

Experiments with windrotors in yaw

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P.T. Smulders
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International symposium on "Applications of fluid mechanics
and heat transfer to energy and environmental problems"

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EXPERIMENTS WITH WINDROTORS IN YAW

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INTRODUCTION

The performance of a windrotor in yaw has as yet received limited attention in wind power research, although the subject is of considerable interest. A real rotor in the turbulent atmospheric boundary layer will nearly always be in a yawed position to the wind, influencing its performance and causing fluctuating loads on the rotor blades and structure.

Understanding of the effects of yaw are necessary to develop control strategies to keep a rotor in the wind. Further, slow running windrotors for waterpumping are usually controlled by a yawing mechanism to protect the pump and rotor against overspeeding and overloading; such a control uses the forces on the rotor, on the main vane and possibly some auxiliary vanes.

In this paper we will consider the following quantities: the power output P , the axial force T , the force working sideways S and the (self directing) torque M_z , taken around on axis lying in the rotor plane (see fig. 1). The direction of the windvelocity is given by the angle δ relative to the normal on the rotor plane.

The measurements presented here were performed with two rotors. The first is a very small rotor with a diameter of 20 cm., two blades and a tip-speed-ratio of 4, and is indicated as THE-2-4-20. The second rotor has two blades, a tip-speed-ratio 6 and a diameter of 1.80 m. It is indicated as THE 2-6-180. Of this last rotor only a few preliminary measurements are presented here.

Earlier research on propellers in yaw has been reported in [1] and [2]. Van der Kinderen and Van Meel [3] derived expressions for the forces and moments acting on a rotor in yaw, on the basis of an analysis as presented by Glauert [1] for a propeller; one of their conclusions was that there is no moment acting around the yawing axis for a two-bladed rotor. Thus a rotor set

in front of the tower is turned out of the wind by the sideforce S . Likewise Anderson [4] notes a rotor's "natural desire to turn out of the wind".

One of the most conspicuous results of the measurements reported here concerns the moment M_z which in many cases tends to keep the rotor in the wind. An attempt is presented to explain these results in a qualitative manner and to that end we will give some consideration to the flow around flat plates, set skew to the undisturbed velocity.

It should be noticed that the rotor of a helicopter in horizontal flight is "in yaw" [6] [1]; models to describe rotor behaviour have been developed using an asymmetric distribution of the induced velocity at the rotor plane. This method was also followed by Lenssen [8].

Finally the work should be mentioned of Jacobs and Lenders [9] who calculated the power output of rotors in yaw applying in principle Glauert's model, but not restricting themselves to small angles as was done by Van Meel and der Kinderen [3].

2. DEFINITIONS

The following dimensionless quantities will be used here, V being the wind speed, R the radius of the rotor, Ω the rotational frequency of the rotor, and ρ the density.

$$C_P = \frac{P}{\frac{1}{2}\rho V^3 \cdot \pi R^2} \quad \text{power coefficient (P = power)}$$

$$C_Q = \frac{Q}{\frac{1}{2}\rho V^2 \cdot \pi R^3} \quad \text{torque coefficient (Q is torque on rotor axis)}$$

$$C_S = \frac{S}{\frac{1}{2}\rho V^2 \cdot \pi R^2} \quad \text{side force coefficient}$$

$$C_T = \frac{T}{\frac{1}{2}\rho V^2 \cdot \pi R^2} \quad \text{axial force (or thrust) coefficient}$$

$$C_{M_z} = \frac{M_z}{\frac{1}{2}\rho V^2 \cdot \pi R^3} \quad \text{pitching moment coefficient (self-aligning)}$$

$$\lambda = \frac{\Omega R}{V} \quad \text{tip-speed-ratio}$$

3. MEASUREMENTS AND RESULTS

3.1 Measurements on the THE 2-4-20 rotor

Measurements on this miniature rotor, that was designed by van Leeuwen and Wasser, were performed in an open 50 x 50 cm wind tunnel (fig. 2). Photo 1 shows the rotor, the blades of which were cut out of a cylindrical brass pipe (\emptyset 50/52 mm). The design tip-speed-ratio was chosen low because of the low Reynolds number values involved ($\sim 1.5 \times 10^4$). The chord and twist of the blade vary linearly along the blade (fig. 3). Details are given in [10]. The blade setting angle can be adjusted in the semi-circular slit in the rotor head (fig. 4). In fig. 4 is also shown how

the torque on the rotor axis is measured with the aid of a cord, running over a friction wheel: one end is fixed to a balance, the other end is loaded by a weight. The rotor frequency is measured with a stroboscope or a photocell counting the number of slits in a round plate fixed to the rotor-axis that pass per unit of time. The forces T and S and the moment M_z (fig. 1) are measured in three distinct series: 1) measuring the force along the axis of the wind tunnel, 2) measuring the force perpendicular to the latter, 3) measuring the moment around an axis situated 30 mm behind the rotor plane (fig. 5). Fig. 6 shows how the forces are measured, the rotor being fixed on a long arm that can move freely, along its own axis. To measure the forces a balance is used. From these measurements T , S and M_z can be calculated. The load on the rotor can, if necessary, be adjusted by means of a piece of felt acting as a brake (fig. 7).

Errors

The main error stems from the measurement of the forces. The accuracy of the balance lies between 3.5 and 10 mN, to be compared with an axial force of 350 mN under optimal conditions and the rotor set perpendicular to the flow. However the resulting inaccuracy in S can become rather high (10% or more).

Results

In fig. 8a and b the power coefficient is shown for different blade setting angles; the flow is normal to the rotor plane ($\delta = 0$). $\Delta\beta$ indicates the angle over which the blade has been turned relative to the design condition $\beta = 2^\circ$. The scatter of the measurements is small and the influence of a small change in β is noticeably seen. At the design tip-speed-ratio $\lambda_o = 4$ the C_{pmax} value is found to be 0.28; this corresponds theoretically [11] to a lift-drag ratio of the profile equal to 10. This low value can be understood if we consider the low Reynolds numbers concerned ($\sim 1.5 \times 10^4$). From fig. 8a and b it can further be seen that the power reduction due to a negative blade angle change is much more pronounced than that due to a positive change (feathering).

The effects of yaw for $\beta = 2^\circ$ are shown in fig. 9. Upto $\delta = 45^\circ$ the value of λ_{opt} hardly changes, while C_p decreases significantly. The values of C_{pmax} versus δ have been plotted in fig. 10, and compared to a $\cos^3\delta$ curve showing a good fit. This was also measured by Schumack [13] for a $\lambda = 2$ rotor. The axial force decreases as the rotor is turned out of the wind (fig. 11); it is used to control slow running rotors against overspeeding and overloading. Note that the axial force is highest if the rotor runs without a load. For this no-load condition the axial force was measured for different blade angles β (fig. 12). The results show that negative blade angle adjustments lead to high axial forces, as opposed to positive angle adjustments (feathering). This result is important for safety and control systems.

The side force S , as can be seen from fig. 13, turns an up-wind rotor out of the wind and a down-wind rotor into the wind. The effect is similar for no-load conditions and for various blade setting angles (fig. 14).

The measurements of the moment M , as defined in fig. 5, are shown in fig. 15. The influence of the (self aligning) pitching moment is stronger than the effect of the side force and the rotor tends to turn back into the wind. The effect is strongest for the unloaded rotor ($C_Q = 0$). The value of C_M (corrected for the side force) is given here for the no-load condition for three values of β . Note the difference between the curves for $\beta = -6^\circ$ and $\beta = +10^\circ$, to which we will come back later.

3.2 Measurements on the THE 2-6-180 rotor

The measurements with this rotor have a preliminary character. The rotor designed by Heil [12] was constructed by van Leeuwen and Wasser (photo 2). The test set-up and measuring methods have been described by Lenssen [8]. A side view is sketched in fig. 17a; fig. 17b show the suspension of the rotor and generator.

The values of T, S and M_z are determined from the measured moments M_1 , M_2 and M_3 :

$$T = \frac{M_1 - M_3}{d_3}, \quad S = \frac{M_2 - M_1}{d_2 - d_1}, \quad M_z = M_1 - S \cdot d_1$$

Some results are shown in fig. 18-23, for $\delta = 30^\circ$, -30° and -60° . Notwithstanding the inaccuracy of the measurements a number of features stand out that are similar to those of the small rotor: the self-aligning pitching moment, the side force pushing the up-wind rotor out of the wind, the increase of M_z and the axial force with the tip-speed-ratio.

4. DISCUSSION

We will mainly restrict the discussion to the self-aligning pitching moment M_z , as this seems the most controversial result. The normal theoretical approach developed for propellers leads to incorrect results. In fact, theory predicts fluctuations during one revolution, but no net pitching moment is found.

An interesting feature, relevant to our problem, is the flow around a plate, of which some of our measurement results are shown in fig. 24 and 25. A plate set "fore of the tower" turns back into the wind at yawing angles up to 70° to 80° !

The force on a flat plate is determined by the pressure distribution and acts normal to the plate. The self-aligning moment is caused by the displacement of the force due to the asymmetric distribution of pressure in yaw (fig. 26). The value of M_z is large compared to that of a rotor, so is the axial force. At a given angle of yaw, there seems to be a correlation between the asymmetry of the pressure distribution and the value of the axial force. If the latter goes to zero, then the air can pass through the rotor plane unimpeded and of course there is no asymmetry. This situation occurs if the blades are feathered, as fig. 12 and 16 clearly show. For a rotor in no-load condition, β being equal to

-6° , high values of C_T and C_{M_z} coincide. Fig. 15 shows a similar effect.

Another factor influencing the pitching moment is the tip-speed-ratio. A slow running rotor with a high torque creates substantial rotation in the wake, tending to smooth out asymmetry in the flow. Such effects have been noted but measurements have not been made.

It is not surprising that propellers do not show the self-aligning moment. The axial force-thrust-works in the opposite direction to the flow through the propeller: the axial force is negative. Asymmetries in the flow are thus smoothed out.

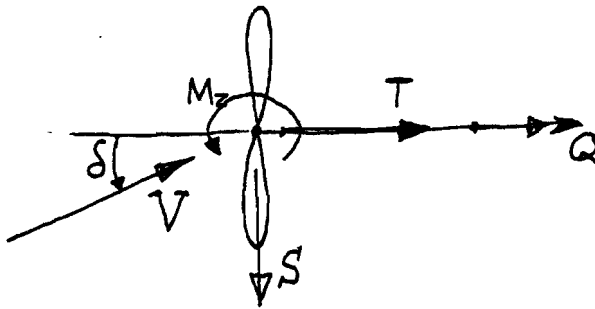


Fig. 1

Definition of the forces and moments on a rotor.

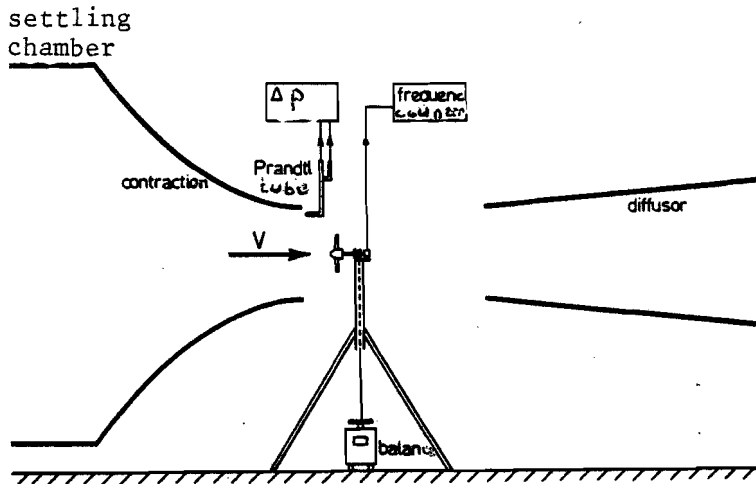


Fig. 2

Open 50 x 50 cm windtunnel

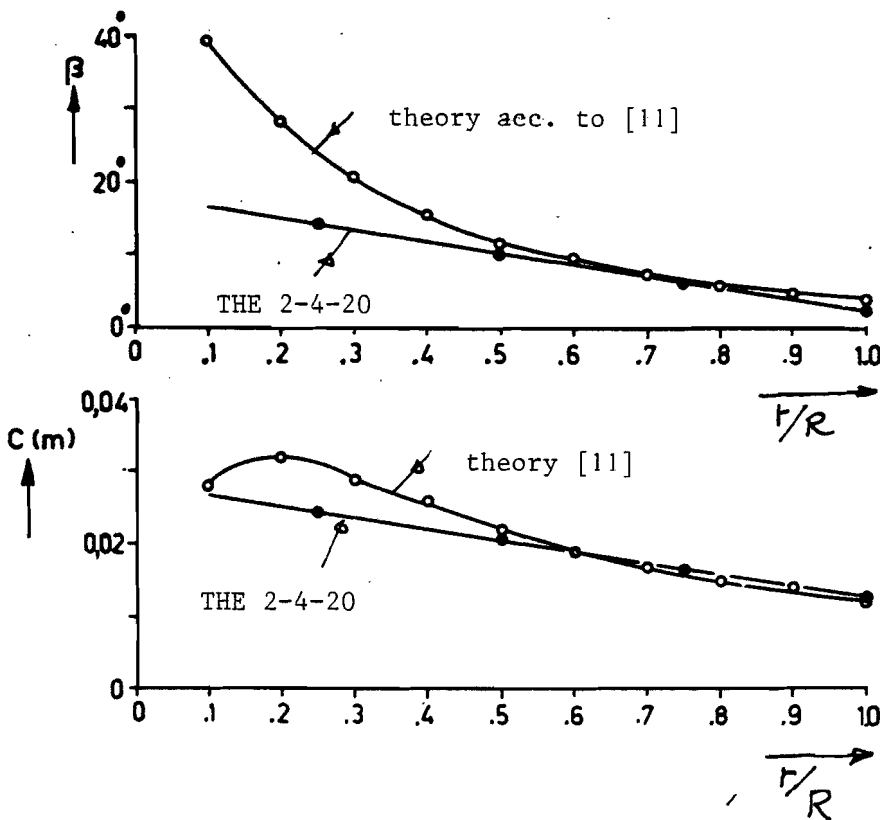


Fig. 3

Blade setting angle and chord of the THE 2-4-20 rotor.

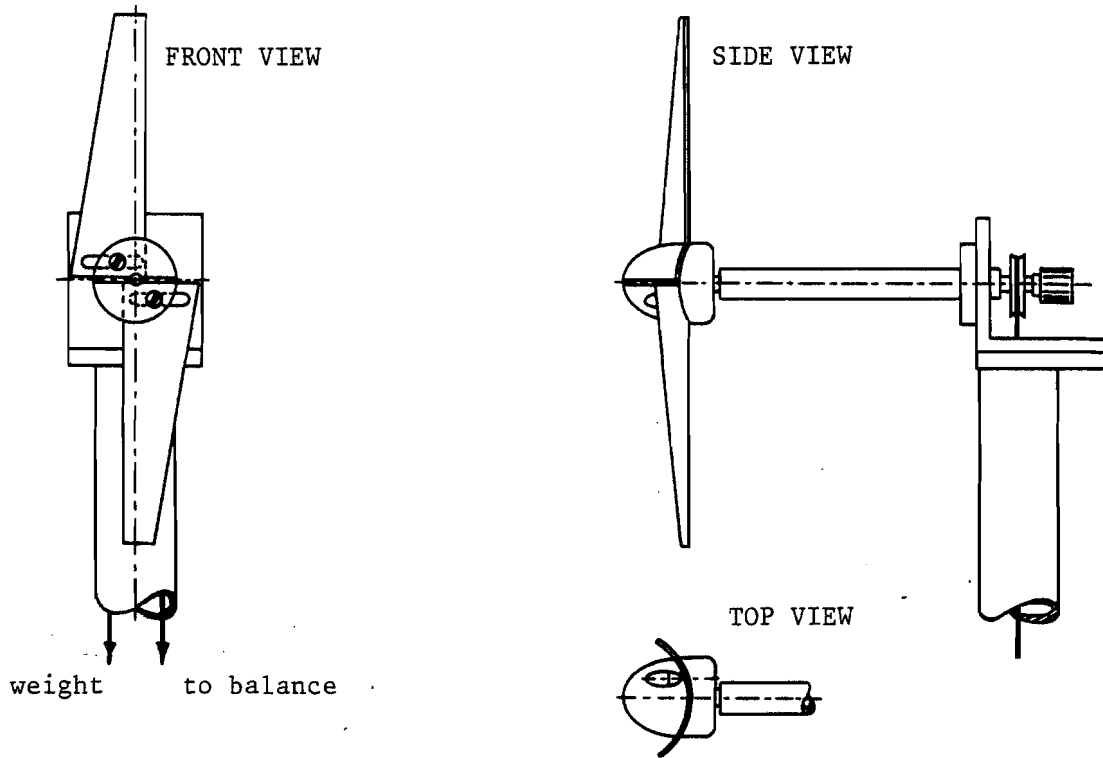


Fig. 4 Measuring the rotor torque of the THE 2-40-20

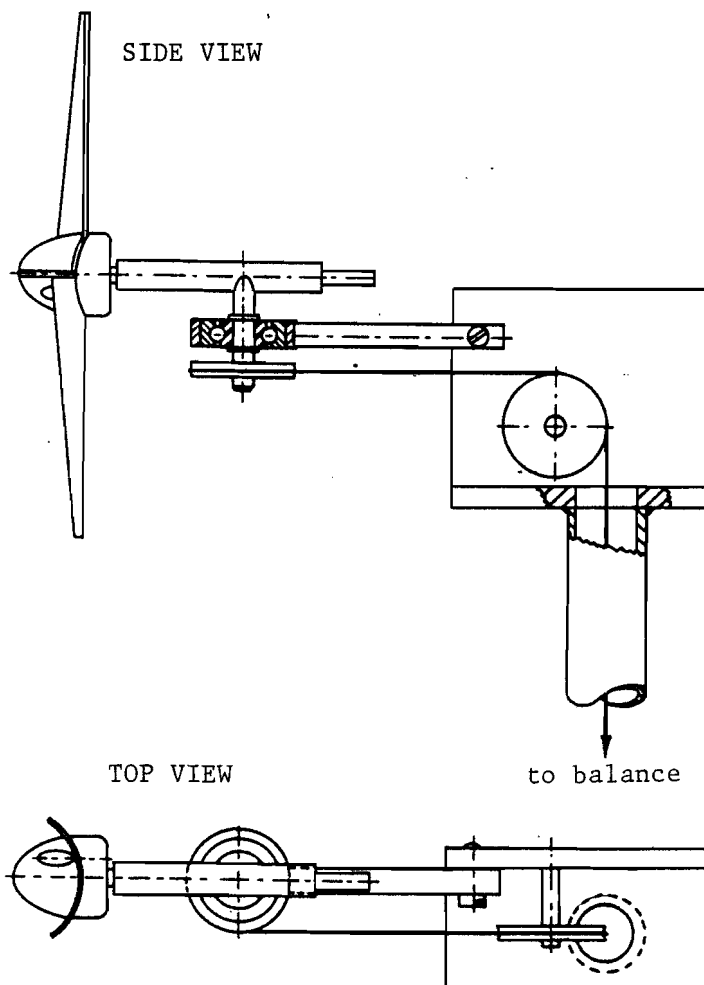


Fig. 5
Measuring the moment M
(and M_z)

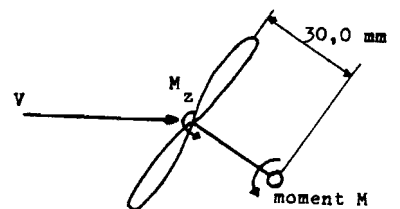


Fig. 6
Support for
measuring forces

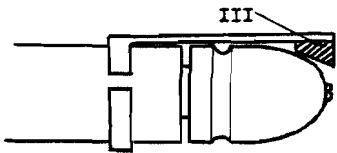
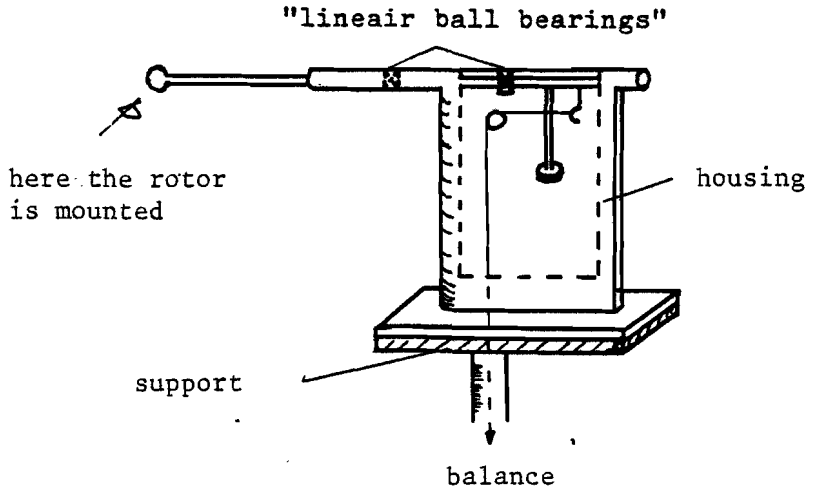


Fig. 7 Adjustable brake (felt)
to load the rotor.

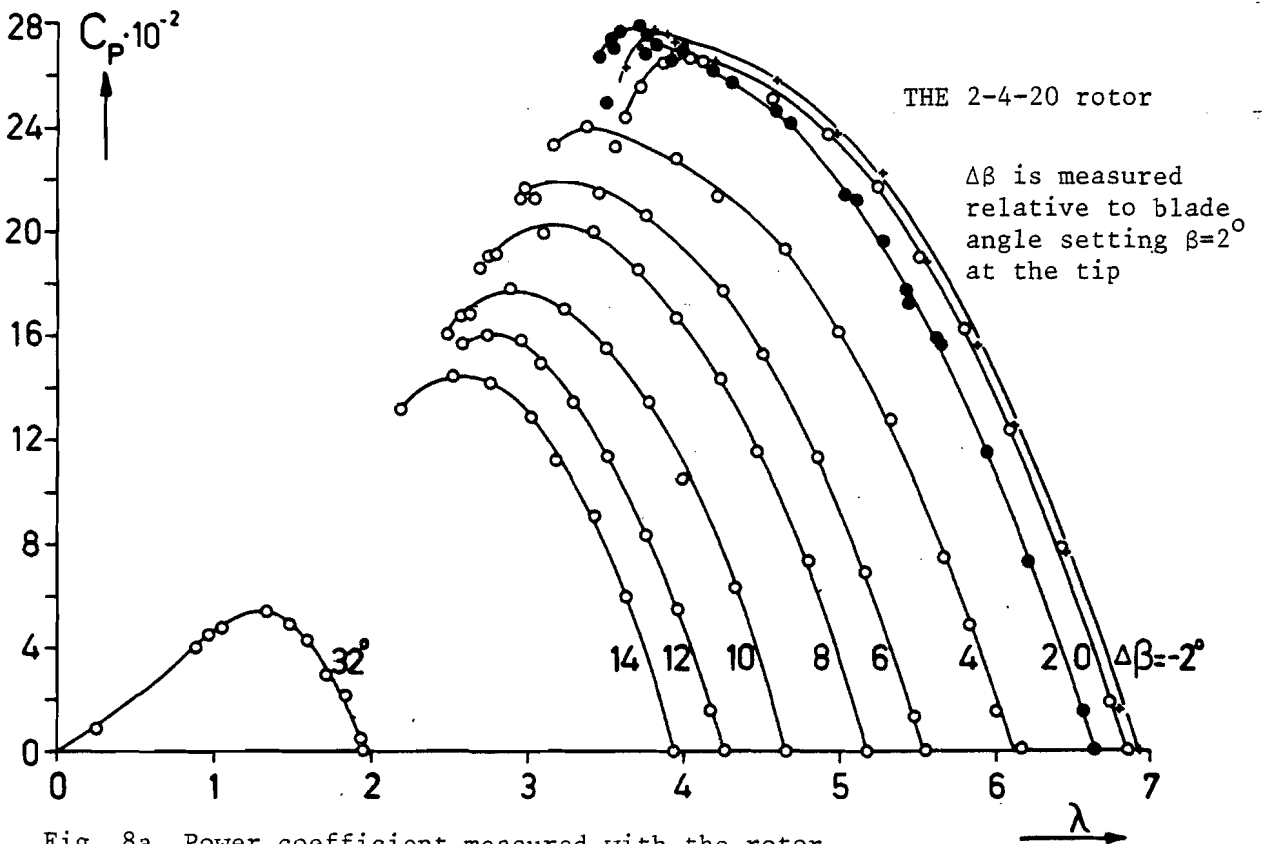


Fig. 8a Power coefficient measured with the rotor
perpendicular to the air flow;
variable blade setting angle β .

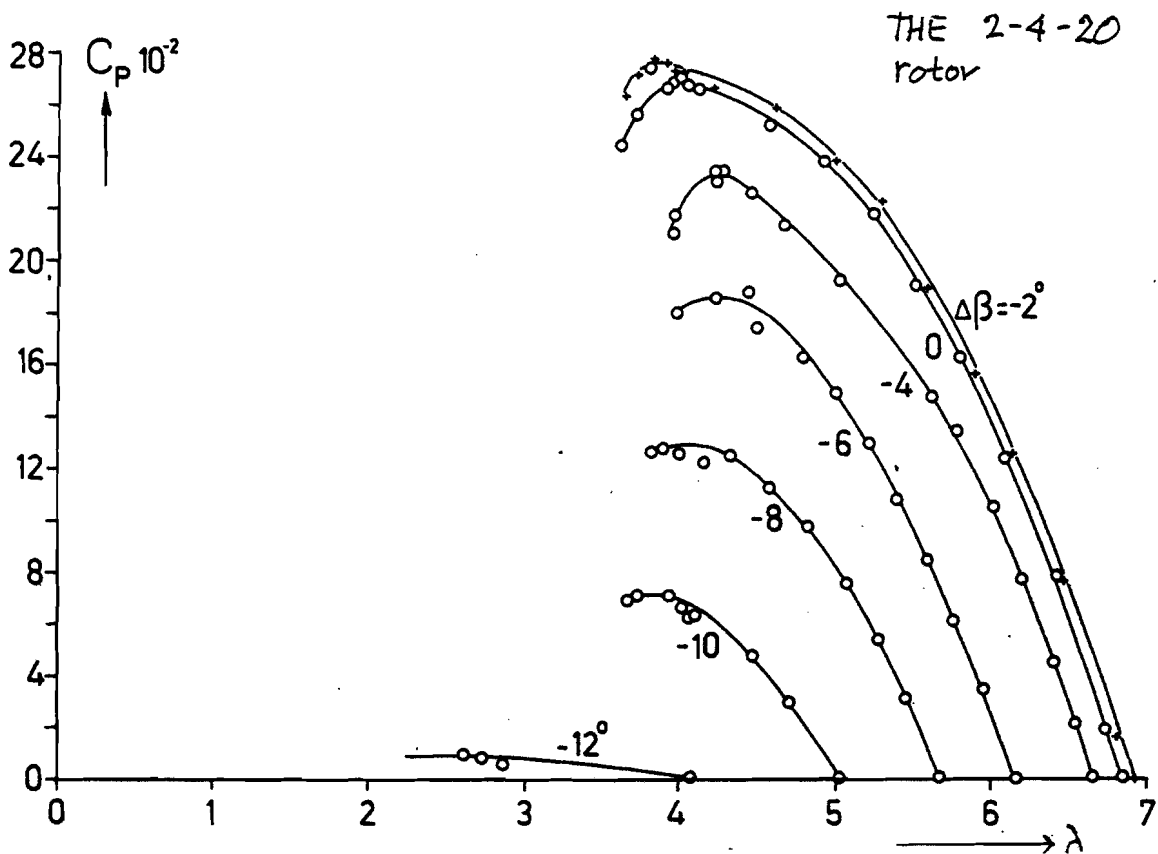


Fig. 8b As fig. 8a but with negative blade angle adjustment.

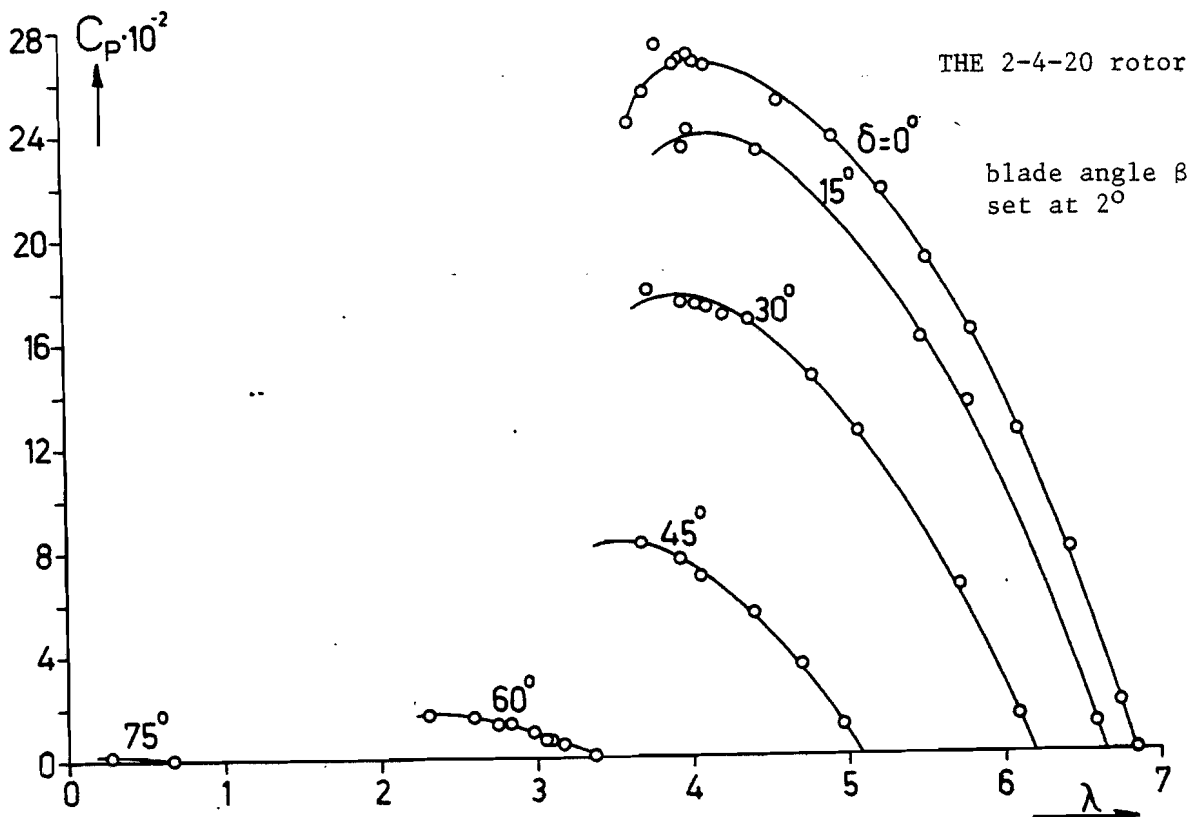


Fig. 9 Measured power/coefficient in yaw.

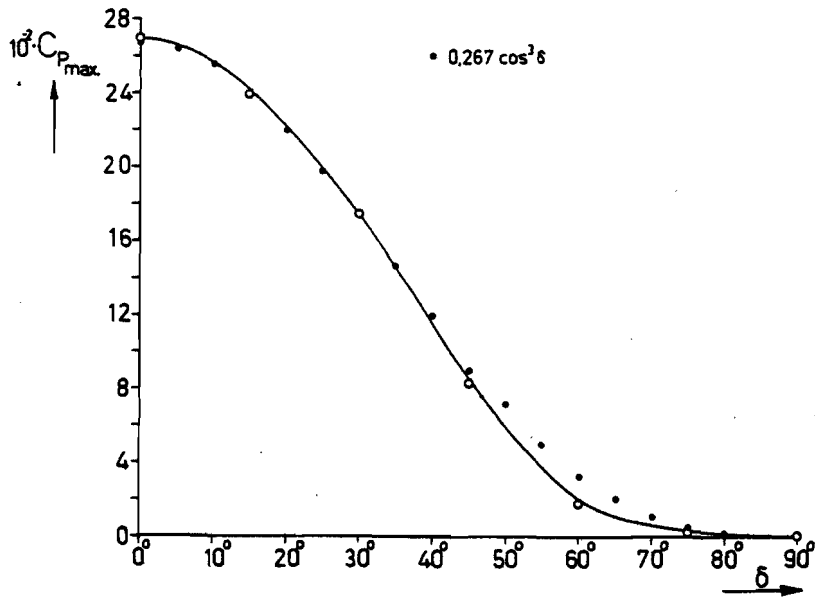


Fig. 10 Maximum power coefficient as a function of the yawing angle δ , THE 2-4-20 rotor.

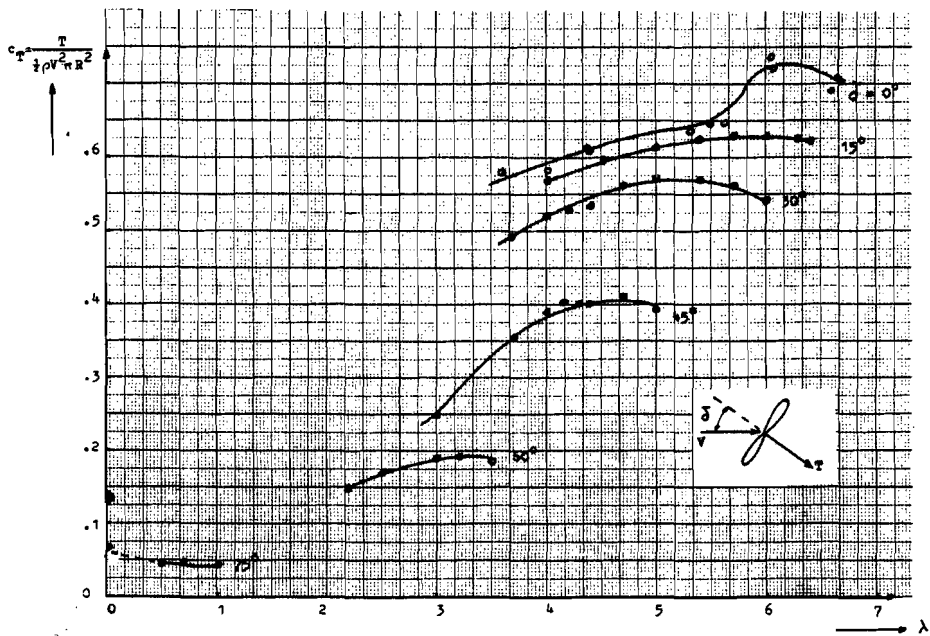


Fig. 11 C_T versus λ for different values of the yawing angle δ ; $\beta = 2^\circ$, THE 2-4-20 rotor.

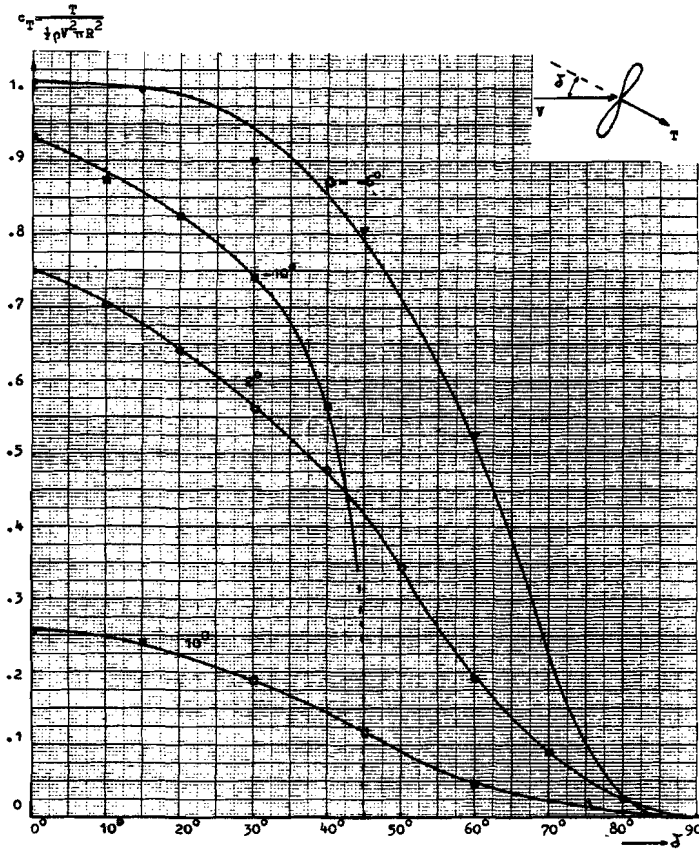


Fig. 12 Axial force coefficient for the no-load condition at various angles of yaw; THE 2-4-20 rotor with variable blade setting angle β .

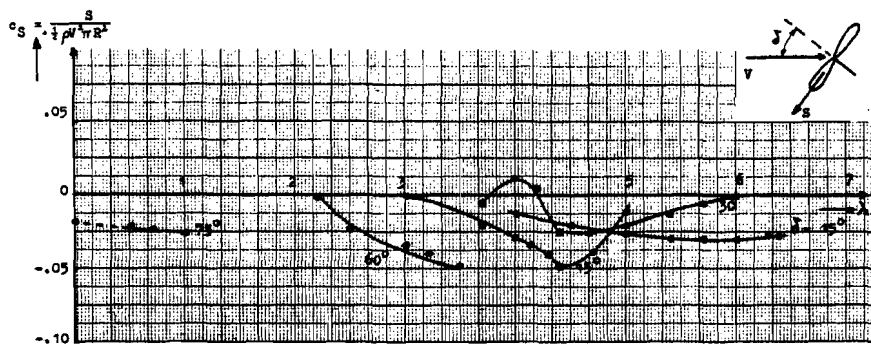


Fig. 13 Side force coefficient as a function of λ for different angles of yaw; THE 2-4-20 rotor with set at 2°.

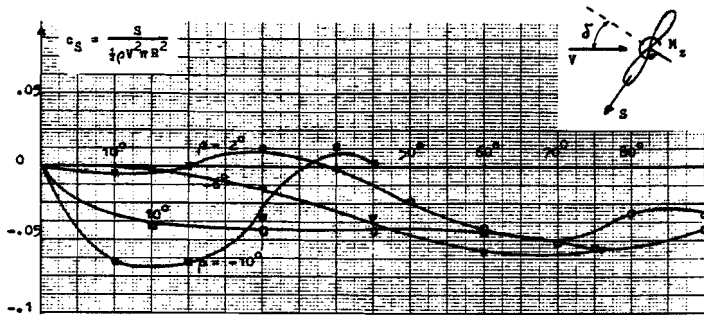


Fig. 14

C_S as a function of δ for the THE 2-4-20 rotor in unloaded conditions, β is variable.

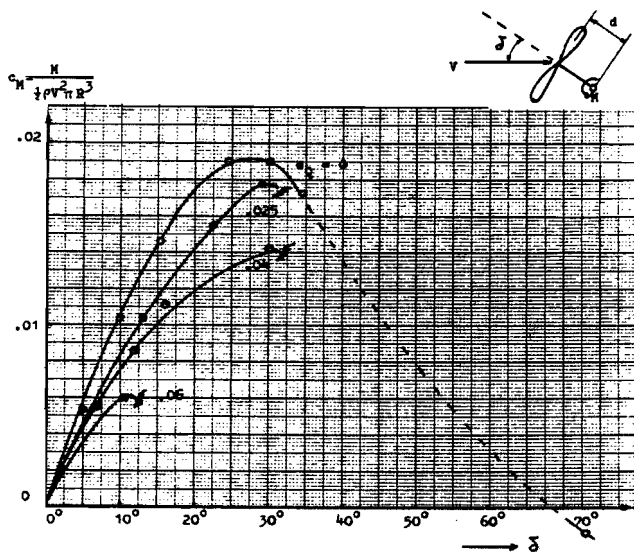


Fig. 15

The dimensionless moment C_M as a function of δ around an axis at a distance $d = 30$ mm behind the rotor plane. The THE 2-4-20 rotor, $\beta = 2^\circ$.

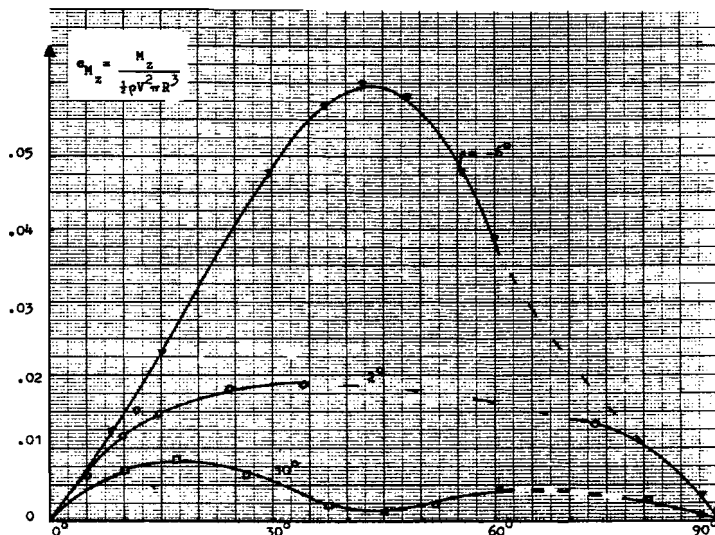


Fig. 16

C_{M_z} als a function of δ for different blade setting angles β . No-load conditions. THE 2-4-20 rotor.

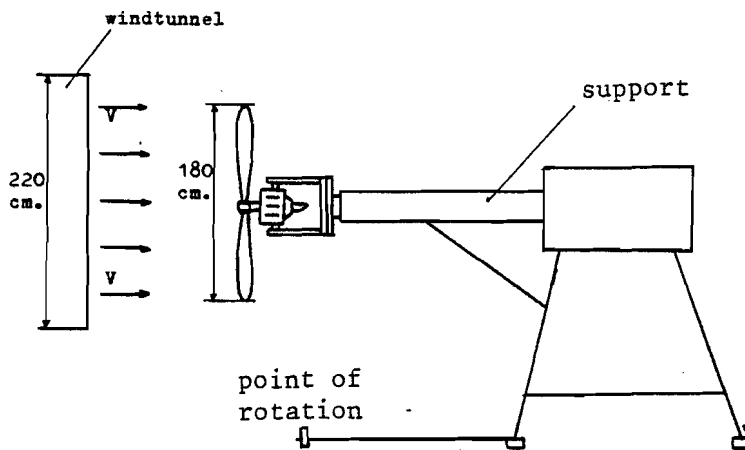


Fig. 17a Test set-up of the THE 2-6-180 rotor
TNO-Waddinxveen

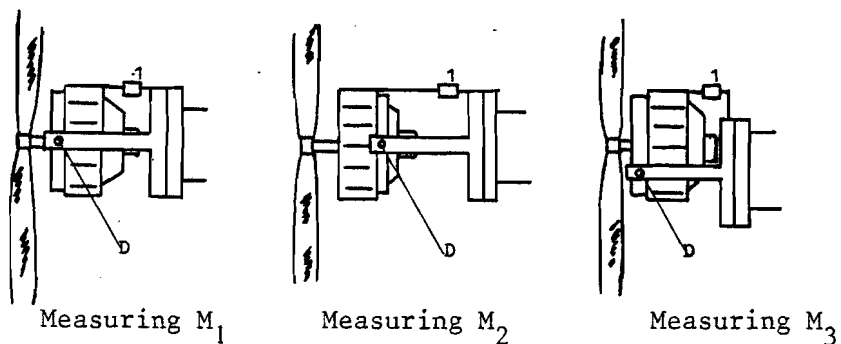


Fig. 17b Measurement of $M_1 \dots M_3$ with force transducer 1.
D is the axis around which M is measured.

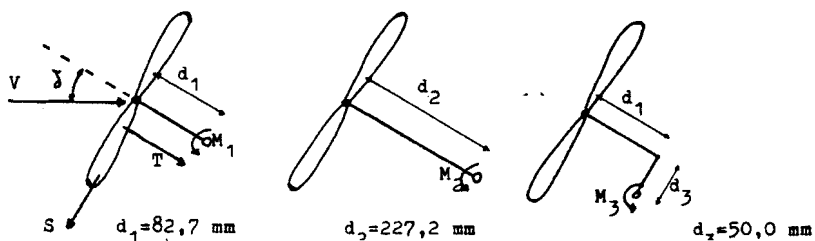


Fig. 17c Showing how M_1, M_2, M_3 are measured.

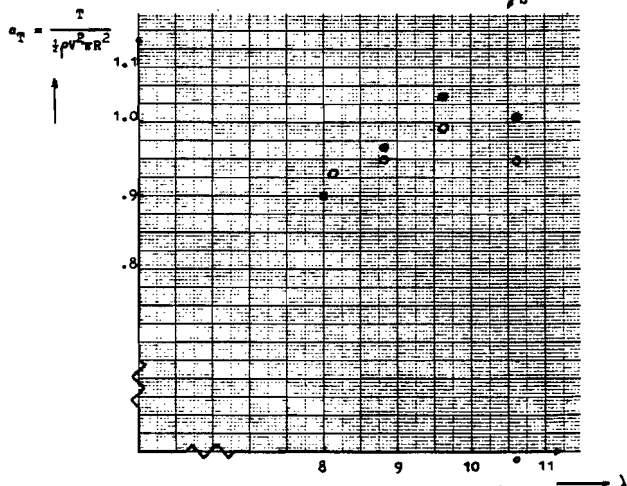
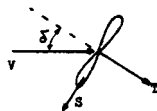


Fig. 18
Axial force on the THE 2-6-180 rotor as a function of λ for $\delta = 30^\circ$ and $\delta = -30^\circ$.

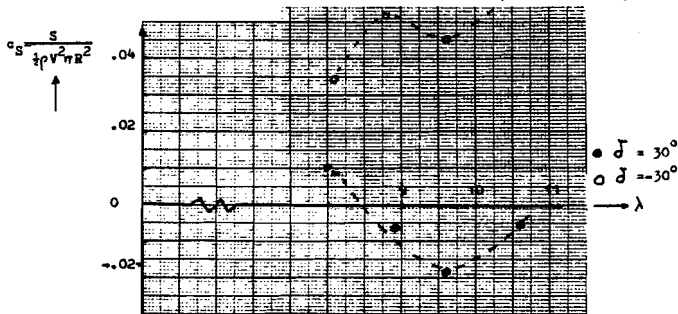


Fig. 19
As fig. 18 but now the side force.

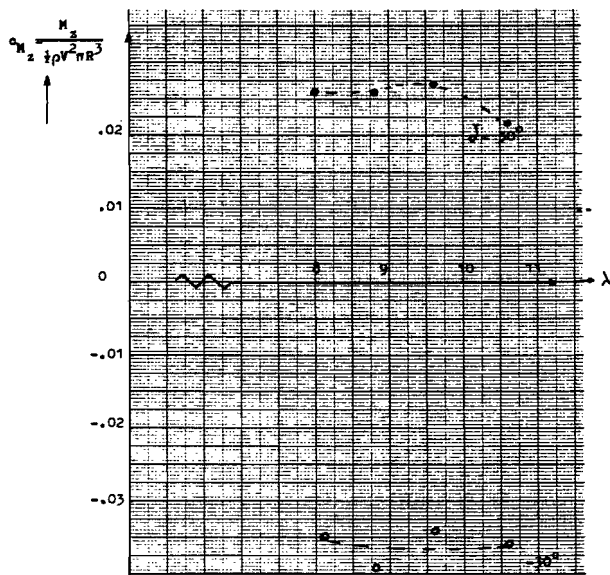
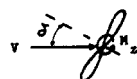


Fig. 20
As fig. 18 but now the pitching moment.

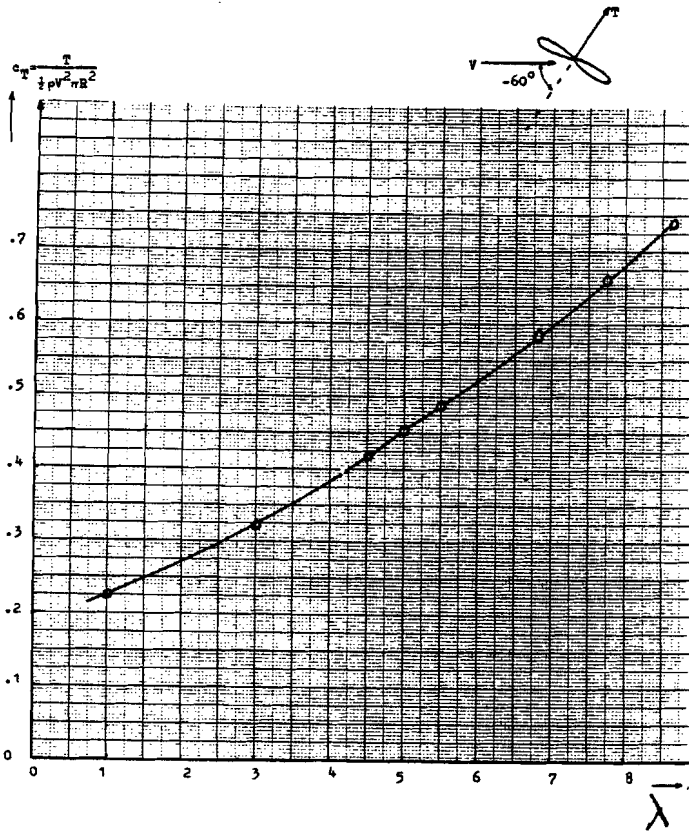


Fig. 21

Axial force coefficient of the THE 2-6-180 rotor as a function of λ for a yawing angle $\delta = -60^\circ$.

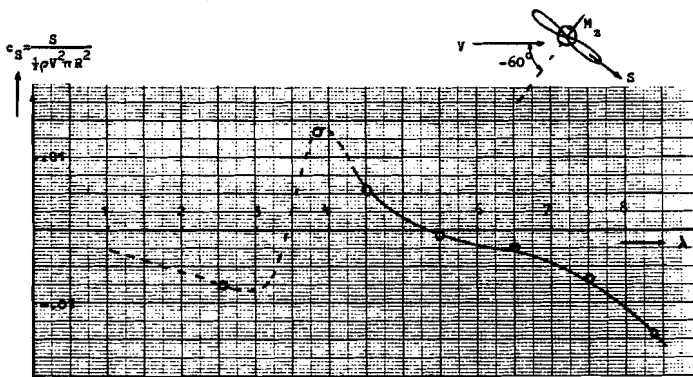


Fig. 22

As fig. 21 but now the side force coefficient.

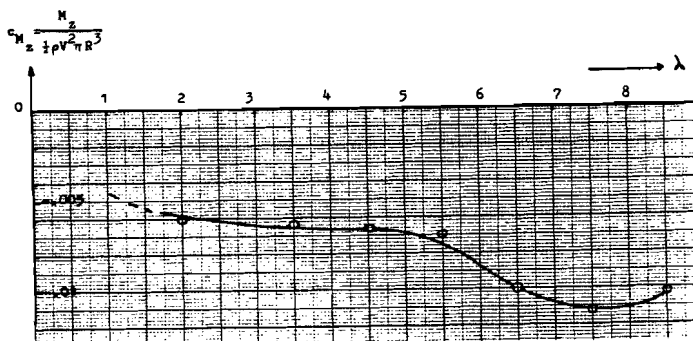


Fig. 23

As fig. 21 but now the pitching moment coefficient.

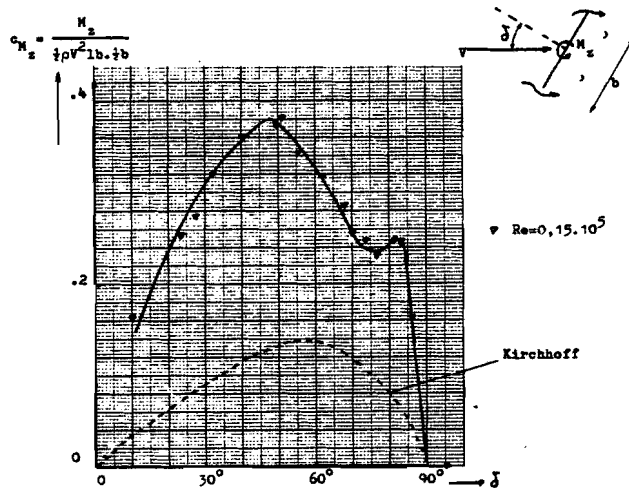


Fig. 24
 C_{M_z} for an inclined plate with $b/l = 10$.

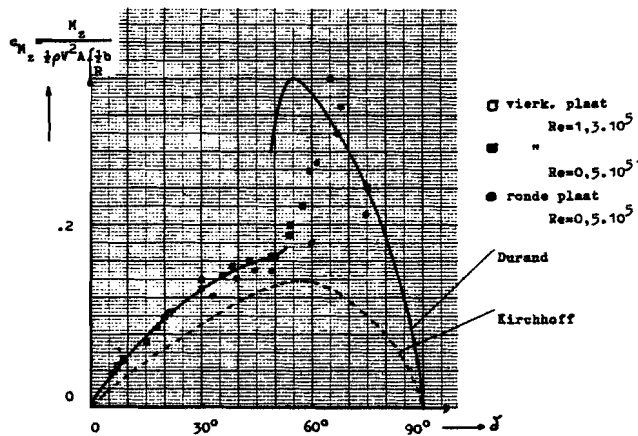


Fig. 25
 Pitching moment of a round and square flat plate as function of δ (see fig. 24).

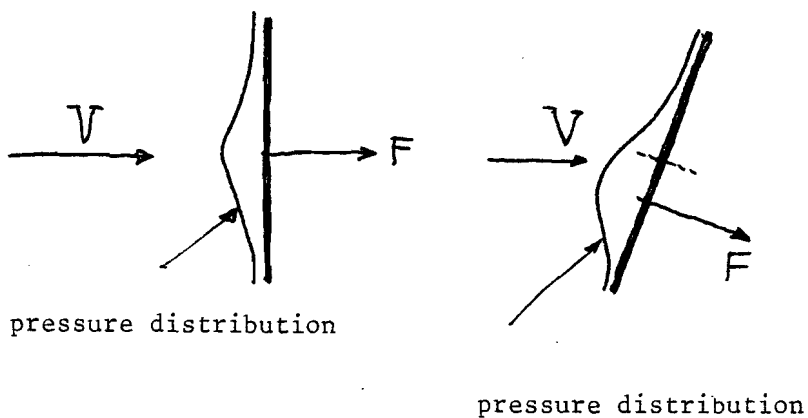


Fig. 26
 Pressure distribution on an inclined plate and the resulting displacement of the axial force F .

LITERATURE

- [1] Glauert, H.
Aerodynamic theory (ed. W.F. Durand)
Vol. IV, Dover publications Inc. New York 1963

- [2] Ribner, H.S.
Propellors in yaw
NACA publication, Report no. 820, (1943)

- [3]* Kinderen, W. der, Meel, J. van
Field performance of wind power machines:
system analysis and measuring methods.
Application to a small wind generator,
Report R 272 A, December 1976.

- [4] Anderson, M.
Horizontal Axis Windturbines in Yaw
1st BWEA conference, Cranfield 1979

- [5] Vries, O. de
Windtunnel tests on a model of a two-bladed horizontal axis
windturbine and evaluation of an aerodynamic performance
calculation method.
National Aerospace Laboratory NLR, Netherlands
Report NLR TR 79071 L, June 1979

- [6] Brammwell A.R.S.
Helicopter dynamics
E. Arnold Ltd., London, 1976

- [7] Payne, P.R.
Helicopter dynamics and aerodynamics
Pitman & Sons, Ltd., London 1959.

- [8] Lenssen, G.
Self-aligning behaviour of fast running horizontal axis
wind rotors in yaw.
Report R 423 A, March 1980
- [9] Jacobs, D., Lenders, H.
The power output of wind rotors in yaw (in Dutch)
Report R 337 S, May 1978
- [10] Bontekoe, I.
Wind tunnel investigation of the influence of the blade
angle setting on the performance of a wind rotor (in Dutch)
Report 332 S, April 1978
- [11] Jansen, W., Smulders, P.
Rotor design for horizontal axis windmills
Steering Committee Wind Energy Developing Countries (SWD)
P.O. Box 85, Amersfoort. May 1977.
- [12] Heil, K.
Theoretical and experimental study on the behaviour of
horizontal axis rotors (in Dutch)
Report R 365 A, 1979
- [13]* Schumack, M.
Results of wind tunnel tests on the scale model of the THE I/2
THE I/2 rotor
Report R 408 S, December 1979
- [14]* Sangen, E.
Corrections for measurements on wings and rotors for open and
closed wind tunnels (in Dutch)
- * Internal reports of the Wind Energy Group, Laboratory of Fluid Dynamics
and Heat Transfer, Dept. of Physics, University of Technology Eindhoven.