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REPORT

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TECHNICAL REPORT 1990

of the Diever 450

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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.

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may 1990

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6. Crank with a variable length
7. transmission with ball-bearings
8. Installation of the 12PU500

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
α	angle of attack	
β	blade angle	
γ	angle between actual position of main vane and its rest position	
δ	angle of yaw (between rotor axis and wind direction)	
ϵ	angle between hinge axis and vertical axis	
ϕ	angle between rotor plane and relative flow speed	
λ	tipspeed ratio	
λ_d	design tipspeed ratio	
λ_r	local speed ratio at radius r	
η_{hydr}	hydraulic efficiency of the pump installation	
η_{inst}	efficiency of the pump installation	
η_{mech}	mechanical efficiency of the pump	
η_{tot}	total efficiency of the windpump	
η_{tr}	efficiency of the transmission	
η_{vol}	volumetric efficiency of the pump	
Ω	rotor angular speed	rad/s
ρ_a	density of air	kg/m ³
ρ_c	density of concrete	kg/m ³
ρ_w	density of water	kg/m ³
σ	stress	N/mm ²
$\bar{\sigma}$	admissible stress	N/mm ²
σ_e	equivalent stress	N/mm ²
σ_{\min}	minimum stress	N/mm ²
σ_{\max}	maximum stress	N/mm ²
σ_v	surface stress	N/mm ²
τ	shear stress	N/mm ²
ω	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 λ (= 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

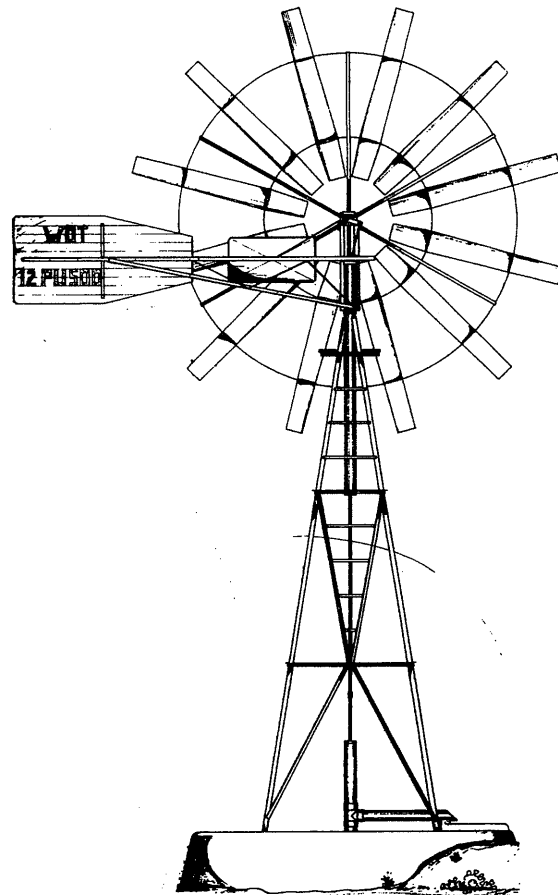


figure 1.1: the 12PU500 windmill

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 too 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.

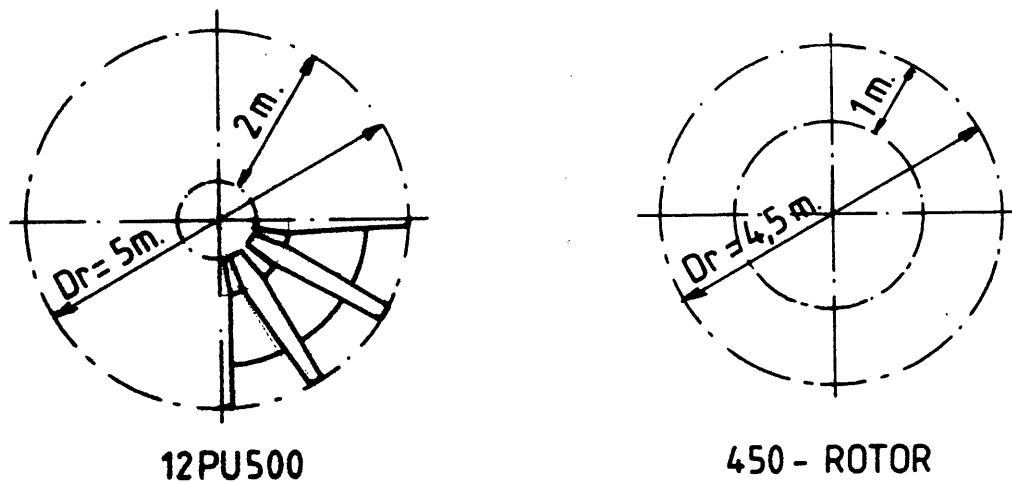


figure 2.1: the 12PU500 and 450 rotor

2.2. The choice of the design tip speed ratio

The design tip speed ratio (λ_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 peak forces in the pumprod at high rotation speeds. We thought that the peak forces 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 peak forces for the windspeeds of 9 m/s (fatigue load) and 12 m/s (maximum 'static' load). The peak forces 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

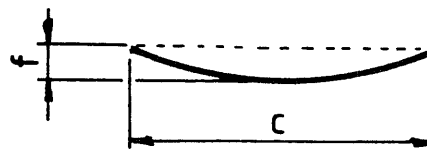


figure 2.2: the blade profile

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:

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

To design the blade dimensions we need the following data:

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

and 4 formulas, see lit.4:

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

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

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

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

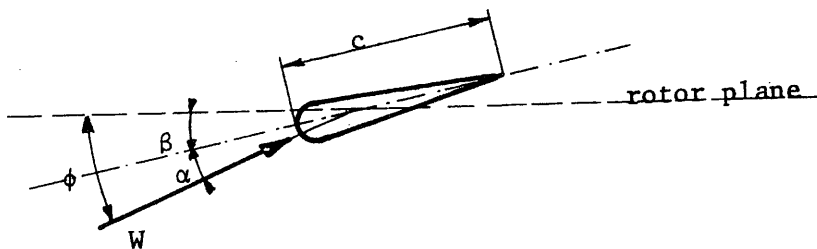


figure 2.3: blade setting β

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 β for the support on the inner ring is 38° and for the support on the outer ring 30° .

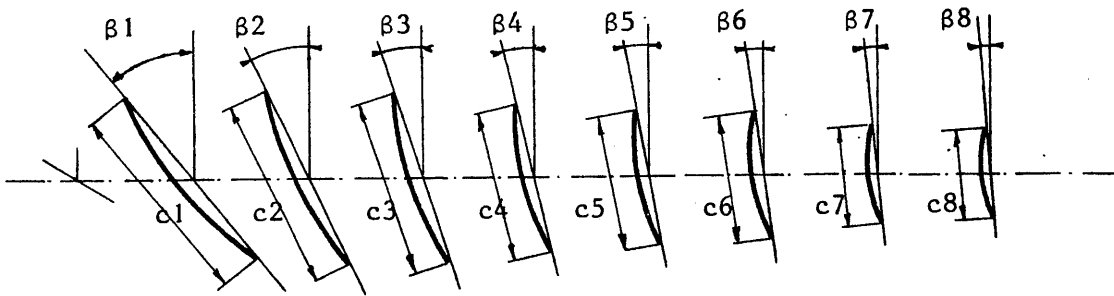
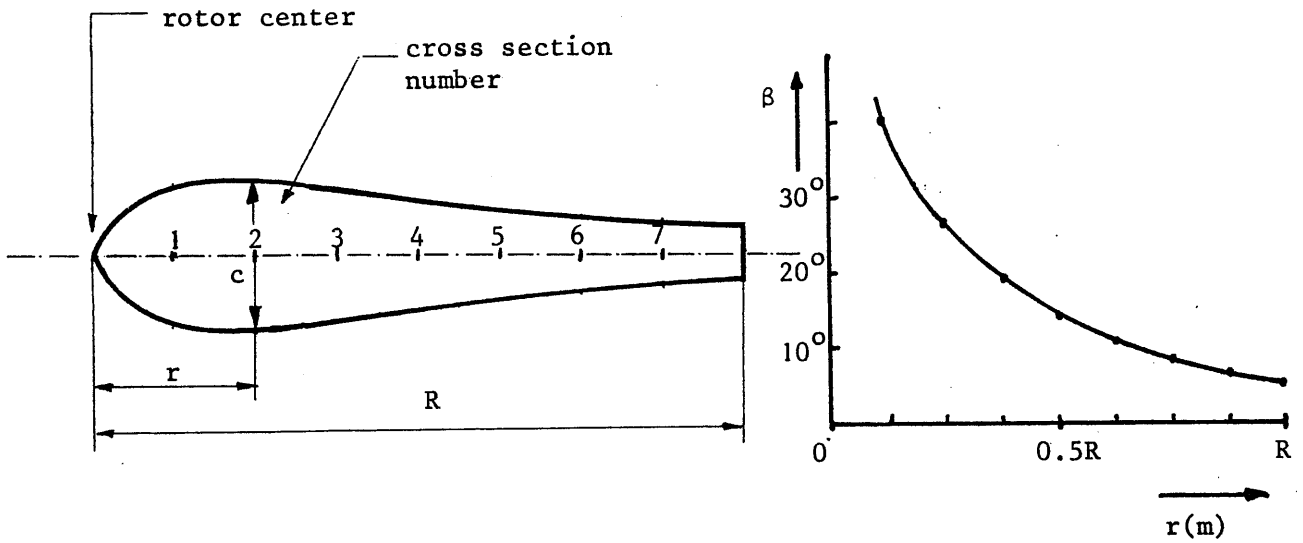


figure 2.4: blade form, twist and cross sections

position	r in m	λ_r	ϕ in $^\circ$	β 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	0,56	40,6	37,6	0,34
	1,90	0,84	33,2	30,2	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:

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

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):

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

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:

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

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

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

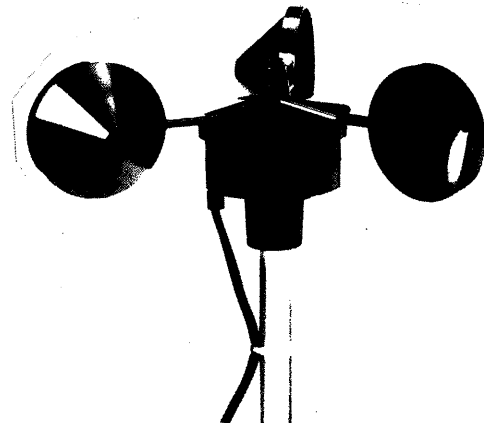


figure 2.5: cup-anemometer

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

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.

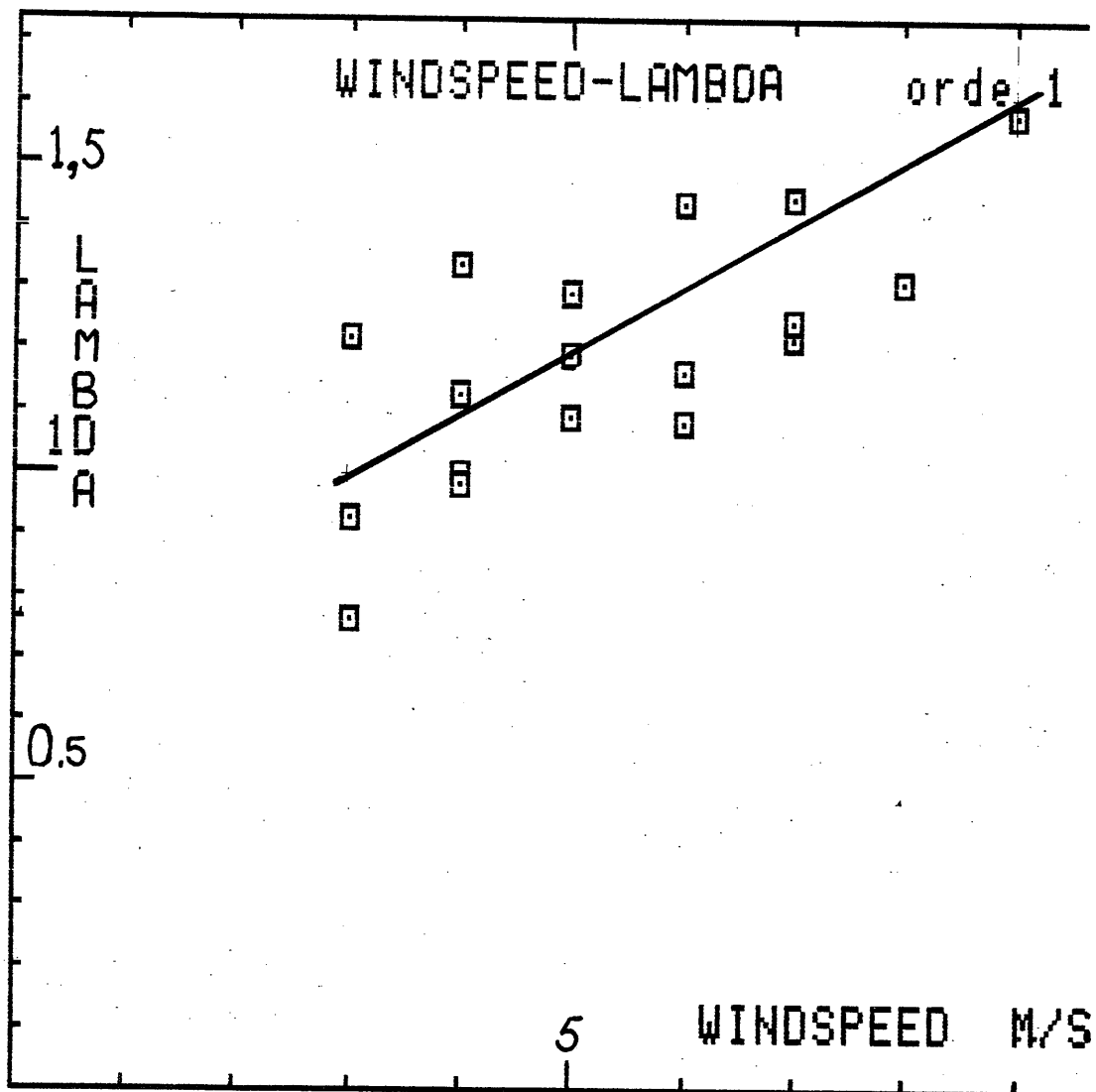


figure 2.6: tipspeed ratio as function of the windspeed with load