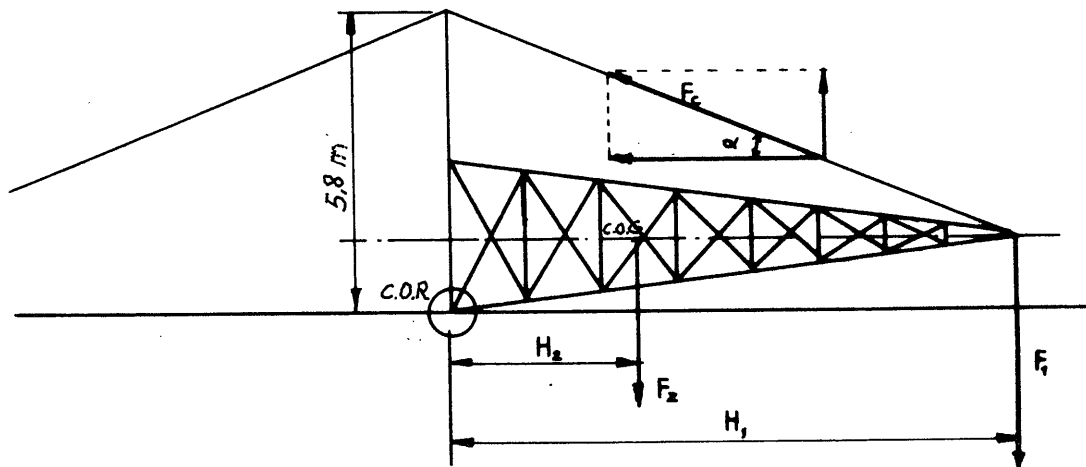


figure 6.6: situation during hoisting

The stresses in the legs and near the centre of rotation (c.o.r.) are checked:

<u>Data:</u>		<u>Value:</u>	<u>Unit:</u>
$H_2$	horizontal distance between c.o.r. and c.o.g. of the tower	4,9	m
$H_1$	height tower till head, see fig. 6.6	10	m
$m_t$	mass of tower	362	kg
$m_{htot}$	mass of head, rotor, transmission and		

	vanes	313	kg
$\alpha$	angle between horizontal and cable	21	degrees
$W_b$	bending moment of resistance L50x50x5	3050	mm <sup>3</sup>

Calculations and results:

$F_c$	tensile force in cable= $(H_2 * m_t + H_1 * m_{htot}) * g / (H_1 * \sin \alpha)$	12166	N
$F_{bar}$	bar force in tower leg= $(F_c * \cos \alpha) / 2$	5134	N
$\sigma_{buckle}$	buckling stress= $F_{bar} * \omega / A$	22,7	N/mm <sup>2</sup>
$F_{c.o.r.}$	reaction force in c.o.r.	5213	N
$D_{min}$	minimum diameter bolts in c.o.r.= $4 / \pi * \sqrt{(F_{c.o.r.} / 160)}$	7,3	mm

Conclusions:

- The towerlegs are strong enough to take the barforces which appears during hoisting.
- The M16 bolts in c.o.r. are strong enough too.
- The tensile force in the cable is 12166 N. This is too high to pull by manpower even with pulleys. It is necessary to use a linch.
- Calculating with a calculation factor of 1,5 and a safety factor of 6 the minimum breaking load of the cable must be 109 kN.

## CHAPTER 7. PROPERTIES AND CHARACTERISTICS

### 7.1. The input-output relation

For installing a windpump at a given site, the next parameters of the site are important:

- the average (annual) windspeed ( $\bar{v}$ )
- the waterlifting head (H)

The power input at the average windspeed  $\bar{v}$  is:

$$P_{\text{wind}} = \frac{1}{2} \cdot \rho_a \cdot A_r \cdot \bar{v}^3$$

The load must be related to the input power. Therefore we have to choose the design windspeed ( $v_d$ ). From lit. 10 and 14 it is recommended to choose the design windspeed more or less equal to the average windspeed:

$$v_d \approx \bar{v}$$

By using formula 5.5 we can determine the optimal swept volume of the pump. A higher design windspeed results in a bigger pump, which causes higher pumprod forces. However the range of the design windspeed is limited by the admissible pumprod forces, see chapter 5. But we must not forget that in chapter 2 we chose  $v_d = 3$  m/s for the rotor. That means that the rotor design is optimal only at the windspeed  $v = 3$  m/s.

The maximum power coefficient of the Diever 450 isn't measured in a windtunnel yet. We assume that the calculation of the  $C_p$ -value of par. 2.4 gives the correct value:  $C_{p,\text{max}} = 0,27$ .

Fig. 7.1 gives the  $C_p$ -value related to the tipspeed ratio, see lit. 16. Of course this graph must be verified by a windtunnel test.

The power of the rotor is:

$$P_{\text{rotor}} = C_p \cdot P_{\text{wind}}$$

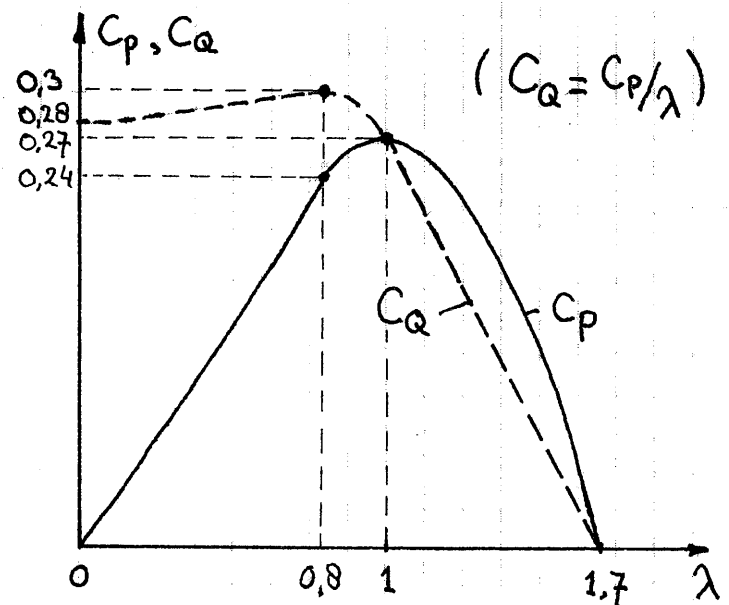


figure 7.1:  $C_p$  and  $C_q$  as function of  $\lambda$



There are other losses of power beside of the rotor:

- in the transmission by friction in the bearings. The efficiency of the transmission with wooden bearings ( $\eta_{tr}$ ) is between 0,92 and 0,98.
  - in the pump installation. The efficiency of the pump installation ( $\eta_{inst}$ ) consists of:
    - \* mechanical efficiency ( $\eta_{mech}$ )
    - \* hydraulic efficiency ( $\eta_{hydr}$ )
    - \* volumetric efficiency ( $\eta_{vol}$ )
- The measurements in chapter 5 shows that efficiency of the pump installation  $\eta_{inst}$  varied between 0,53 and 0,83. The volumetric efficiency  $\eta_{vol}$  varied between 0,82 and 1,07.

The total efficiency of the pump installation and the transmission is:  $\eta_{tot} = \eta_{tr} * \eta_{inst}$ .

$$\left. \begin{array}{l} \text{We assume that: } \eta_{inst} = 0,70 \\ \eta_{tr} = 0,95 \end{array} \right\} \rightarrow \eta_{tot} = 0,67$$

The relation between the input- and output power is:

$$P_{out} = C_p * \eta_{tot} * P_{wind} \quad (\text{formula 7.1})$$

(The product  $C_p * \eta_{tot}$  is called the overall efficiency of the windpump)

The output power is also equal to:

$$P_{out} = \rho_v * g * H * \Phi_{eff} \quad (\text{formula 7.2})$$

$$\text{with: } \Phi_{eff} = \eta_{vol} * V_s * n \quad (\text{formula 7.3})$$

The formulas 7.2 and 7.3 together:

$$P_{out} = \rho_v * g * H * \eta_{vol} * V_s * n \quad (\text{formula 7.4})$$

The volumetric efficiency can variate from 0,9 for low rotation speeds till 1,1 for high rotation speeds. We assume that  $\eta_{vol}$  is constant, namely 0,9.

The relation between the windspeed and the rotation speed of the rotor is put in a graph, see fig. 7.2. The graph is made by using the graphs in fig. 3.7 and 3.8 and the  $\lambda$ -values in fig. 2.6. The  $\lambda$ -values are measured with a 4" pump and a

waterlifting head of 10,5 m, see par. 2.6.

The rotation speed in formula:

$$n = v \cdot \cos \delta \cdot \lambda / (\pi \cdot D_T) \quad (\text{formula 7.5})$$

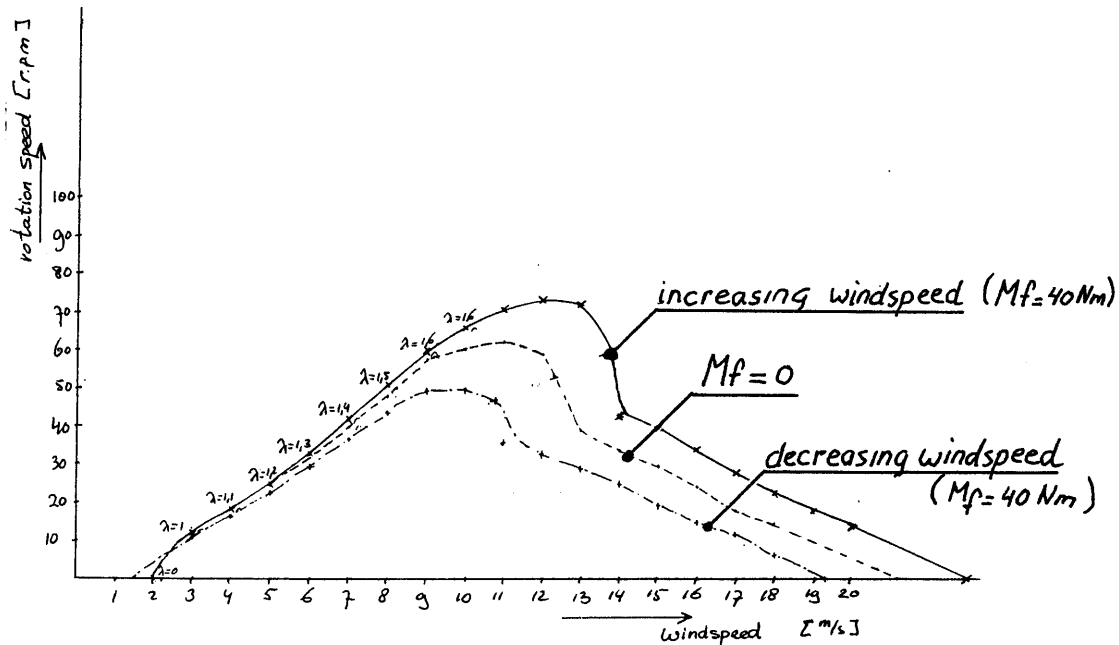


figure 7.2: the rotation speed as function of the windspeed

Now we can make the graph of the power output as function of the windspeed. When we use the formula 5.6 of par. 5.4 (with  $v_d = 3$  m/s):  $V_s = 24,8 \cdot 10^{-3} / H$  [m<sup>3</sup>] in formula 7.4 then the output power is:

$$P_{out} = 243 \cdot n \quad [\text{W}], \quad n \text{ in } [\text{r.p.s.}] \quad (\text{formula 7.6})$$

$$(\quad = 4,05 \cdot n \quad [\text{W}], \quad n \text{ in } [\text{r.p.m.}])$$

In fig. 7.3 the power output is given as function of the windspeed, without the influence of the friction in the yaw bearing.

The formula 7.6 is only valid for the design windspeed of 3 m/s. If the average windspeed isn't equal to 3 m/s then it is more efficient to choose another swept volume of the pump. For example:  $\bar{v} = 4$  m/s

$$v_d = \bar{v} = 4 \text{ m/s}$$

Assuming that  $\lambda_d = 1$  and  $C_{p,max} = 0,27$  the optimal swept volume is:

$$V_s = 40 \cdot 10^{-3} / H \quad [\text{m}^3] \rightarrow P_{out} = 392 \cdot n$$

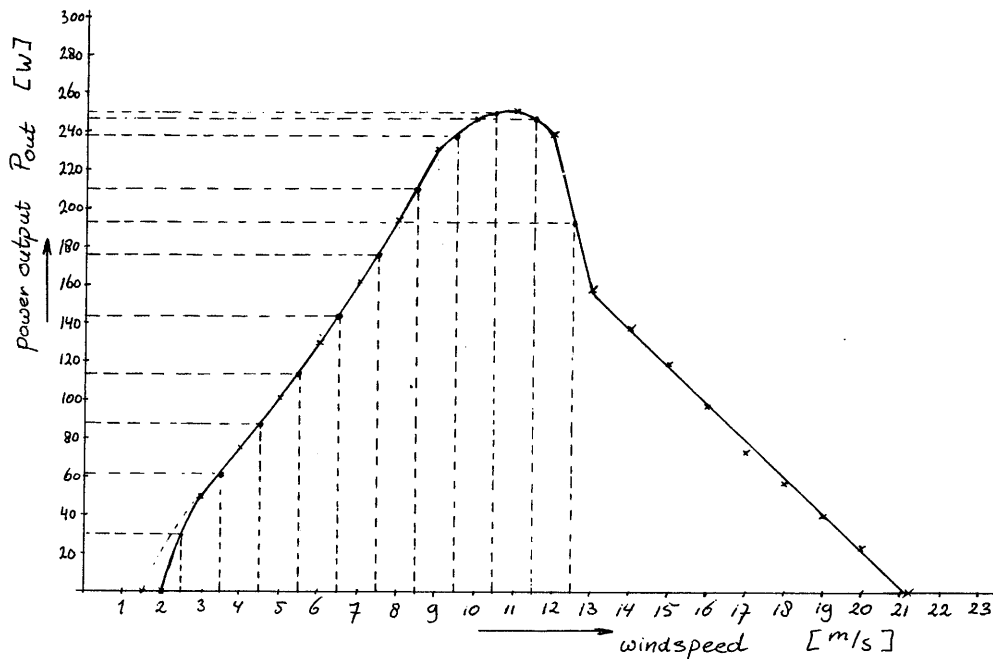


figure 7.3: the power output as function of the windspeed

## 7.2. Prediction of the output

The calculation of the average power output of a windpump can be made by a simple equation of formula 7.1:

$$\bar{P}_{out} = C_p \cdot \eta_{tot} \cdot \frac{1}{2} \cdot \rho_a \cdot A_r \cdot \bar{v}^3 \quad (\text{formula 7.7})$$

This formula is simple but not very accurate. A more accurate method is using a frequency distribution of the windspeeds, see lit. 1 and 5. In the following example the graphs of fig. 7.3 and 7.4 are used. Fig. 7.4 gives an example of the frequency distribution of hourly windspeeds in Babatpur, India of the month March over the years 1976 and 1979. If such a frequency distribution is known the next method can be used for a more accurate calculation of the output:

- First we take  $\bar{v}_h$  as the hourly average windspeed of an interval, which is the windspeed in the middle of the interval, see fig. 7.4.
- From fig. 7.3 we find  $P_{out}$  at the windspeed  $v_h$ :  
 $\bar{P}_{out}(\bar{v}_h) = \text{average power output of an interval}$
- The water output:  $\Phi_{eff} = P_{out} / (\rho_w \cdot g \cdot H) \text{ [m}^3/\text{s]}$   
 $= 3600 \cdot P_{out} / (\rho_w \cdot g \cdot H) \text{ [m}^3/\text{h]}$

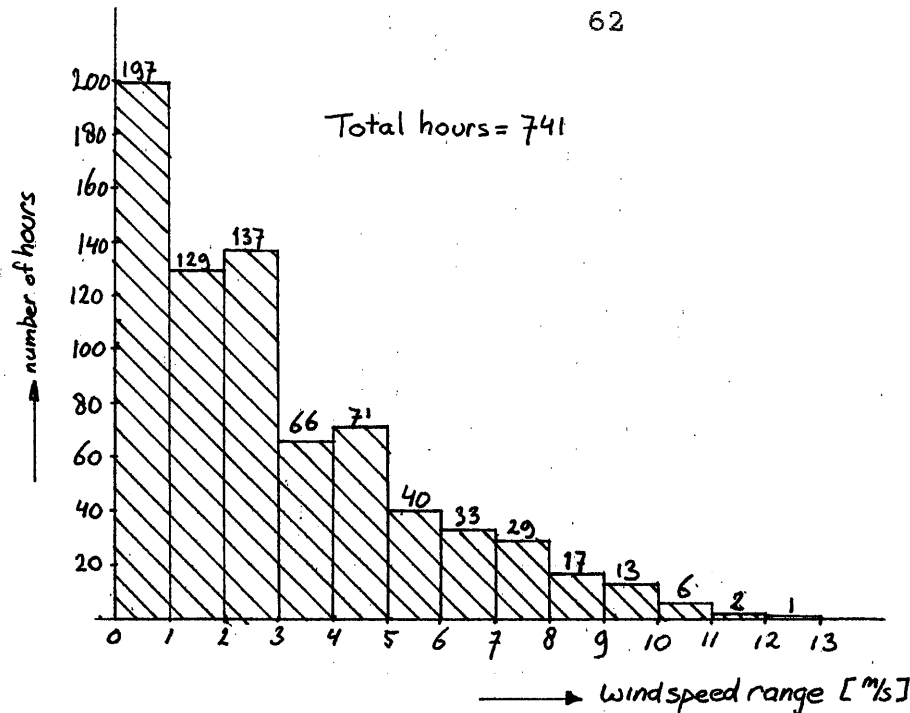


figure 7.4: frequency distribution of hourly windspeeds in Babatpur

the total water output in the month=

$$\Phi_{\text{month}} = 3600 / (\rho_w * g * H) * \sum_{v_{\text{start}}}^{v_{\text{max}}} t * \bar{P}_{\text{out}}(\bar{v}_h) \quad [\text{m}^3/\text{month}]$$

with:

$v_{\text{max}}$  = maximum windspeed by which the rotor turns (in the example  $v_{\text{max}} = 21$  m/s)

$v_{\text{start}}$  = starting windspeed (in the example 2 m/s)

$t$  = number of hours per interval, see fig. 7.4

$H$  = waterlifting head (in the example 10,5 m)

$$\begin{aligned} \Phi_{\text{month}} &= 144 + 141 + 219 + 160 + 166 + 179 + 108 + 52 + 17 + 7 = \\ &= 1318 \text{ m}^3/\text{month} (= 42,5 \text{ m}^3/\text{day}) \end{aligned}$$

Remark: the rotor stops turning at  $v_{\text{stop}}$  which is lower than  $v_{\text{start}}$ . So sometimes there can be output when the windspeed is between  $v_{\text{stop}}$  and  $v_{\text{start}}$ . In the calculation we neglect it because we don't know how many times and the output is very small in comparison to the total output.

The calculation of the output with formula 7.7:

the average windspeed  $\bar{v} = 3,2$  m/s

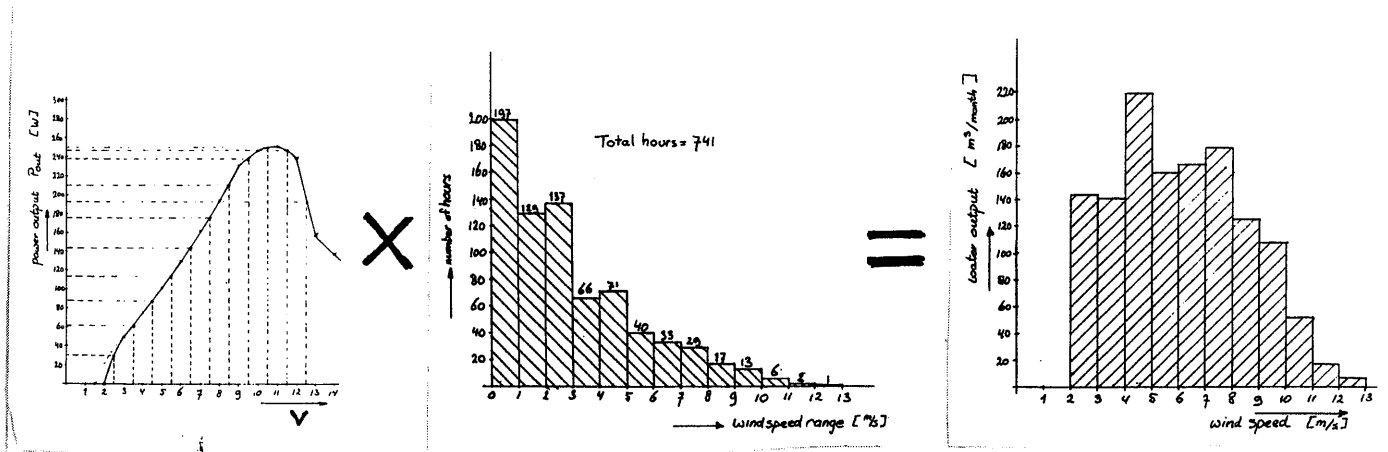


figure 7.5: the calculation of the water output

$$\bar{P}_{out} = 60 \text{ W}$$

$$\Phi_{eff} = 50 \text{ m}^3/\text{day}$$

$$\Phi_{month} = 1562 \text{ m}^3/\text{month}$$

This is almost 20% more than the first result. The formula 7.7 is less reliable but it is a way to predict the water output roughly if only the average windspeed is known.

### 7.3. Costs and benefits

The goal of a financial analysis is to find out if the benefits outweigh the costs. The costs of a windpump system are:

- production and installation
- storage tank
- maintenance and reparations

The costs depend on:

- number of windpumps (the cost of a windpump is lower when the number is higher)
- materials
- transport
- depreciation of equipment
- number and price of manhours
- capacity of the storage tank

The optimum capacity of the storage tank can be calculated when we know:

- the time distribution of the windspeed (lit. 1 and 5)
- the demanded water quantity
- the chosen design windspeed of the windpump

When we choose a high design windspeed the water output will be high too, but also the starting windspeed. That makes the periods without output longer. A storage tank is necessary to bridge the periods without output. With a high design windspeed the storage tank needs a big capacity and that makes it expensive. Studies are made to find out how to choose the optimum design windspeed, see lit. 10 and 14. The conclusion is that the optimum design windspeed is more or less equal to the average windspeed of the site.

The benefits are difficult to calculate. It is possible to predict the water output when there are wind data available. But more difficult is to find out for example what the agricultural benefits are when the windpump is used for irrigation. It depends on the type of crops, the availability of water in critical months, the seasonal variation in the available water quantities, the evaporation, etc. Benefits depend also on the life of the windpump which depend on the quality of the design, the production and the maintenance. Because the design is still new it is difficult to predict the life.

## CONCLUSIONS

The Diever 450 can be manufactured in a simple workshop, like the 12PU500. The materials are used efficiently, easily available and cheap. The dimensional accuracy of the design is low for most parts. The windmill is transportable on a roof-rack or a car trailer.

The design tip speed ratio is lower (one instead of two of the 12PU500) because it results in less wear of the piston and the pumpcylinder and lower gyroscopic moment of the rotor.

The disadvantage of the rotor is a lower  $C_{p,max}$ -value than the  $C_{p,max}$  of the 12PU500, 0,27 instead of 0,32. The value of 0,27 has to be checked by a windtunnel test. On the other hand the  $C_{Q,start}$  is higher, 0,28 instead of 0,125 which results in a better starting behaviour.

The design windspeed is limited by the admissible pumprod forces (maximum 4,3 m/s for the 8" and 4,2 for the 5" p.v.c. pump). For the rotor design we chose:  $v_d = 3$  m/s.

The rotor construction appears to be strong enough. Till now there are no cracked blade tips and blade supports on the prototype.

The inclined hinged vane system seems to be a better safety system than the hysteresis system. Of course it has to be tested on the prototype to find out its behaviour ( $\delta$ -v curve) and the influence of the friction in the yaw bearings on the behaviour. The yaw bearings are made of impregnated wood which need less lubrication but has more friction than for instance ball-bearings.

The head cannot lift from the towerpipe because of a ring fixed on the towerpipe above the upper yaw bearing.

The four bars mechanism of the transmission replaces the crank/connecting-rod/cross-head mechanism, so the problems

with the cross-head are solved. the crank of appendix 6 is partly removable. The transmission with wooden bearings can be cheaper than with ball-bearings, but it is necessary that all the bearings are axially parallel. This makes the manufacturing rather difficult. With self-aligning ball-bearings as in appendix 7 the accuracy of axial parallelism can be less.

The acceleration of the piston in its lowest position is lower with the four bars mechanism.

The peakforces in the pumprod can be lower by:

- a lower design windspeed
- a lower  $(A_p - A_{pr}) / (A_{rn} - A_{pr})$  ratio. This can be achieved by:
  - \* a longer stroke  $\rightarrow (A_p - A_{pr})$  smaller
  - \* larger rising mains  $\rightarrow (A_{rn} - A_{pr})$  larger
- a lower spring stiffness of the pump system. This can be achieved by airchambers.

The pump of the Diever 450 has no airchambers. Therefore the construction is simple. The disadvantage is that the design windspeed is limited because the peakforces may not overstep the admissible forces, see fig. 5.2.

The number of strokes for the Diever 450 is more or less 6,5 million pro year at an average windspeed of 3 m/s. The wear of the 6" p.v.c.pump was small after 3,37 million strokes on the test rig. But a longer life test is advisable to test the wear after two years pumping at  $\bar{v} = 3$  m/s (13 million strokes).

The tower is 10 m high. The tower construction is strong enough according to the requirements and calculations in chapter 6.

The windmill can be installed by hand. The use of a lynch makes the installation easier, safer and faster than the method of the 12PU500 (see appendix 8).

The rated power output is more or less 250 W at  $v = 11$  m/s and a rotation speed of 60 rpm, neglecting the friction in the yaw bearings. In chapter 5 we chose  $n = 60$  rpm at  $v = 9$  m/s and the rotor perpendicular in the wind for the fatigue strength

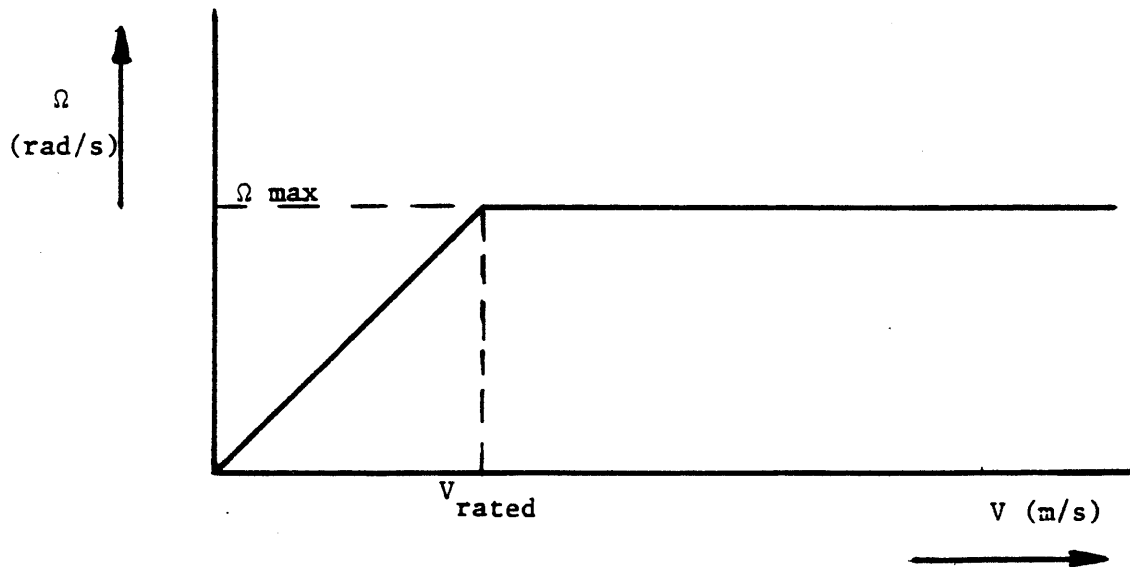


calculations. According to fig. 7.2 the rotation speed is 57 rpm at  $v = 9$  m/s. The fatigue strength calculations are made 'on the safe side'.

## RECOMMENDATIONS

The windpump Diever 450 isn't been tested completely. More research is advisable before large number of these windpumps can be produced. Recommendations for more research are:

- Windtunneltests. In a windtunnel tests can be done with a small model of the Diever 450 to measure:
  - \* the tipspeed ratio with and without load
  - \* the behaviour of the safety system by measuring the angle  $\delta$  at different windspeeds
- Improving the starting behaviour by a contra weight and a leak hole in the piston.
- Design of a transmission which gives a longer stroke length than 250 mm. This can be done in combination with a design of a rotor eccentric from the towerpipe in stead of the side vane. It means a completely different head construction. The behaviour of a safety system with a eccentric rotor is more smooth than with a side vane. A longer stroke needs a smaller piston area to keep the same swept volume of the pump. Therefore the pumprod forces will be smaller, see formula 5.2.
- Changing the prototype according to the design changes as aforesaid and measuring the relation between the rotation speed-windspeed and the output characteristic
- Improving the safety system on the prototype to approach the ideal behaviour, see the graph on the next page.
- Lowering the spring stiffness of the pump system by a more elastic piston valve.
- The WOT is trying to find more possibilities for the material choice of the pump cylinder. Tests are done with p.v.c cylinders which resulted in a wear of 0,2 till 0,5 mm after 3,37 million strokes (par. 5.6). The experiences with cylinders of brass are better than with p.v.c. but these are more difficult to obtain. Sheets of brass are easier to obtain. Therefore the WOT is testing a pump with a pump cylinder made of iron with inside a 2 mm brass sheet glued against the wall with araldite. The WOT expects to have results of these tests at the end of this year.



ideal  $v$ - $\Omega$  characteristic

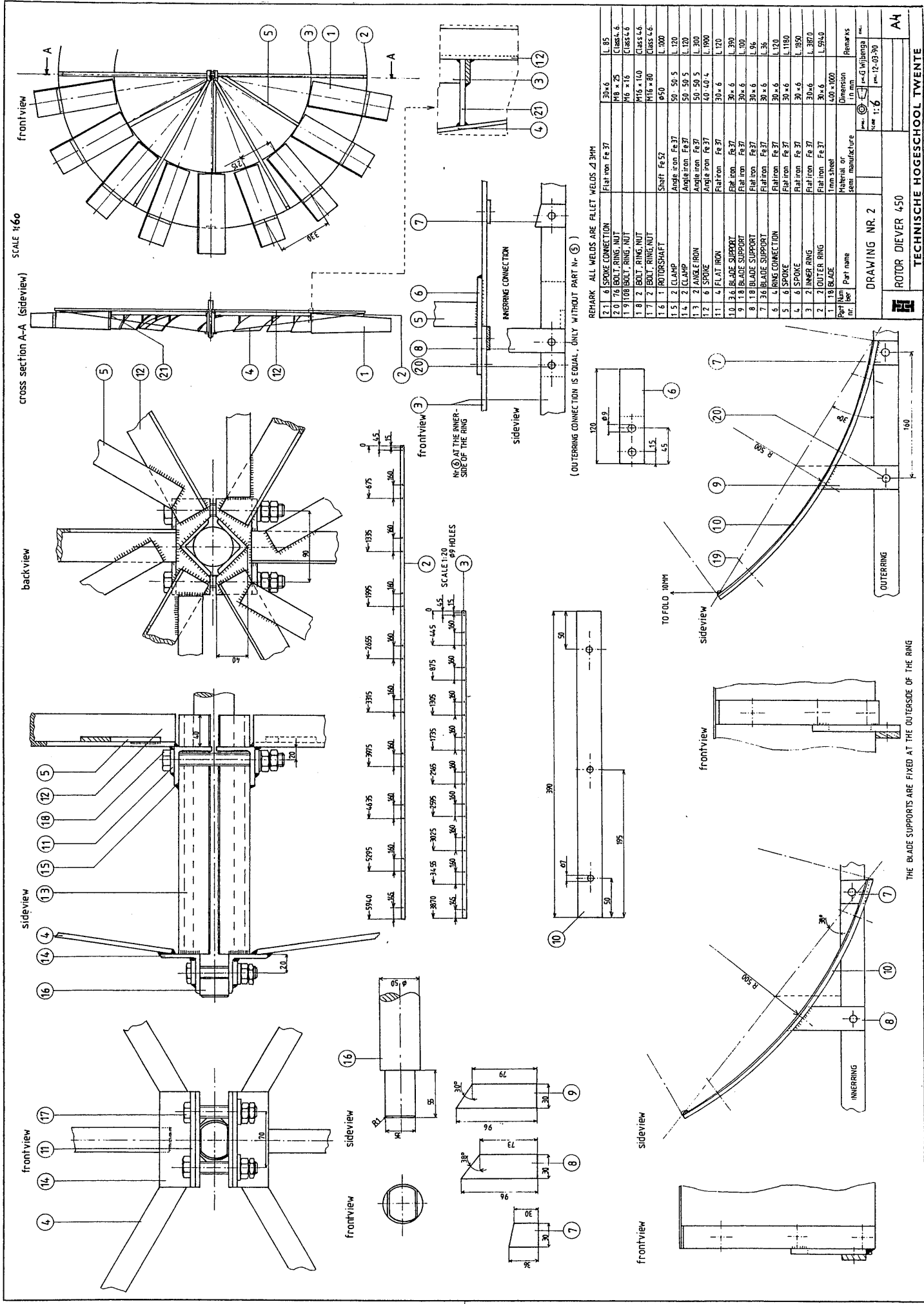
- The Diever 450 can be too expensive for farmers with less than 1-1,25 ha land. The WOT is working on a smaller windpump, the 4PU250, which is much cheaper and simpler to produce.
- Before starting to introduce windmills it is very important to do first a feasibility study. This study must contain a costs-benefits analysis and a comparison to other pumpsystems like dieselpump, kerosinepump, solarpump, etc.

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15. 'Improving the starting behaviour of a windmill driving a piston pump by balancing the pumprod weight' by R. Schermerhorn, CWD, 1984
16. 'Rotor design, part two' by A. Kragten, CWD, 1989







Part No.	Part name	Material	Dimension	Remarks
2.1	6 SPOKE CONNECTION	Flat iron, Fe 37	30x6 L 95	
2.9	BOLT, RING, NUT	M6 x 25	Class 4.6	
1.9	BOLT, RING, NUT	M6 x 16	Class 4.6	
1.7	2 BOLT, RING, NUT	M16 x 100	Class 4.6	
1.7	2 BOLT, RING, NUT	M16 x 80	Class 4.6	
1.6	1 ROTOR SHAFT	Shaft Fe 52	Ø 50 L 1000	
1.5	2 CLAMP	Angle iron, Fe 37	50 x 50 L 120	
1.4	2 ANGLE IRON	Angle iron, Fe 37	50 x 50 L 120	
1.3	2 ANGLE IRON	Angle iron, Fe 37	50 x 50 L 300	
1.2	6 SPOKE	Angle iron, Fe 37	40 x 40 L 1800	
1.1	4 FLAT IRON	Flat iron, Fe 37	30 x 6 L 120	
1.0	3.6 BLADE SUPPORT	Flat iron, Fe 37	30 x 6 L 390	
9	1.8 BLADE SUPPORT	Flat iron, Fe 37	30 x 6 L 90	
8	1.8 BLADE SUPPORT	Flat iron, Fe 37	30 x 6 L 90	
7	3.6 BLADE SUPPORT	Flat iron, Fe 37	30 x 6 L 35	
6	4 RING CONNECTION	Flat iron, Fe 37	30 x 6 L 120	
5	6 SPOKE	Flat iron, Fe 37	30 x 6 L 1180	
4	6 SPOKE	Flat iron, Fe 37	30 x 6 L 950	
3	2 INNER RING	Flat iron, Fe 37	30 x 6 L 390	
2	2 OUTER RING	Flat iron, Fe 37	30 x 6 L 90	
1	1.8 BLADE	Flat iron, Fe 37	30 x 6 L 950	
Part No.	Part name	Material <td>Dimension</td> <td>Remarks</td>	Dimension	Remarks
6	OUTERRING	Iron Steel	Ø 100 x 1000	

DRAWING NR. 2

ROTOR DIEVER 450

TECHNISCHE HOOGESCHOOL TWENTE

SCALE 1:60

12-03-90

A4

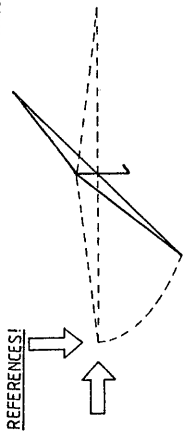
THE BLADE SUPPORTS ARE FIXED AT THE OUTERSIDE OF THE RING





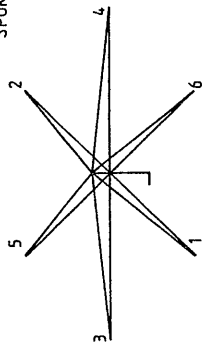
**IMPORTANT**

ROTORFRAME IS COMPOSED ON ITS SHAFT TO PREVENT "JUMPING AND DANCING" OF THE SPOKES AND RINGS.

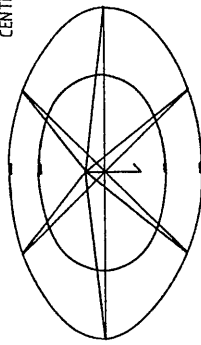


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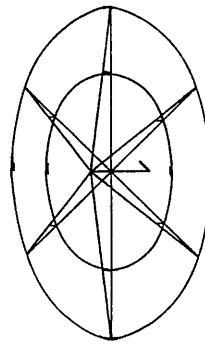
ORDER FOR WELDING OF THE SPOKES SEE NUMBERING 1-6



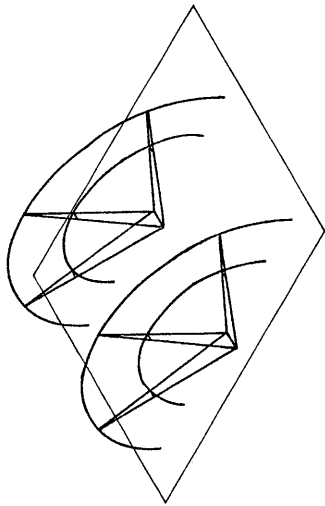
RINGS ARE POSITIONED, CENTERED AND WELDED.



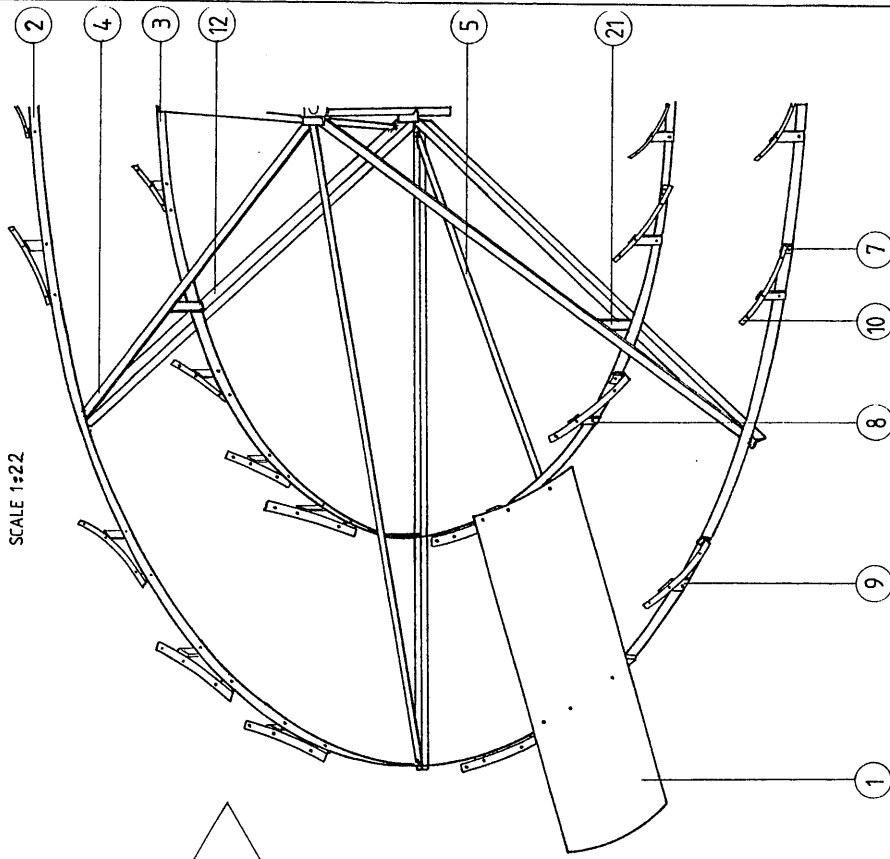
PARTS No 21 ARE WELDED.



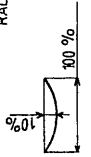
THE TWO ROTORHALVES



SCALE 1:22



SHEET IS ROLLED IN A BENDING - RADIUS OF APPR. 500mm.



PART No 1

POS.	BENAMING	AANTAL	MATERIAAL	TEKENE COÖRDIN.	OPMERKING	B.B. BESTELD VOORRAAD	
	DRAWING NR. 2 A		nie geol. metaal ± 0,5 mm	proj.:  schaal: 1:88	prc: Gwijbenga	dt:	
ROTOR DIE VER 450						prc: 20-03-90	A4
<b>TECHNISCHE HOGESCHOOL TWENTE</b>							









