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THE TEST STATION
FOR WINDMILLS

Risø National Laboratory, DK-4000 Roskilde, Denmark
November 1984

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AERODYNAMIC PERFORMANCE OF A NEW LM 17.2 M ROTOR

Flemming Rasmussen
The Test Station for Windmills

Abstract. The paper describes measurements of the aerodynamic properties of a 17.2 m diameter LM rotor mounted on a VESTAS 55 kW windmill. Power curves were measured for a range of blade tip angles to find the best angle both in relation to energy production and stalling characteristics. With this optimum blade setting the flapwise blade root bending moment was measured as a function of wind speed. Also the drag coefficient at 90° angle of attack is calculated from measurements of the integrated value, i.e. the flapwise blade root bending moment as a function of wind speed during stand still.
With some simplified considerations the profile properties (C_L, C_D-curves) are estimated from aerodynamic calculations and the results compared to existing profile data from 3-dimensional wind tunnel measurements.

(Continued on next page).

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The flapwise blade root bending moment versus blade angular position during one revolution was measured in skew wind and is compared with calculations.
The influence of surface roughness introduced at a certain percentage of the section chord and the dependency on the Reynolds Number is investigated and discussed from observed discrepancies in the measured power curves.

EDB Descriptors: AERODYNAMICS; PERFORMANCE; ROTORS; TURBINE BLADES; WIND LOADS; WIND TURBINES.

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NORMENCLATURE

V	Wind speed
PE	Electrical power
PM	Mechanical rotor power
MBX	Flapwise blade root moment, r=0,87 m
r	Radius
C_L	Lift coefficient
C_D	Drag coefficient
Alpha	Angle of attack
POS	Angular position of blade (Blade upwards: POS=0)
Yaw	Angle of skew wind

1. INTRODUCTION.

The investigation presented in this paper concerns the first prototype of the 17.2 m rotor from LM Glasfiber. The rotor was installed on a VESTAS 55 kW machine at The Test Station for Windmills and tested in operation for about one year from January 1983. The tests covered both aerodynamics and structural response, but only investigations concerning aerodynamics are presented in this paper.

The focus is on more fundamental aerodynamic properties that could make a basis for a change of different parameters if necessary.

The design was after these investigations slightly modified and the performance of the final commercially available rotor is described in Ref. (1). The main data for the prototype rotor and the Vestas machine are described in Table 1 and the measurement parameters in Table 2.

2. FUNDAMENTAL MEASUREMENTS

Of direct importance, of course is the power curve of the actual rotor. It has to be measured in order to define its performance because the prediction of the power curve may be very inaccurate. But afterwards, what is important is the possibility of gaining information that makes it possible to predict the behaviour of modified rotors.

To describe the aerodynamic behaviour of a rotor the fundamental parameters are the rotor shaft torque and the axial thrust. The axial thrust is equivalent to the forces producing the flapwise blade root bending moment, and this parameter is more convenient to measure. The rotor shaft torque and the flapwise blade root moment represent the inplane forces and forces perpendicular to the rotorplane, respectively. These forces result from the section lift and drag, and thus make it possible to gain information on the actual lift and drag coefficients as they form during the operation of the rotor.

2.1 Power curves

The electrical power curve was measured for three different blade tip angle settings to find the optimum in relation to efficiency and stalling characteristics. The result is shown in Fig. 1. The power curve at high wind speeds at 2.5° tip angle is measured at reduced rotor rotational speed (25 rpm) and converted to 50 rpm. The power curve is sensitive mainly to blade tip angle in the stalling region. To avoid too much drop off of the power after the stalling point a blade tip angle of 2.5° is the most convenient and is used for all further investigations in this paper.

The mechanical power curve at 2.5° tip angle was not measured directly. It is derived based on earlier measurements of drive train and generator efficiency of the VESTAS machine, and is also shown in Fig. 1.

2.2 Flapwise Blade Root Moment Curve

The flapwise blade root bending moment was measured at a distance $r = 0.87$ m from the centre of the rotor and as a function of wind speed. The curve is shown in Fig. 2. At wind speeds above 17 m/s the curve is converted from measurements at reduced rotational speed (25 rpm). It is seen that the relation is nearly linear, and the shape of the curve rather typical for a stall controlled rotor (see Ref. (2)).

2.3 Drag Coefficient

The drag coefficient at 90^{o} angle of attack is important when calculating the extreme loads to which a windmill is exposed during stand still at high wind speeds and generally when making aerodynamic calculations. This drag coefficient could be found from measurements of the blade root bending moment as a function of wind speed with the blade stopped in an upright position and with the nacelle direction following the wind direction.

This measurement was performed and the result is shown in Fig. 3. The drawn curve is a fitted second order curve where the bending moment is expressed by

$$MBX(N) = 14.5 \cdot V^2 \ (m/s)$$

The drag coefficient is now found by integrating the moment performed by the drag force along the blade. Assuming that the drag coefficient is constant we get:

$$C_D = 1.24$$

This value around 1.3 is found from earlier measurements on another blade with other profile section, and is in agreement with wind tunnel measurements on a flat plate with aspect ratio about 7, but far from two dimensional measurements where approximately 2 is obtained.

3. ESTIMATION OF PROFILE PROPERTIES

The basis for aerodynamic calculations and thereby the design of new rotors with qualifications desired is the profile data for an angle of attack of from 0 to 90°. These data are normally nonexistent but with some simplified considerations they could be estimated from aerodynamic calculations.

The basis for the estimation is to obtain as good agreement as possible between the measured and the calculated power curve and flapwise blade root moment curve, respectively. This means that the measured and calculated moments derived from the sum of the total aerodynamic forces on the blade are identical both in magnitude and direction.

The estimation is made by assuming constant profile properties along the blade and just correcting the C_L and C_D values to give the right results.

Figure 4 shows the C_L and C_D curves estimated under these assumptions; the corresponding calculated mechanical power curve and flapwise blade root moment curve are shown in Figs. 1 and 2, respectively. The power curve is very close to the measured one but the flapwise moment curve is somewhat different at about 10 m/s. Some of the difference could be explained by the release of a few percent of the load on the blade when bending due to the centrifugal force. This means that the flapwise moment from the aerodynamic force is slightly higher than measured.

When making these kinds of estimations the measurement accuracy should be very high as the estimated values are very sensitive to changes in the power and flapwise blade root moment curves. Probably we are operating near the limit of what could be obtained from these kinds of measurements.

One application of these estimated profile properties is to predict the properties of rotors using the same blades but with changes in rotational speed, rotor diameter or tip angle (see also Ref. (3)). Another application is when designing new blades using the same profiles. In these cases one would expect that even if the profile properties are perhaps not definitely correct, they are adjusted to give results in accordance with reality.

Investigating the lift and drag coefficient curves in Fig. 4 more closely one recognizes that up to angles of attack of about 16° they are in very good agreement with two-dimensional wind tunnel measurements on the same profile.

Also shown in Fig. 4 is a reproduction from Ref. (4) of C_L and C_D values for a wing with an aspect ratio of 8 and two free tips. The airfoil is Clark Y. One realises that reasonably good agreement is obtained above the stall point, at least much better than corresponding to two dimensional data. Even better agreement is obtained, especially for the drag, if the estimated values are compared to the measurements of Ref. (4) at different aspect ratios and in such a way that the aspect ratio is decreased with increasing angle of attack.

These calculations lead to the conclusion that two dimensional data for the specific profile are adequate up to about 16° angle af attack. In the stall region the lift and drag coefficients depend as well upon the specific profile used, and could probably not be estimated exactly without previous measurements.

4. DYNAMIC LOADS IN SKEW WIND

One important aspect of a stall-controlled rotor is the occurrence of dynamic loads in skew wind. The phenomenon is fully described in Refs. (2) and (5). To investigate the loads for this specific blade the flapwise blade root bending moment was measured as a function of wind speed, yaw angle and blade angular position using a "three-dimensional method of bins" described in Ref. (2).

One result is presented in Fig. 5 as the flapwise blade root bending moment during one revolution at a wind speed of 13.2 m/s and -32^{o} yaw (definition, see Ref. (2)). Also shown is the calculated curve under the same conditions. The calculation in skew wind is performed by The Department of Fluid Mechanics, The Technical University of Denmark, using a code based on ordinary momentum theory. The blade is assumed to be infinitely stiff. There seems to be a systematic difference in the mean value but according to dynamics the two curves are in quite good agreement. There is a small phase lag of the measured curve which could be explained by the delayed response of the rather soft blade when activated by the 0.85 Hz oscillating load.

One interesting thing is seen at a blade angular position of 300^{o} where the load suddenly drops off. A similar phenomenon is seen on another rotor under nearly the same conditions (Ref. (2), Fig. 15). It could be explained by the fact that at this blade position a great deal of the outer part of the blade goes from the stall region back to a condition of unseparated flow (determined from the calculations). Under these dynamic circumstances probably the re-creation of the unseparated flow is delayed, and this causes the drop in the bending moment.

5. INFLUENCE OF SURFACE ROUGHNESS

It could generally be of interest to investigate the possibility of changing the profile properties and thereby the power curve by introducing roughness at a certain part of the blade. If it is generally possible to decrease the stalling power without decreasing the efficiency at lower wind speeds, it would be seen as an advantage.

An investigation on this problem was performed with the LM-rotor where a 20 mm broad strip of rough tape was placed all along the blade at different percentage of the blade section chord.

The first tape investigated had an average grain size of about 0.3 mm and the power curve at 50 rpm was measured with the tape placed first at the leading edge, then at 5% chord and at last at 20% chord at the upper side of the profile. No significant changes in the power curve was obtained by using this tape. The second tape had a mean roughness height of about 1 mm and measurements were carried out only with the front tape edge at 5% chord all along the blade.

The power curves were measured both at normal (50 rpm) and reduced (25 rpm) rotational speeds and are shown in Figs. 6 and 7, respectively, together with the ones without roughness tape. It is obvious that at 50 rpm the maximum power is decreased about 7 kW, but there is also a reduction at lower wind speeds down to about 8 m/s where the two curves coincide. This means that the reduction of the peak power in this case also infers a reduction of energy production at lower wind speeds.

Quite opposite and perhaps somewhat surprising results are obtained at the reduced rotational speed (reduced Reynolds Number), where the power output has been generally increased by using the roughness tape.

This increase in efficiency with roughness at low Reynolds Numbers led to the assumption that it would be possible to increase the maximum power coefficient slightly at normal rotational speed by placing tape only on the inner half of the blades, where the Reynolds Number is low. The test was initiated but no sure verification was obtained before the test had to be interrupted.

6. CONCLUSION

A description has been given of important measurements to define the behaviour of a stall controlled rotor. It seems that the method used to estimate the profile properties gives data that are quite reasonable. The procedure therefore seems rather adequate for design purposes.

The calculations in skew wind gives the right fundamental relationship, but the method probably could be developed to result in better absolute accordance with measurements. But measurements could also be performed at greater accuracy and this is probably essential in order to develop the calculational method.

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Table I. Main data for LM 17.2 m/VESTAS 55 kW.

Rotor

Three-bladed, stall-regulated, horizontal-axis rotor positioned in front of tower.

Direction of rotation:	Counter clockwise
Rotor diameter:	17.20 m
Rotational speed:	50.3 rpm
Reduced rotational speed:	25.1 rpm
Cone angle:	0°
Tilt angle:	5°

Blades

Blade manufacture:	LM 8.6 m
Natural frequency flapwise:	2.4 Hz
Profile series:	NACA 63-212/24
Blade data:	

Radius (m)	Chord (m)	Twist (Deg)	Thickness %
1.375	1.07	14.9	24.7
1.80	1.033	11.6	22.7
2.65	0.955	7.4	19.5
3.50	0.876	4.8	18.0
4.35	0.796	3.1	17.0
5.20	0.717	2.0	16.0
6.05	0.638	1.2	15.0
6.90	0.558	0.7	14.0
7.75	0.478	0.3	13.0
8.60	0.400	0.0	12.0

Generator

Rated power:	55/11 kW
Slip at full load	2%

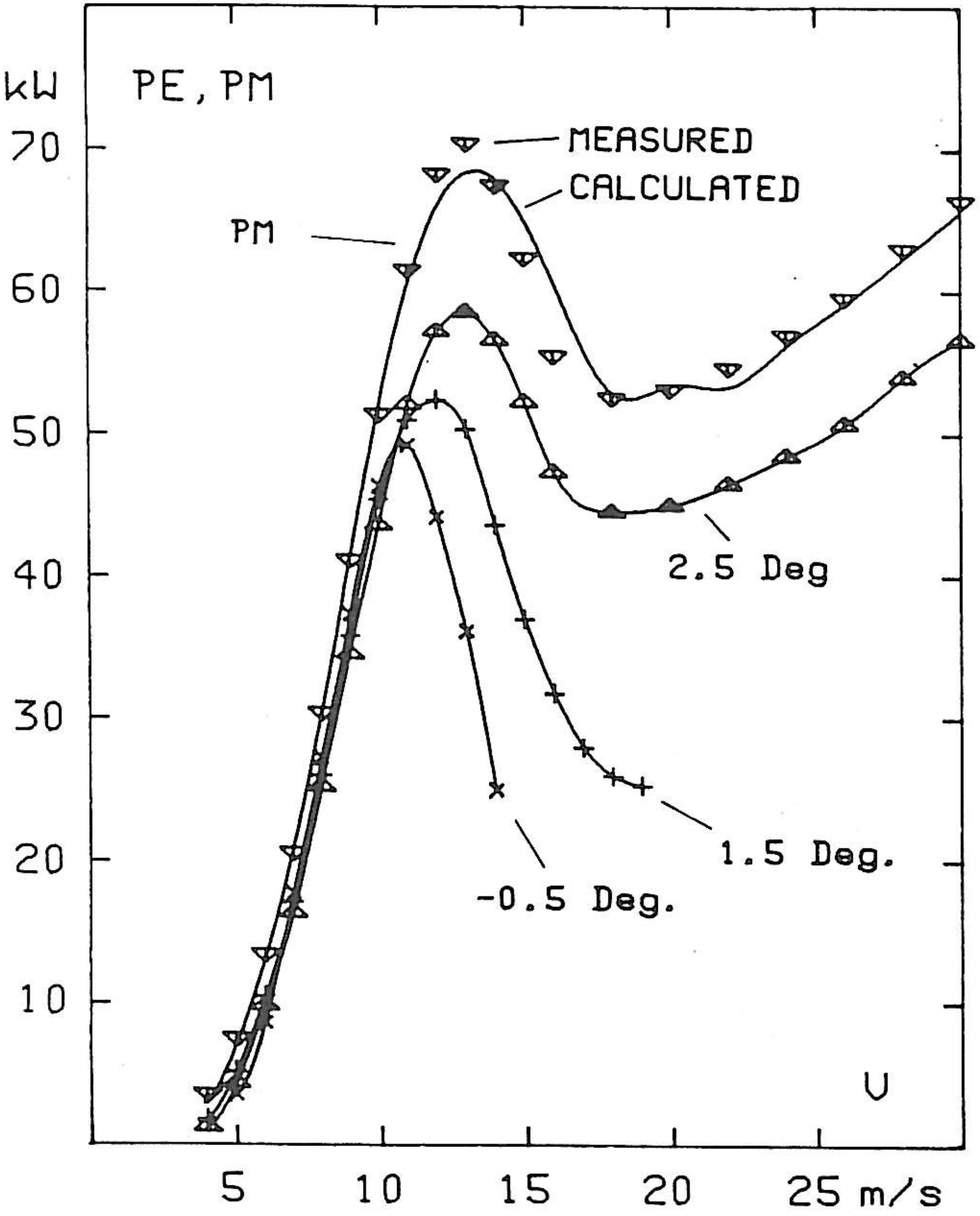
Table II. Measurement parameters.

Meteorological readings.

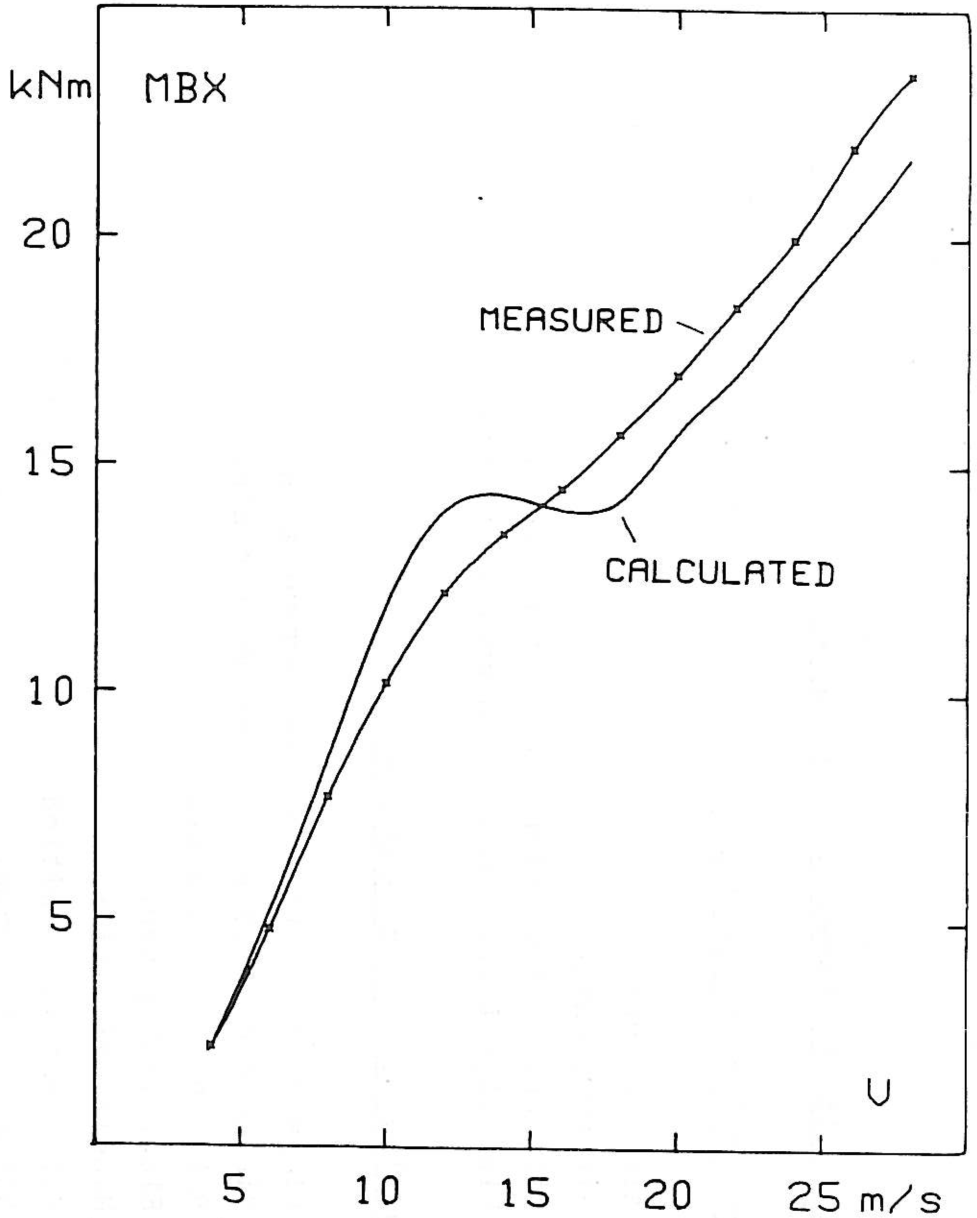
- o Air pressure.
- o Air temperature.
- o Wind speed, two rotor diameter upstream.
- o Wind direction, two rotor diameters upstream.

Turbine structure readings.

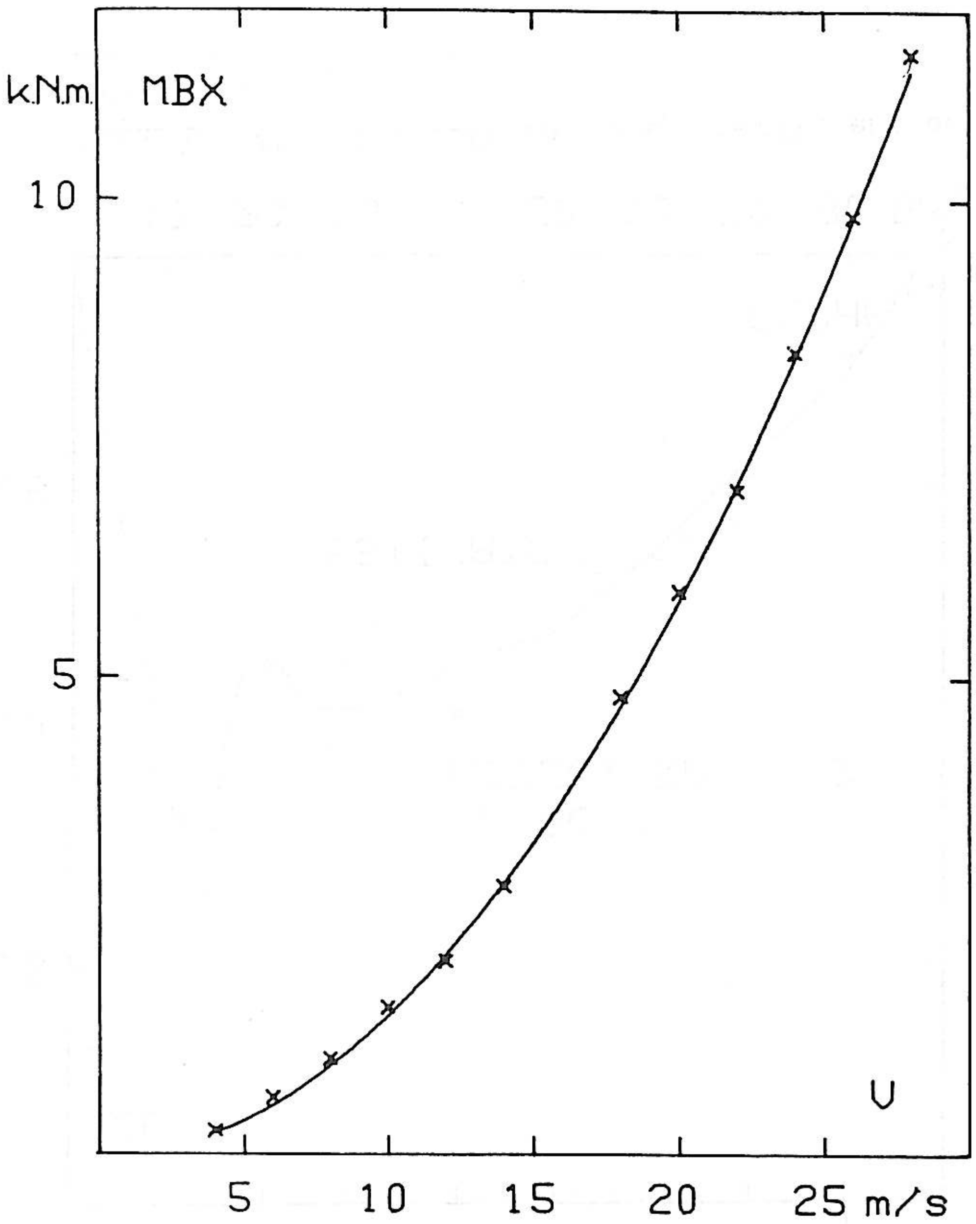
- o Flapwise blade root bending moment at a distance of 0.87 m from the rotor centre.
- o Rotor rotational speed.
- o Electrical power.
- o Nacelle direction.
- o Blade angular position.
- o Rotor shaft torque.



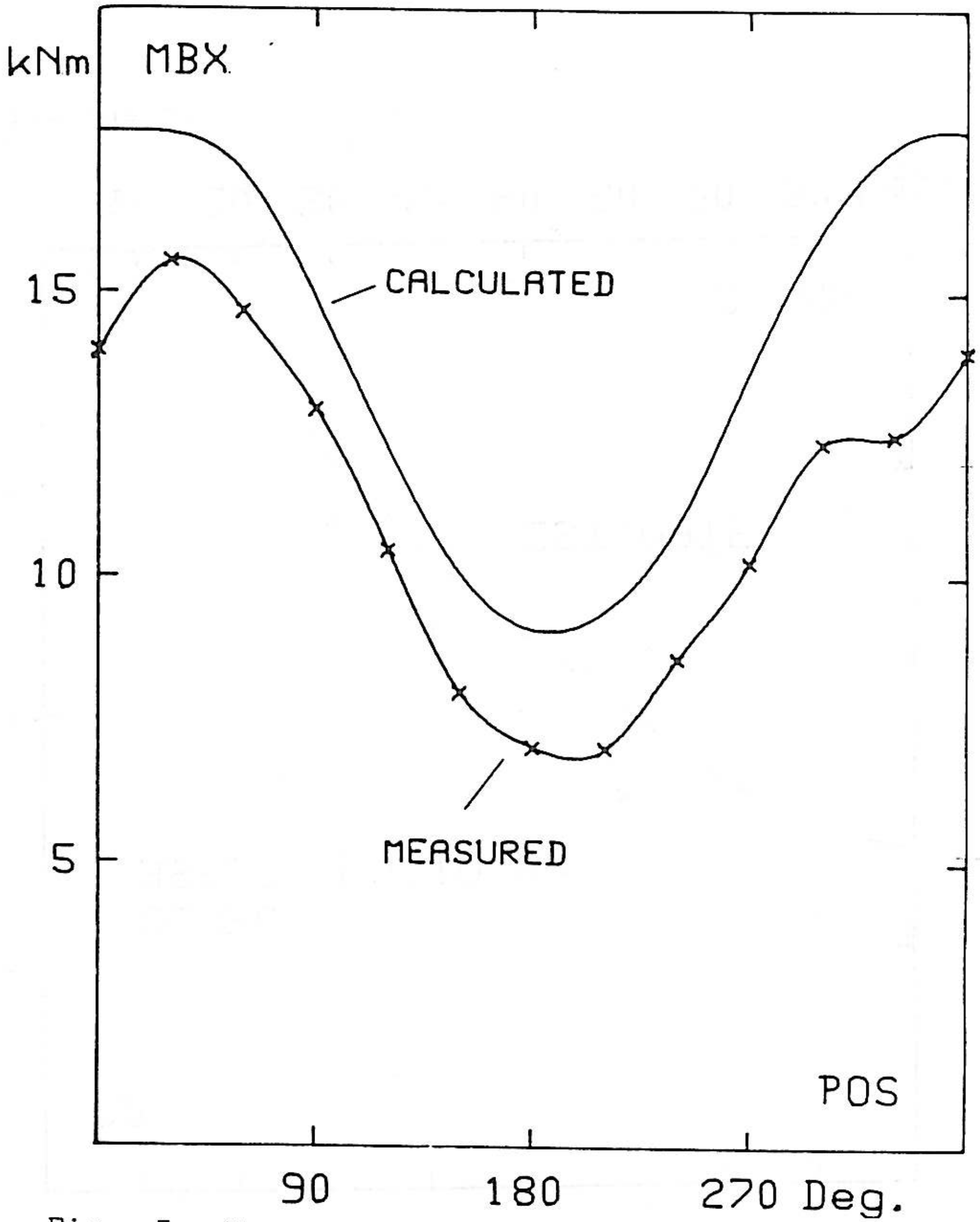
<u>Fig. 1.</u> Measured electrical power curves at different blade tip angles and measured mechanical power curve at 2.5° tip angle compared to a calculated curve.



<u>Fig. 2.</u> Measured and calculated flapwise blade root bending moment curves at 2.5° blade tip angle



<u>Fig. 3.</u> Measured flapwise blade root moment as a function of wind speed during stand still.



<u>Fig. 5.</u> Measured and calculated flapwise blade root moment as a function of blade angular position at V = 13.2 m/s and Yaw = 32o.

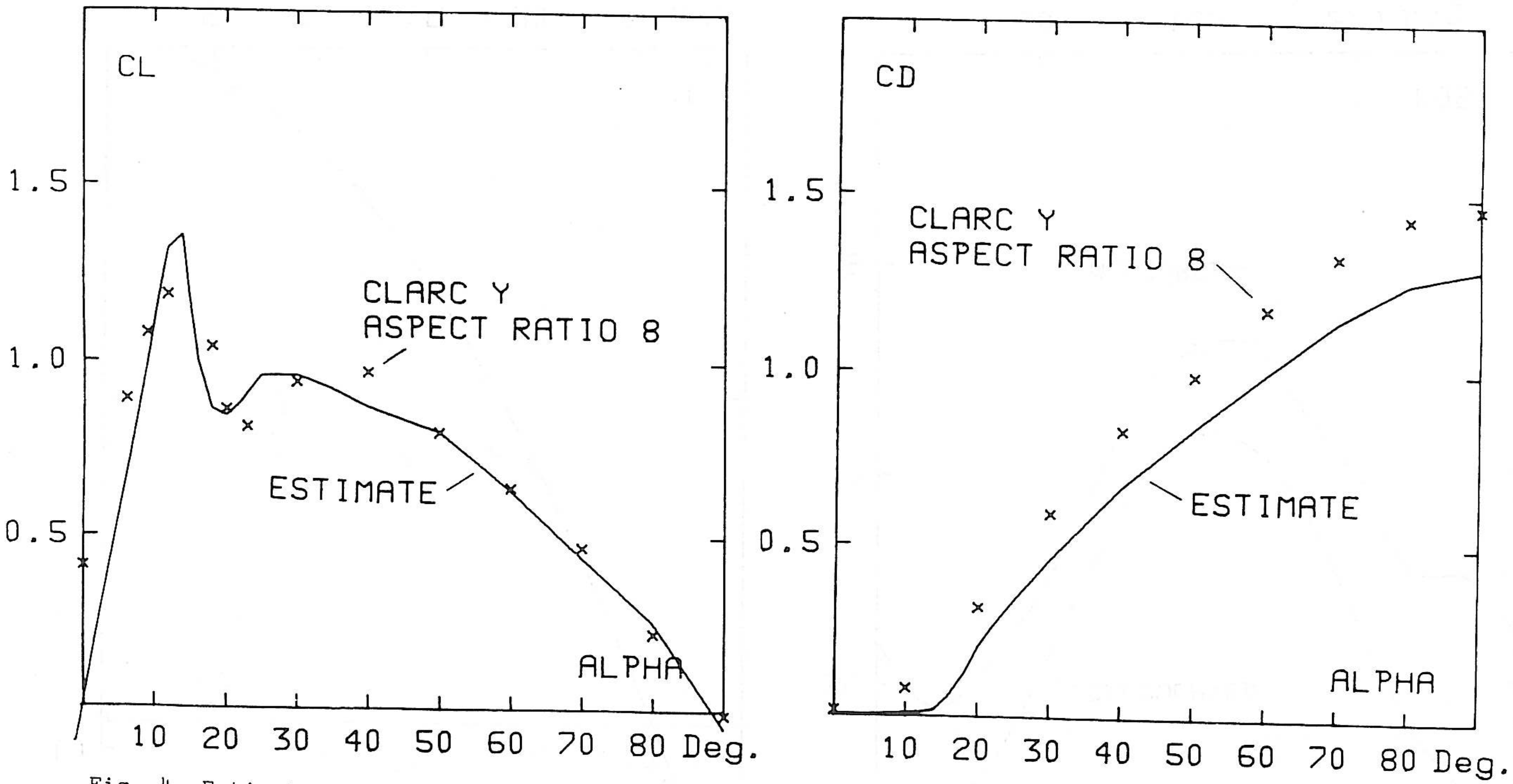


Fig. 4. Estimated lift and drag coefficient curces for the blade profiles.

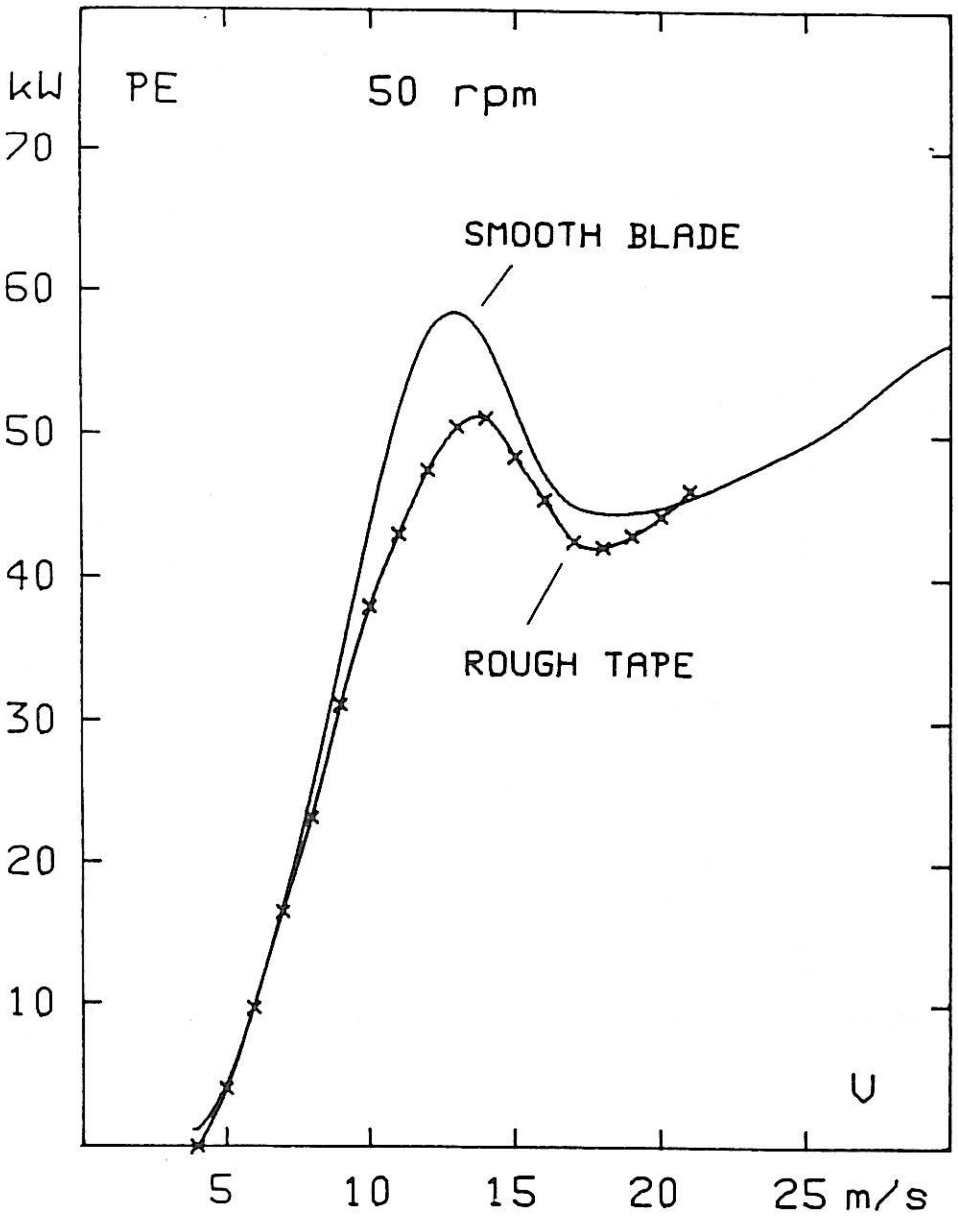


Fig. 6. Measured power curves with and without roughness tape at 50 rpm.

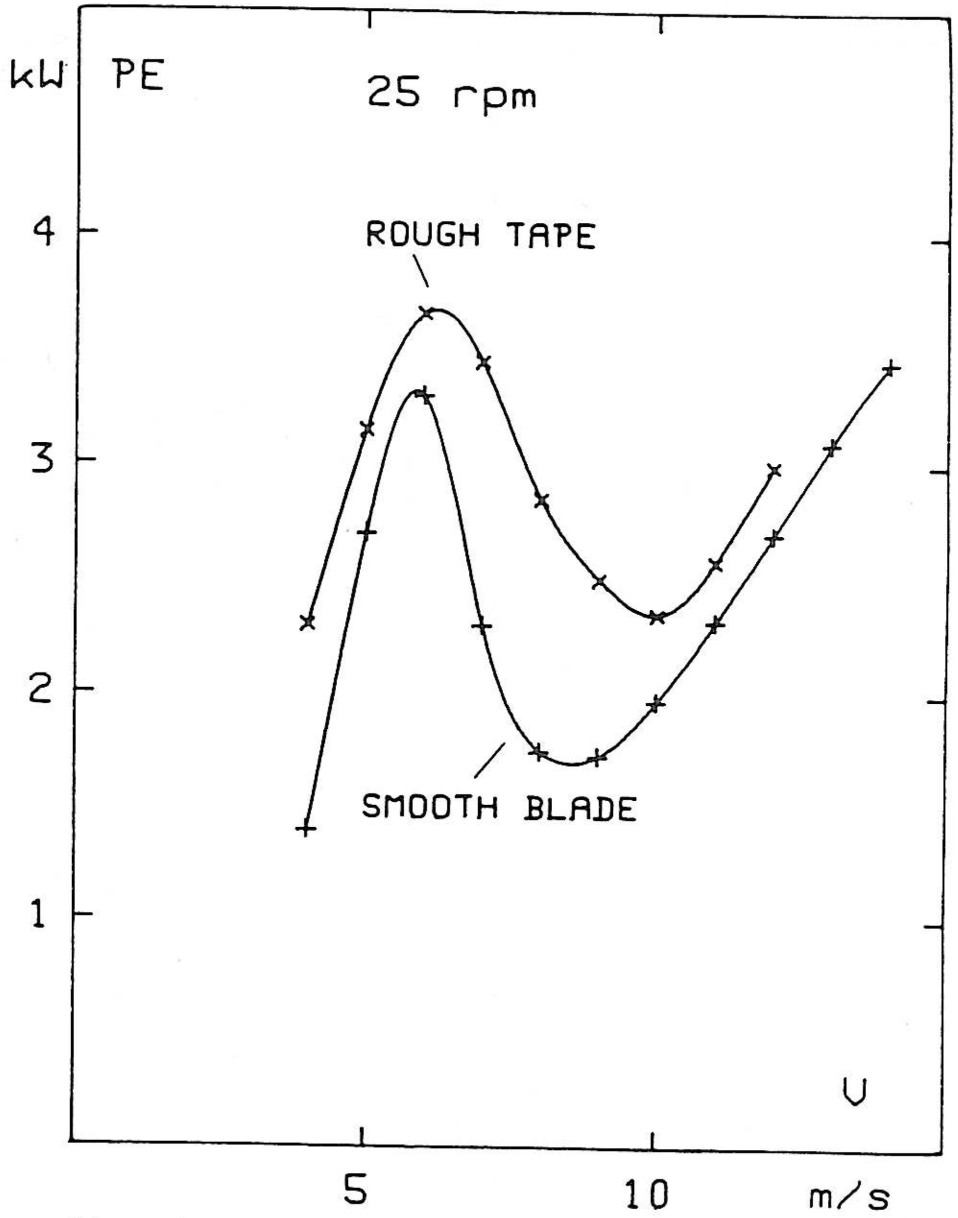


Fig. 7. Measured power curves with and without roughness tape at 25 rpm.

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