Translation of parts of report R 343 D of June 1978 from Dutch into English. R 343 D gives wind tunnel measurements for a rotor with tapered blades made out of a cylinder

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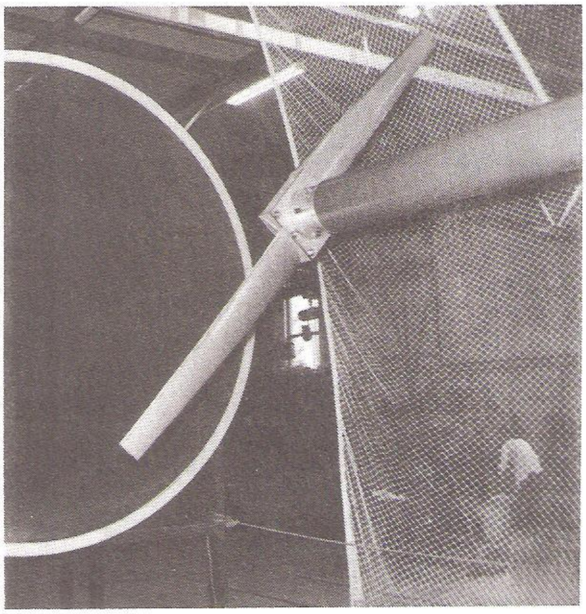
KD 616



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1 Introduction

Already in June 1978 I have performed measurements on a 2-bladed windmill rotor with tapered blades cut from a cylinder. The rotor and the measurements are described in the Dutch report R 343 D (ref. 1) of which the title can be translated as: "Report of wind tunnel measurements performed on a 2-bladed rotor with blades made out of a cylinder". This report is no longer available but it seems useful to make an English translation of the most promising parts of it.

In 1978 I was working as a technical designer of water pumping windmills, pumps and test rigs at the Wind Energy Group of the University of Technology Eindhoven. This group was a member of CWD, Consultancy services Wind energy Developing countries.

The measurements have been performed in the open wind tunnel of TNO Waddinxveen. TNO was a member of CWD during the first five years of CWD. This wind tunnel is later moved to the University of Delft and I have measured several other rotors in this wind tunnel. The wind tunnel is blowing air into the open space and the wake therefore can expand around the rotor which also happens in real wind. So there is no tunnel blockage as it is the case for closed wind tunnels. The measurements are therefore very accurate. The wind tunnel has a diameter of 2.2 m and the maximum rotor diameter of a rotor which can be measured is 1.8 m. All measured rotors as described in R 343 D have a diameter of 1.8 m.

The measurements have been performed on five different days, for two different rotor geometries made from three different materials. In 1978 we only had the report "Rotor design for horizontal axis windmills" (ref. 2) in which it is explained how to design a windmill rotor. I have used this report and several others to write my report KD 35: "Rotor design and matching for horizontal axis wind turbines" (ref. 3). It is possible to check the rotor geometry using my report as it is newer and available for free on my website: www.kdwindturbines.nl but I havn't verified if the geometry is right as it is given on drawing 7701-2 (see figure 1).

Blades of fast running wind turbine rotors are normally provided with an asymmetric NACA or Götingen airfoil. However, measurements performed by Volkers at the UT-Delft show that rather low C_d/Cl values can also be realised for a 10 % curved plate airfoil if the Reynolds value is not too low. The measurements are given in memorandum M-276 of June 1977 (ref. 4). Although this report is almost 40 years old, it can be found on the Internet if the complete title is typed in Google. These aerodynamic characteristics of a 10 % curved plate airfoil are given at figure 4. For constant chord blades, I prefer to use a 7.14 % curved plate airfoil measured by Imperial College. Characteristics for the three different cambers 7.14 %, 10 % and 12.5 % are given in my report KD 398 (ref. 5).

A low C_d/Cl value can only be realised if the airfoil has no support pipe and if the sheet thickness is rather thin with respect to the chord. But such blades have a rather low bending and torsion stiffness. The bending stiffness increases by increasing camber (the ratio in between the airfoil thickness and the chord) but the torsion stiffness is not influenced by the camber and is rather low for slender blades. Freely supported curved blades are therefore sensible to flutter if the sheet thickness and the chord are chosen small with respect to the free blade length. Flutter is a combined bending-torsion vibration which happens suddenly at a certain tip speed. 2-bladed rotors have wider chords for the same design tip speed ratio than 3-bladed rotors and this is one reason why a 2-bladed and not a 3-bladed rotor is chosen. The other reason is that it is rather easy to connect two blades to the hub.

2 Description of the rotor and the tests

In 1987 we thought that a fast running wind turbine must have tapered blades with a small chord at the blade tip and a large chord at the blade root. If a rotor is designed for the optimum lift coefficient, this indeed is the right shape but it is also possible to design a rotor with a constant chord if the used airfoil has an acceptable C_d/C_l value over a large range of C_l-values. This is illustrated in the examples of chapter 5 of KD 35.

Constant chord blades with a curved plate airfoil are much easier to manufacture than tapered blades. However, it seems possible to find an acceptable manufacturing procedure for tapered blades.

Two rotors have been designed, one with a design tip speed ratio λ_d = 6 and one with a design tip speed ratio λ_d = 5. The hub was the same for both rotors which means that the chord at the blade root was also the same for both rotors. The rotor with λ_d = 6 had the smallest chord at the blade tip and was designed close to the aerodynamic theory. It had the best characteristics and so only this rotor is taken into account for this report KD 616.

To be able to make the rotor blades and the hub connection easily, the following criteria should be fulfilled:

1 It must be possible to make a blade from a cylinder without the need to twist it.
2 A blade must have the shape of a trapezium.
3 The tailing edge of the blade must be in parallel to the cylinder axis.
4 The connection of the blade to the hub must be solid. This can easily be realised for the chosen 2-bladed rotor if the hub sheet has a length of 200 mm and if two blades are clamped in between two clamping blocks by totally six M8 bolts
5 The blade geometry must de such that eight blades can be made from a 1 m long pipe with an outside diameter of 300 mm
6 The blade length is chosen 1 m because in this case, blades can be made from a sheet size 1 * 2 m with only limited losses. A rotor with 1 m long blades gets a diameter of 1.8 m and this is the maximum diameter which can be tested in the available wind tunnel.

The blades are made out of a cylinder which means that the bending radius is constant for the whole blade. However, as the chord is small at the blade tip, it means that the camber will be small for the given bending radius. As the chord is large at the blade root, the camber will be much larger for the same bending radius. The aerodynamic characteristics of a cambered plate airfoil depend on the camber so this means that one can make only correct design calculations if characteristics for a range of cambers are available. But at that time we had only characteristics available for 10 % camber and I can’t remember how I have solved this problem of variation of the camber from blade tip to blade root. Probably I have estimated the characteristics for cambers smaller and larger than 10 %. The result of the design calculations is given in a table on top of the drawing of the rotor which has drawing number 7701-2. In this table it can be seen that the camber is 6.3 % at the blade tip at cross section D and r = 0.9 m and 11 % at cross section A and r = 0.225 m.

The drawing was originally made on sheet size A1 but a reduced version on sheet size A4 was added to report R 343 D. This drawing has been copied and is added as figure 1. As the drawing size is now reduced by almost a factor 3, it might be difficult to read the text but this is all what’s available. I have rewritten some important measures

The direction of rotation on the drawing is left hand if the rotor is seen from the front side. However, the mirror image of the blades has been manufactured, resulting in a real rotor with a right hand direction of rotation! The photo on the front page is made from the back side and on this photo it can also be seen that the direction of rotation is right hand.

Originally the idea was to make the blade from a pipe with a diameter of 300 mm. In this case eight blades can be made from 1 m pipe with almost no waste material. The shearing plan is given in the picture at the left bottom side of figure 1. Later it was decided to make the blades from flat sheet and to camber the blades after cutting. In this case, sixteen blades can be made from sheet size 1 m * 2 m. The shearing plan for this option is given in the middle bottom picture. The width of a strip for two blades is 233 mm. So a waste strip of 136 mm wide is left if 16 blades have been cut. It might be better to use a 250 mm wide strip for two blades which means that the chord has to be enlarged by about a factor 1.07.

If the strip width at the blade tip is chosen 80 mm in stead of 75 mm and if the strip width at the other side is chosen 170 mm in stead of 158 mm, this is realised. Probably the design tip speed ratio can be maintained at $\lambda_d = 6$ but the starting torque coefficient will be higher.

For the rotor with $\lambda_d = 6$, three different materials have been tried. The first tests were executed for a rotor made from 3 mm PVC pipe. This was a complete disaster as flutter of the blades already started at a wind speed of 3 m/s. So 3 mm PVC was cancelled immediately.

The next tests were executed for blades made from 2 mm aluminium sheet. The leading edge of this rotor was rounded and the tailing edge was sharpened. The use of 2 mm aluminium sheet resulted in strong flutter behaviour at a rotational speed of 750 rpm belonging to a tip speed ratio of 6.5. These blades have also been tested for a tunnel wind speed of 5.5 m/s and then there was no flutter even if the rotor runs unloaded but it was thought that an unloaded rotor must be resistant to a wind speed of at least 11 m/s if it is perpendicular to the wind direction, so 2 mm aluminium was cancelled too. For the 2 mm aluminium rotor, measurement have been performed for V = 5.5 m/s and for V = 11 m/s. For V = 11 m/s, the measurements could only be done up to a tip speed ratio of maximal 6.5 because flutter starts at higher tip speed ratios. The maximum C_p was about 0.43 at $\lambda = 6$ and at V = 11 m/s and about 0.39 at $\lambda = 6$ and at V = 5.5 m/s.

The next tests were executed for blades made from 3 mm aluminium sheet and for a tunnel wind speed of 11 m/s. This resulted in strong flutter behaviour at a rotational speed of 930 rpm belonging to a tip speed ratio of 8, so 3 mm aluminium was cancelled too.

The next tests were executed for blades made from 4 mm aluminium sheet. However, 4 mm is very thick for the given chord at the blade tip and therefore the cambered airfoil was transformed into about an Eppler (Gö 804) airfoil. This rotor wasn't suffering from flutter but making of an Eppler airfoil isn't easy and the maximum power coefficient of the rotor was a lot lower than for the 2 mm aluminium rotor measured at a wind speed of 5.5 m/s. So 4 mm aluminium was cancelled too.

The last tests were done for blades made out of 2 mm stainless steel. There was no strong flutter at a wind speed of 11 m/s even if the rotor was running unloaded at a maximum rotational speed of about 1040 rpm. However, the rotor was rather noisy if it runs at tip speeds higher than 8 so the fluttering speed is approached very closely. In practice the rotor won't run unloaded so 2 mm stainless steel is an acceptable option. The leading and the tailing edge were probably not rounded or sharpened, at least, this isn't mentioned at the measurement sheets like it was done for the 2 mm aluminium rotor. The free blade length outside the hub is 0.8 m. For rotors with a constant chord and 2 mm stainless steel blades, I also advice a maximum free blade length of 0.8 m.

The C_p-λ curve of the 2 mm stainless steel rotor has only been measured for a wind speed of 11 m/s which is rather high and which results in rather high Reynolds values. The maximum C_p for 2 mm stainless steel blades was about 0.41 at $\lambda = 6$. This is a little lower than for the 2 mm aluminium rotor but this is because the stainless steel rotor has no rounded leading edge and sharpened tailing edge. In practice it will be advised to round both the leading edge and the tailing edge like it is also done for the airfoil measurements of Volkers. The maximum C_p will also be lower at V = 5.5 m/s than at V = 11 m/s. The measured C_p-λ and C_q-λ curves for the 2 mm stainless steel rotor are not copied from R 343 D but made in Excel by copying the measuring points as accurately as possible (see chapter 4).

In real wind, much higher wind speeds than 11 m/s will occur. So the windmill must be provided with a safety system which prevents that the maximum rotational speed can become higher than about 1000 rpm. As the load may fall off for whatever reason, this speed limit must be maintained even for an unloaded rotor.

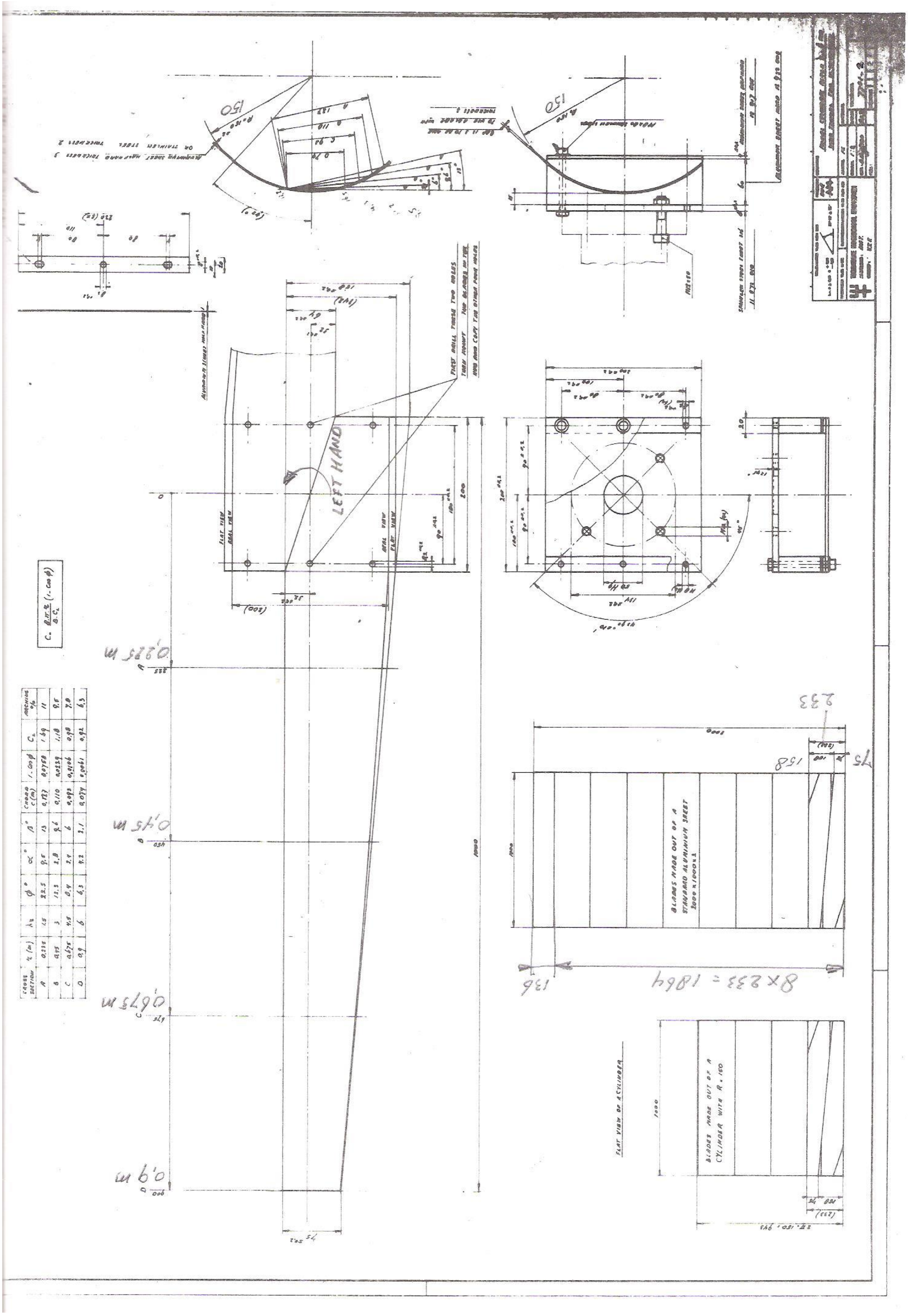

fig. 1 Drawing of 2-bladed rotor with λ_d = 6 and R = 0.9 m

3 Manufacture of the 2 mm stainless steel blades

The two blades of the prototype were curved on a standard roll bender. If a sheet with a certain width is curved on a roll bender, one always ends with a non curved part at each side of the strip. So the original strip width was chosen much wider than 233 mm. The shape of the two blades were drawn in the middle of the strip. Next the strip was put through the roll bender until it has the correct bending radius of 150 mm. Next the blades are ground from the curved strip using a rectangular grinding machine. It is difficult to do this accurately but workers of the work shop of the University have managed it. For serial manufacture this is a non realistic way of making blades as there is a lot of waste material and it is a lot of work. For serial manufacture the blades should be cut first and cambered afterwards using a special hydraulic blade press.

In figure 1 it can be seen that a blade is clamped in between two clamping blocks by three bolts M8. The clamping blocks are made out of aluminium and have a width of 20 mm. The inside part of the blade is tapered such that the blades don’t touch each other. The 8 mm hole near the tailing edge of the blade is drilled first. Next both blades are clamped in between the clamping blocks using the two central bolts. Next the four remaining holes are milled (so not drilled) in the blades using the clamping blocks as a milling jig. As the blade isn’t perpendicular to the hub sheet at this position, these last four holes are not circular!

For the constant chord blades of the VIRYA wind turbines I have developed an hydraulic blade press for a sheet width of 125 mm using two 6 tons hydraulic car jacks. A blade is curved in one big stroke. The strip is pushed upwards by a long heavy strip which has the right curvature at the top to realise the correct bending radius of the blade strip once the blade strip is removed from the blade press. As the blade bends back in the elastic region, the bending radius of the heavy strip must be much smaller than the required bending radius of the blade. The blade is supported at the upper side by two bevelled strips which make contact only at the edges of the blade strip. This construction isn’t possible for a tapered blade. For a tapered blade, the blade should be supported at the upper side by another heavy strip which has the correct hollow curvature over the whole strip length. Manufacture of such blade press will be rather expensive but this is acceptable for serial production of the rotor.

The scale laws of flutter predict that the critical tip speed for flutter is the same if all dimensions of the blade are scaled with the same factor. So if 2 mm is an acceptable sheet thickness for a stainless steel blade with a total length of 1 m, 3 mm will be an acceptable sheet thickness for a stainless steel blade with a total length of 1.5 m.

4 Presentation of the measuring results for the 2 mm stainless steel rotor

The measured C_p-λ and C_q-λ curves for the 2 mm stainless steel rotor are not copied from R 343 D but made in Excel by copying the measuring points as accurately as possible. In chapter 4 of report KD 35 it is derived that $C_p = C_q * \lambda$. So the C_p-λ curve can be derived from the C_q-λ curve by multiplying a certain C_q value by the corresponding value of λ.

For wind tunnel measurements, the rotor is mounted on a device with which it is possible to measure the torque Q (Nm) and the rotational speed n (rpm). The corresponding C_q and λ values are calculated for the given wind speed V (m/s) of the tunnel using formula 4.3 and 4.8 of KD 35. The air density ρ was calculated for the given air pressure and temperature but it is about 1.2 kg/m^3 for an air temperature of 20 °C at sea level. The C_p-λ curve is given in figure 2. The C_q-λ curve is given in figure 3.

In figure 2 it can be seen that the C_p-λ curve has a maximum value of about 0.41 for $\lambda = 6$. However, there is a sudden peak in the C_p-λ curve for $6.3 < \lambda < 7.5$. In the first instance it was thought that this is caused by a measuring error. But the measurements were repeated several times and a similar peak was also found for the 3 mm aluminium rotor.

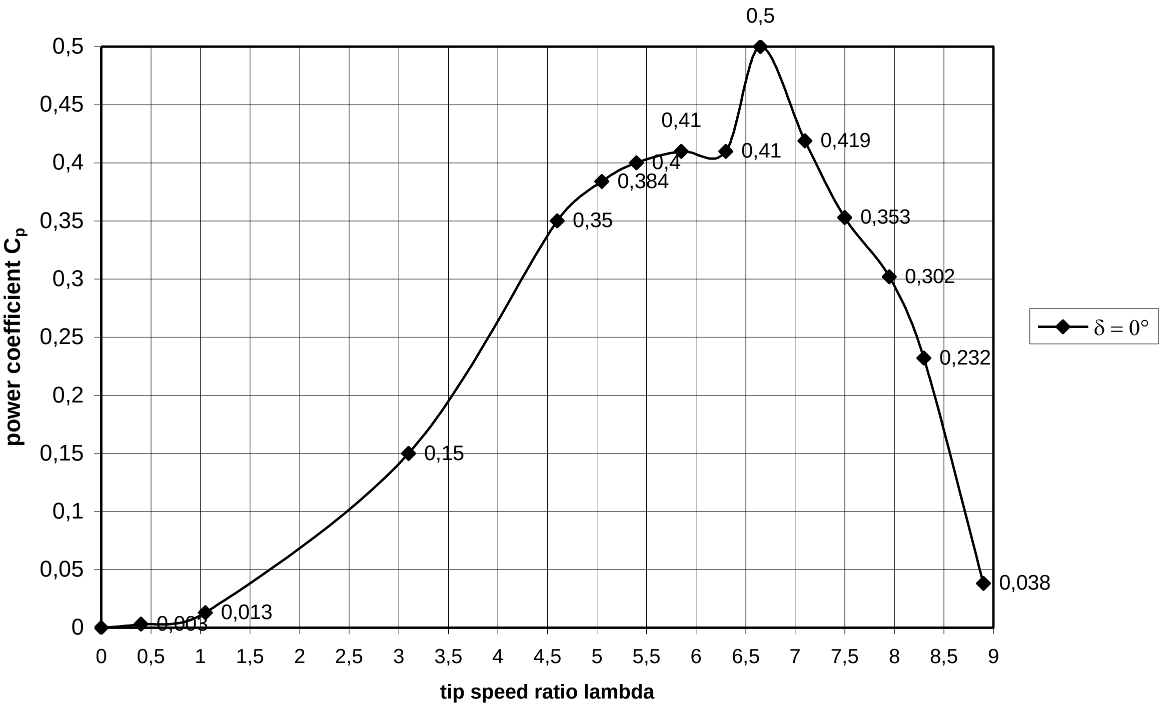

fig. 2 Measured C_p-λ curve for a 2 mm stainless steel rotor for a tunnel wind speed of 11 m/s

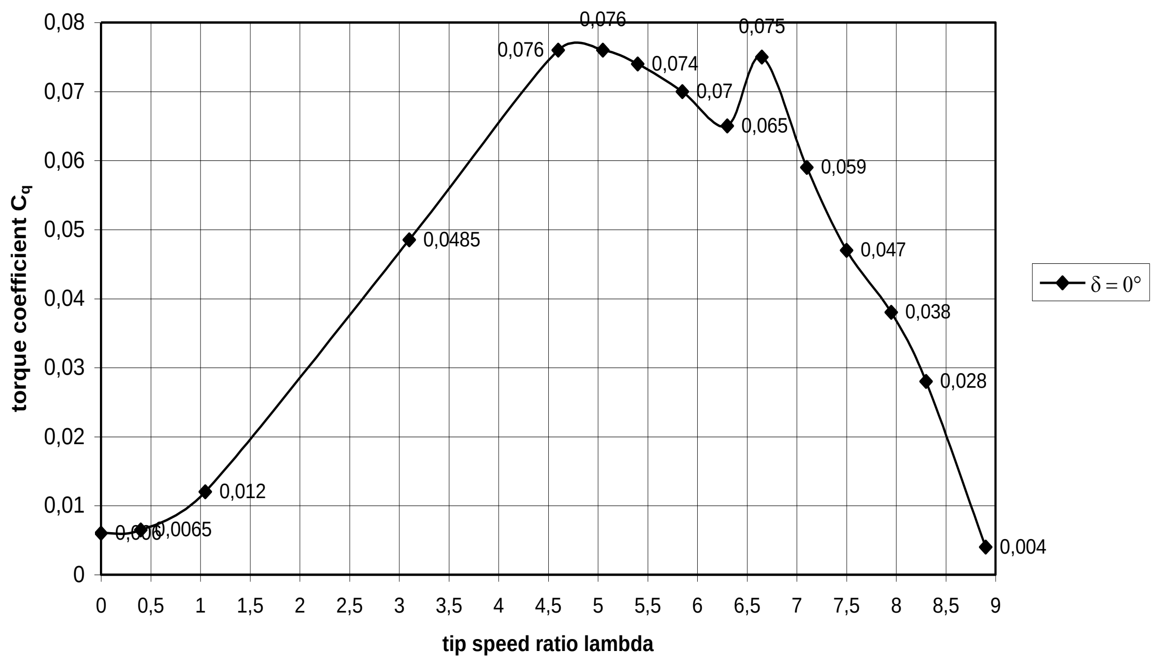

fig. 3 Measured C_q-λ curve for a 2 mm stainless steel rotor for tunnel wind speed of 11 m/s

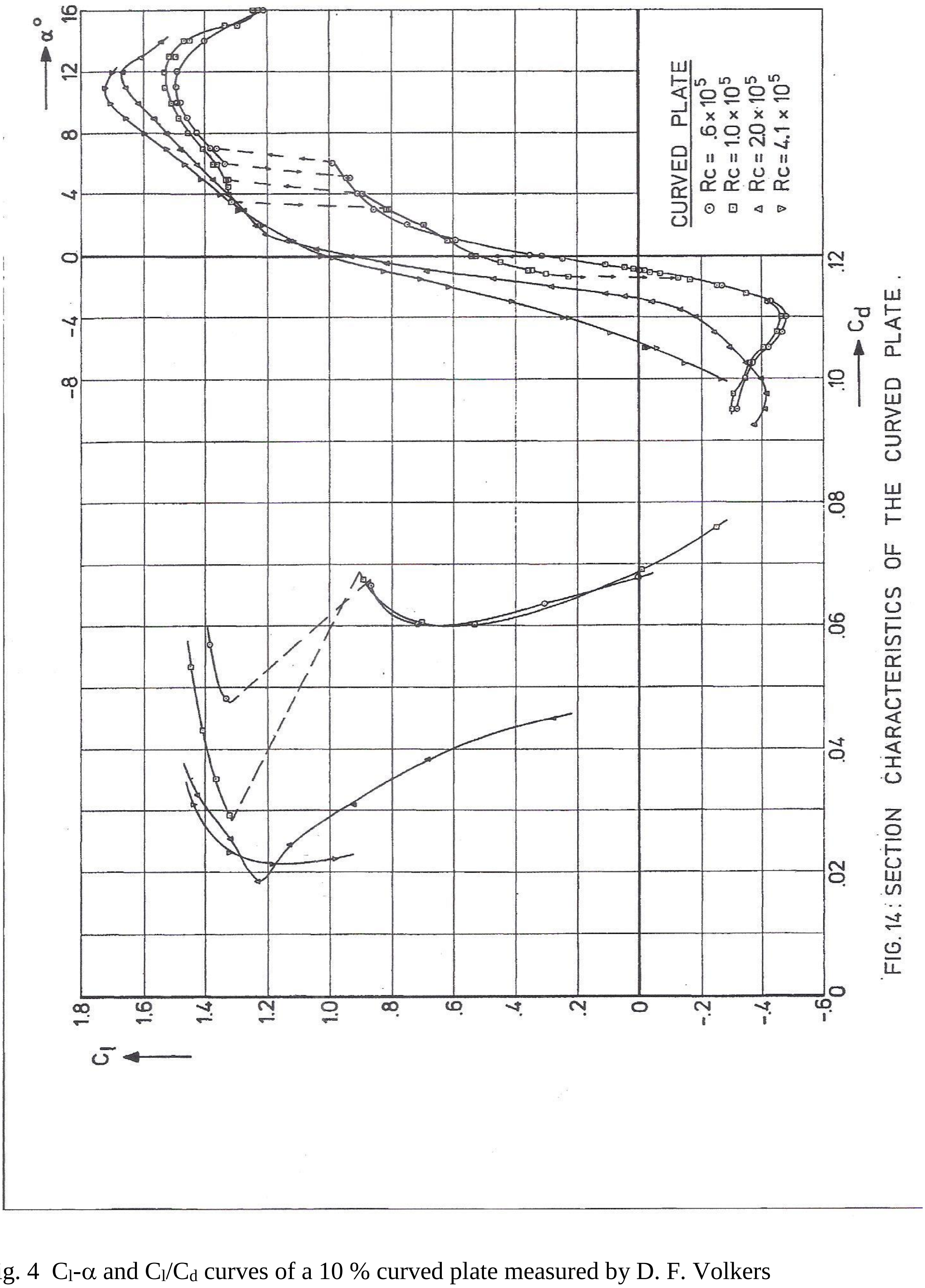

fig. 4 C_l-α and C_l/C_d curves of a 10 % curved plate measured by D. F. Volkers

Another aspect was that the rotor became very silent when it was running at the tip speed ratio which belongs to the peak. This is an indication that something special was happening.

It appeared that the measurements performed on 10 % curved plate as presented by Volkers in memorandum M-376 (ref. 4), show a sudden peak in the C_d/C_l curves for Reynolds values of 0.6 * 10^5, 1 * 10^5 and 2 * 10^5. A copy of these measurements is given in figure 4. The minimum C_d/C_l value is found for a line through the origin which touches the $C_d/Ç_l$ curve for a certain Reynolds value. The minimum C_d/C_l ratio is about 0.016 for Re = 2 * 10^5 which is very low for a 10 % curved plate.

The measurements for the 10 % curved plate of Imperial College as given in report KD 398 (ref. 5) don't show these peaks. This might have to do with the fact that Volkers was using a wind tunnel with a very low turbulence level, that he was using a wake rake to measure the drag coefficient or that both the airfoil nose and the tailing edge were rounded.

The peak in the C_d/C_l curve can be explained as follows. A curved sheet airfoil has a sharp nose and the boundary layer is therefore normally turbulent. This results in a rather high drag coefficient. However, at a certain angle of attack α, the direction of the relative wind W becomes the same as the direction of the tangent which touches the leading edge of the airfoil. For this angle of attack, the boundary layer suddenly becomes laminar. This results in a sudden decrease of the drag coefficient. For a rotor with tapered blades this may happen at the same time for almost the whole blade length and this results in a sudden rise of the C_p-value. If the tip speed ratio increases, the angle of attack becomes smaller and therefore the boundary layer becomes turbulent again. So the peak disappears if the tip speed ratio becomes larger than about 7.5. But even without the peak, the measured characteristics are very good for a rotor which makes use of curved plate airfoils.

5 Ideas about a larger rotor

In chapter 2 and figure 1 it is shown that the chosen blade geometry is optimal if the blade is made out of a pipe with a diameter of 300 mm but that a 136 mm wide and 1000 mm long strip is wasted if the blade is made from a sheet size 1 * 2 m. There are countries like India where sheet size 1 * 2 m isn't available and where one only can get sheet size 1.25 * 2.5 m.

Another point is that a considerable amount of material is used in between the two clamping blocks and that this material doesn't contribute to the generated power. Experiments with the constant chord cambered blades of my smaller VIRYA wind turbines with 2 mm stainless steel blades show that a blade can be connected with sufficient strength to a connecting strip if the overlap in between the blade and the connecting strip is only 25 mm and if three M6 bolts are used.

A special machine is required to make the curvature in both parts of an aluminium clamping block and the two clamping block are therefore rather expensive.

Assume that 2 mm and 3 mm stainless steel sheet is available for sheet size 1.25 * 2.5 m and that the rotor is designed such that it can be made from this material with minimum waste material. Assume the 2 mm sheet is cut into 15 sheets size 250 * 833 mm. Each sheet is cambered on a hydraulic blade press similar to the blade press which is used for the constant chord blades of the VIRYA windmills. The sheet is ground (or laser cut) in two pieces such that two tapered blades are created. It must be possible to find a way to do this accurately enough to prevent blade imbalance. Assume that the grinder takes 2 mm and that the blade has a width at the tip of 82 mm. The width at the root will be 250 – 82 – 2 =166 mm. So 30 blades can be made from a standard sheet size 1.25 * 2.5 m with almost no waste material.

Assume that the 3 mm sheet is cut into 45 sheets size 416 * 166 mm. So the width of this connecting strip is the same as the width of the blade at the blade root. A connecting strip is twisted such that the correct blade angle is created at the blade root. Both ends of the connecting strip are curved with the same radius as the radius of the blades, so no clamping blocks are required. A blade is connected to the connecting strip by three bolts and nuts M8.

Assume that the overlap in between a blade and the connecting strip is chosen 31 mm. This results in a rotor diameter of 2 * 833 + 416 – 2 * 31 = 2020 mm = 2.02 m. The windmill with this rotor is therefore called the VIRYA-2.02. The rotor diameter is a factor 2.02 / 1.8 = 1.122 larger than that of the tested rotor. The chord at the blade tip is increased by a factor 82 / 75 = 1.093 so almost by the same factor. To get a blade geometry which is almost congruent to that of the tested rotor, the bending radius should be increased from 150 mm up to 165 mm. The geometry of the effective part of the blades of this rotor is almost congruent to that of the tested rotor and the rotor will therefore have almost the same characteristics. A very important aspect of these characteristics is that the rotor is very silent if it runs with a tip speed ratio in between 6 and 7.5. Rotors with a constant chord and with the same design tip speed ratio λ_d = 6, are rather noisy. A sketch of the VIRYA-2.02 rotor is given in figure 5.

The connecting strip is bolted to a hub which itself is connected directly to the generator shaft. The hub can only be designed if the generator type is chosen.

The generated power is proportional to the swept area so proportional to D^2. This means that the power at a certain wind speed increases by a factor $(2.02 / 1.8)^2$ = 1.26. So increase of the rotor diameter is worth wile as almost no more material is used for the blades and the hub.

Another aspect is that 2-bladed rotors are sensible to vibrations caused by the gyroscopic moment. These vibrations can be reduced strongly if the blades are connected to the hub by an elastic element. The chosen thickness of 3 mm of the connecting strip and the rather long length of it, are making the connecting strip enough elastic to reduce the vibrations to an acceptable level. If it might come to realisation of this VIRYA-2.02 rotor, it will be necessary to make new design calculations using the aerodynamic characteristics of curved plates with different camber as given in report KD 398 (ref. 5).

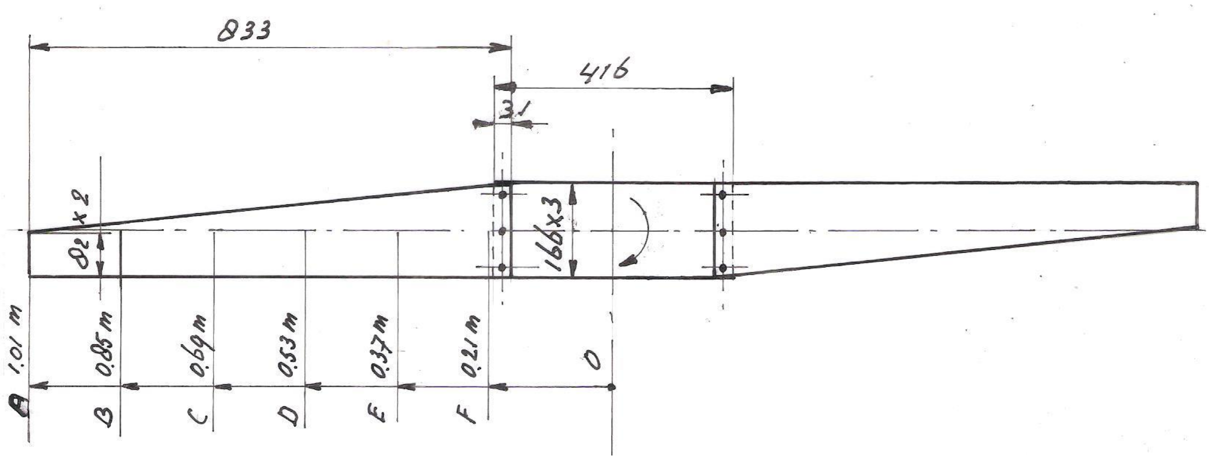

fig. 5 Sketch VIRYA-2.02 rotor, 2 mm stainless steel blades, B = 2, λ_d = 6

6 References

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2 Jansen W. A. M. and Smulders P. T. Rotor design for horizontal axis windmills, CWD publication 77-1 May 1977, no longer available.

3 Kragten A. Rotor design and matching for horizontal axis wind turbines, July 1999, latest review November 2015, free public rapport KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Volkers D. F. Preliminary results of wind tunnel measurements on some airfoil sections at Reynolds numbers between $0.6 * 10^5$ and $5 * 10^5$, June 1977, Memorandum M-276 Delft University of Technology, Department of Aerospace Engineering. The measurements of the 10 % cambered sheet are given at page 20 of this report and in figure 4 of this new report KD 616. The report of Volkers is made available on the Internet by the current wind energy group of Delft University. It can be found by typing the first part of the title in Google.

5 Kragten A. The 7.14 %, 10 % and 12.5 % cambered plate as airfoil for windmill rotor blades, Aerodynamic characteristics, geometry, moment of inertia I and moment of resistance W, November 2008, free public report KD 398, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.