Translation of parts of report R-668-A “Optimalisering van een windservo” (Optimizing of a wind servo) from Dutch into English. Ideas about the VIRYA-2B8.

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KD 671

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1 Introduction

Report R-668-A “Optimalisering van een windservo” (ref. 1) of the Wind Energy Group of the University of Technology Eindhoven was written already in 1984 by the student J. Swinkels. I was one of his supervisors. This rather thick report (96 pages) was written in Dutch. The Dutch title can be translated as: “Optimization of a wind servo”. The report contains wind tunnel measurements executed on a scale model for four different blade angles β and seven different yaw angles δ. As this report is no longer available and as it is written in Dutch, I thought that it is useful to make the measurements for the most promising blade angle β = 30°, public again in English in this report KD 671. Translation of the whole report is too much work as it rather long and as it contains many tables, pictures and figures.

The report starts with a Dutch and an English Summary. The English summary is copied completely.

English summary of report R-668-A

For a windmill project on the Cape Verdean Islands, electricity generating windmills (Lagerwey van de Loenhorst) will be installed. The requirements are that a windmill can be yawed in the wind independent of the grid. To this purpose, servo-rotors are applied; turning a vertical plane perpendicular to the (main) rotor and yawing the head into the wind when the (main) rotor is in yaw. The aim of this research is to make a design of a servo-rotor, which has been accomplished in the following way:

- For the present servo-rotor, the starting torque has been calculated as a function of the wind speed and an estimation of the yawing speed has been made.
- Within the constraints, arising from the requirement that the servo-rotor must be mounted on the existing windmill, a servo-rotor has been designed and an estimation of the starting torque of this rotor has been made.
- Of this design for a servo-rotor, an adjustable scale model (scale 1 : 4) has been designed and made.
- Of this scale model, torque-rpm curves have been measured in the wind tunnel for various blade setting angles and yawing angles.
- From these measurements, dimensionless rotor characteristics have been determined, on the basis of which the optimum blade angle has been selected.
- The optimum rotor geometry has been determined as listed hereunder.

Diameter:	D = 0.8 m
Number of blades:	B = 8
Blades:	Flat plates 0.25 * 0.25 m (1 mm stainless steel sheet)
Blade setting angle:	β = 30° (end summary)

So a wind servo is used to turn the head of the main rotor in the wind. This is done by a reducing worm wheel gearing with a very big total gear ratio in between the wind servo and the head frame. The rotor axis of the wind servo makes an angle of 90° with the axis of the main rotor. This means that a small angle in between the wind direction and the axis of the main rotor results in a big angle in between the axis of the wind servo and the wind direction. So a wind servo has to be chosen which has an acceptable torque level at large yaw angles. Wind servos were used in some of the older Danish electricity generating windmills.

The scale model had scale 1 : 4, so the diameter of the scale model was 0.2 m and the blades had size 62.5 * 62.5 mm. The blades of the original rotor are bolted to spokes which are made of strip size 25 * 8 mm. To make the rotor symmetrical from both sides, four strips are connected to the front side of the blades and four strips are connected to the back side.

For the scale model, a spoke is made of bar round ϕ 4 mm which is soldered to a blade. Four bars are soldered to the front side of a blade and four bars are soldered to the back side.

The spokes of the scale model were clamped in the hub and could be adjusted to any blade angle. The correct blade angle for a certain range of measurements was measured by a protractor. Measurements were executed for blade angles $\beta = 30°$, $\beta = 40°$, $\beta = 50°$ and $\beta = 60°$. Only the measurements for $\beta = 30°$ will be given in this report KD 671. A technical drawing of the wind servo is given in appendix XIX at page 96 of R-668A. This drawing is scanned and is given as appendix 1.

2 Description of the wind tunnel and the test rig

The wind tunnel was originally a closed wind tunnel with a square measuring section with size 0.5 * 0.5 m. To prevent problems with tunnel blockage, the measured object should have dimensions not larger than about 0.1 m. However, the measured rotor had a diameter of 0.2 m. It was thought that tunnel blockage could be prevented by removing the tunnel walls at the measuring section. But the measured maximum C_p for a blade angle $\beta = 30°$ appeared to be unrealistic high ($C_{pmax} = 0.48$) and this proves that removing the tunnel walls is not enough to prevent tunnel blockage completely. This problem is discussed in chapter 4. The C_p-λ and C_q-λ curves as given in chapter 3, are the measured curves without correction for tunnel blockage! The definition of the power coefficient C_p, the torque coefficient C_q and the tip speed ratio λ is given in chapter 4 of my public report KD 35 (ref. 2).

The wind speed was measured by a Betz manometer which measures the pressure difference in between the resting chamber of the wind tunnel and the tunnel opening. The wind speed is calculated from this pressure difference using the correct air density ρ which depends on the temperature and the atmospheric pressure. The wind speed has also been measured by a Pitot tube in the free air flow but there was no difference.

The test rig contains a column on which top the rotor of the scale model is mounted. The column can rotate 90° to vary the yaw angle δ. The position of the yaw axis was chosen such that the heart of the rotor stays at the centre of the wind tunnel for every yaw angle. Seven different yaw angles were measured being $\delta = 0°$, $\delta = 30°$, $\delta = 50°$, $\delta = 65°$, $\delta = 75°$,
$\delta = 80°$ and $\delta = 85°$,

The back side of the rotor shaft was provided with a cylinder with 24 sleeves in it. Inside the cylinder was a lamp and outside the cylinder was a photo cell. The rotational speed n of the rotor was measured by a pulls teller which counts the number of fluctuations of the light pulses per minute and divides this number by 24.

The rotor shaft was also provided with a disk in which a V-groove was made. A thin wire was running in the V-groove. A certain weight was connected to both ends of the wire. The heaviest weight was placed on an accurate balance. The pulling force in one side of the wire is known because the weight of the smallest weight is known. The pulling force in the other side of the wire is measured as the difference in between the measured value of the balance and the heaviest weight. The torque Q is the difference in between the forces in between both wire ends multiplied by the radius of the bottom of the V-groove in the disk. So the torque could be measured rather accurately this way. The mechanical power P is given by:

$$P = Q * n * \pi / 30 \qquad (W) \qquad (1)$$

The measured torque Q and rotational speed n were put in one of the first Apple computers and this computer calculated the corresponding values for λ, C_q and C_p using a calculation program. The measuring points for all measurements are given in appendix IX of R-669-A and I have used these measuring points to make the graphs as given in chapter 3. Although a computer was used to make the calculations, all graphs given in R-669-A were hand drawn. I have used the program Excel to make the graphs given in chapter 3.

3 Presentation of the C_p-λ and the C_q-λ curves for $\beta = 30°$

Graph 12 in appendix X of R-669-A gives the starting toque coefficient C_{qstart} for all measurements, so for four different blade angles β and for seven different yaw angles δ. In this graph it can be seen that the starting torque coefficient for large yaw angles δ is highest for a blade angle $\beta = 30°$. For a blade angle $\beta = 60°$, the starting torque coefficient becomes even negative for large yaw angles which means that the direction of rotation reverses. A low starting torque coefficient for large yaw angles is very unfavourable for a wind servo. This is the main reason why a blade angel $\beta = 30°$ is preferred if the rotor is used as a wind servo.

The rotor with $\beta = 30°$ also had the highest maximum C_p for $\delta = 0°$ of all four blade angles. So if the rotor is used as a normal windmill rotor to drive a certain load with the rotor perpendicular to the wind, a blade angle $\beta = 30°$ is also the optimum for the given solidity. This is another reason why I have presented only the measurements for $\beta = 30°$.

All curves have been measured for a tunnel wind speed of 8 m/s. Some measurements have been repeated for a tunnel wind speed of 6 m/s to see if there is any difference because of a lower Reynolds value but no substantial difference was found. This was expected because the aerodynamic characteristics of square plates are also not sensible for the Reynolds value.

In figure 2 it can be seen that the C_q-λ curves are almost straight lines. This means that the C_p-λ curves are almost parabolas. In figure 2 it can also be seen that all the C_q-λ curves are about in parallel to each other. This means that C_q is reduced by about the same factor as λ if the yaw angle is increased. Not all measured points are lying on fluent curves which means that probably the torque hasn't been measured really accurately.

Chapter 7 of report KD 35 (ref. 2) gives the formulas for n_δ, $F_{t\delta}$, Q_δ and P_d for a yawing rotor with a yaw angle δ. It is assumed that only the component of the wind speed perpendicular to the rotor plane, V cosδ, is effective for the determination of these four quantities. This means that the rotational speed n_d and λ_δ are reduced by cosδ, that the torque Q_δ and the torque coefficient $C_{q\delta}$ are reduced by $\cos^2\delta$ and that the power P_δ and the power coefficient $C_{p\delta}$ are reduced by $\cos^3\delta$. The measured C_q-λ curves are not really in accordance to these formulas because the torque is reduced by about the same factor as the rotational speed. I think that this is because the rotor isn't designed according to the rotor theory and because square plates are used as blades. Wind tunnel measurements executed for the CWD 2740 rotor in the open wind tunnel of the University of Delft for different yaw angles are much better in accordance to the formulas given in chapter 7 of KD 35 (see report R 408 S ref. 3).

The maximum C_p which has been measured for $\delta = 0°$ is about 0.48 for $\lambda = 2.16$. However, there is just a bulge in the curve for this tip speed ratio and a maximum C_p of about 0.47 for $\lambda = 2.2$ seems more realistic. This results in an optimum torque coefficient $C_{qopt} = 0.47 / 2.2 = 0.2136$. In figure 4.10 (for B = 8) of report KD 35 (ref. 2) it can be seen that a maximum theoretical C_p of 0.47 requires a C_d/C_l ratio of about 0.02 for a tip speed ratio of 2.16. This is extremely low and it can never be realised for a square flat plate.

Aerodynamic characteristics of a square flat plate are given in chapter 2 of report KD 551 (ref. 4). For the determination of the minimum C_d/C_l ratio one needs a C_l-C_d curve which isn't given in KD 551. However, the measured values of C_l and C_d are given in table 1 of KD 551. It can be calculated that the lowest C_d/C_l ratio is 0.225 for $\alpha = 5°$. It might be that a somewhat lower value would be found for a smaller angle α. It might also be that the fact that the blades have a certain overlap, results in a lower C_d/C_l ratio. Assume that a C_d/C_l ratio of 0.1 is realised. Using figure 4.10 of KD 35 we now find a maximum theoretical C_p of about 0.37 for $\lambda = 2.18$. So the measurements have to be corrected for tunnel blockage.

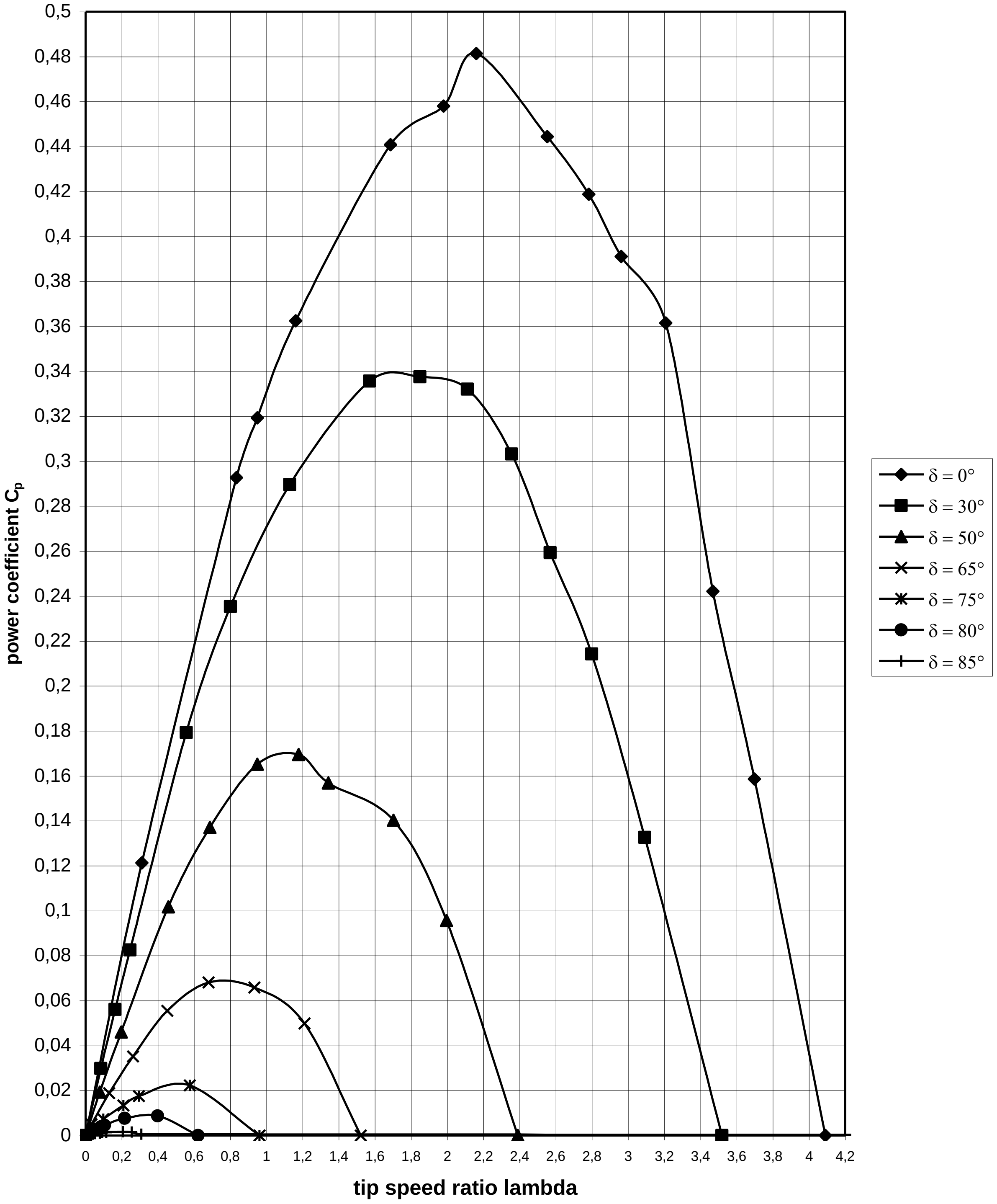

fig. 1 Measured C_p-λ curves for the scale model of the servo rotor with $\beta = 30°$ depending on the yaw angle δ. Tunnel wind speed V = 8 m/s.

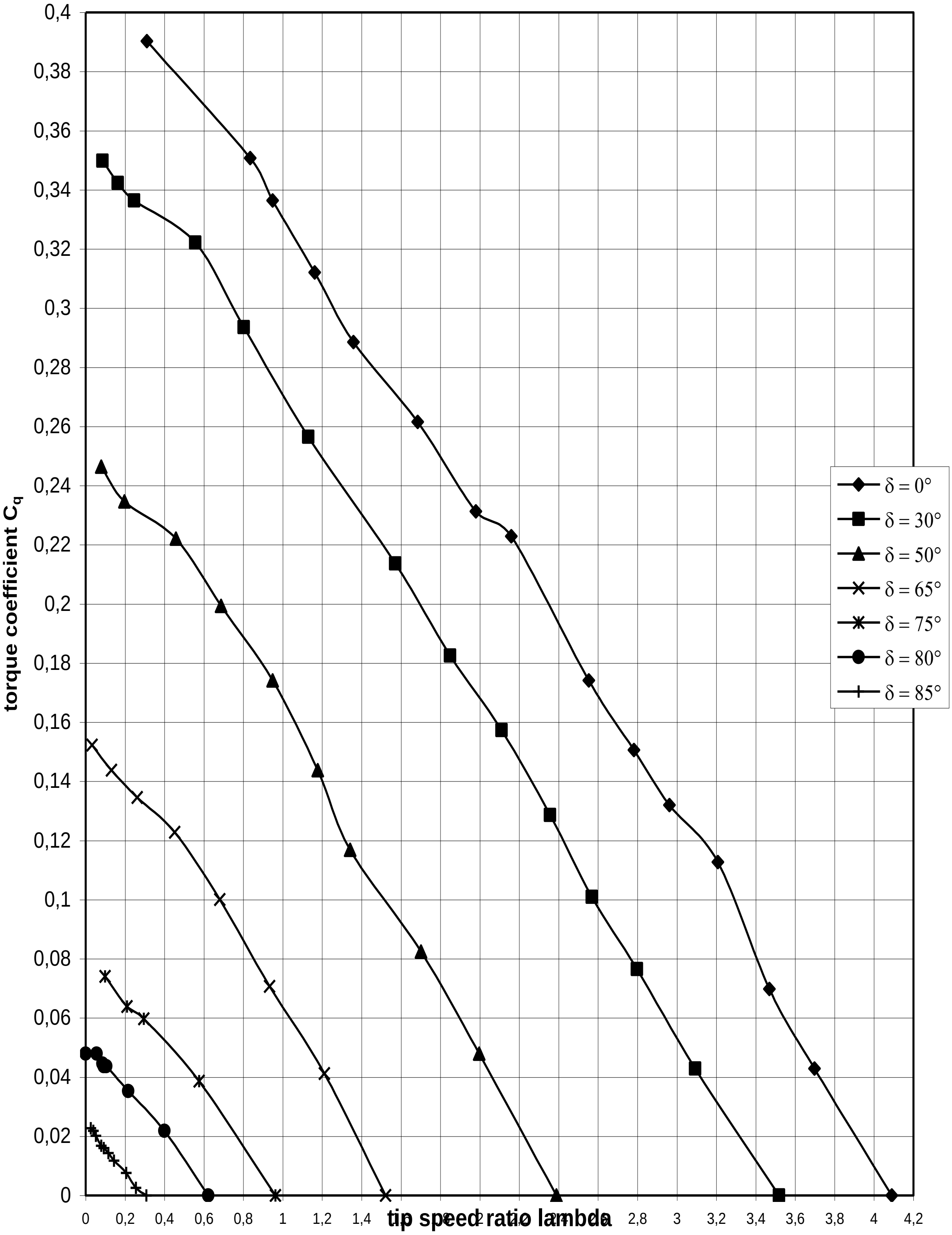

fig. 2 Measured C_q-λ curves for the scale model of the servo rotor with β = 30° depending on the yaw angle δ. Tunnel wind speed V = 8 m/s.

4 Correction of the curves for $\beta = 30°$ and $\delta = 0°$ for tunnel blockage

Assume that the measured wind speed is a factor 1.09 too high. This means that the rotational speed n and the tip speed ratio λ have to be corrected by a factor 1 / 1.09 = 0.9174. The torque Q and the torque coefficient C_q have to be corrected by a factor $(1 / 1.09)^2 = 0.8417$. The power P and the power coefficient C_p have to be corrected by a factor $(1 / 1.09)^3 = 0.7722$. So now the maximum C_p becomes about 0.7722 * 0.47 = 0.36 for an optimum tip speed ratio of 0.9174 * 2.2 = 2. If the maximum C_p is 0.36 for $\lambda = 2$, it means that the optimum torque coefficient $C_{qopt} = 0.36 / 2 = 0.18$ (see KD 35 formula 4.5). These seem to be much more realistic values.

In figure 2 it can be seen that the unloaded tip speed ratio λ_{unl} is about 4.08 for $\delta = 0°$. This means that the ratio $\lambda_{unl} / \lambda_{opt} = 4.08 / 2.2 = 1.85$. This is much higher than for a windmill which is designed according to the aerodynamic theory and for which this ratio is about 8/5 = 1.6 (see KD 35 formula 6.4).

If the C_q-λ curve is exactly a straight line, the C_p-λ curve will be exactly a parabola and λ_{unl} will be exactly twice λ_{opt}. The fact that the real ratio is 1.85 indicates that the C_q-λ curve isn't exactly a straight line. If the measured C_q-λ curve in figure 2 for $\delta = 0°$ is observed accurately, it can be seen that indeed there is some slight curving for tip speed ratios in between C_{qstart} and C_{qopt}. This effect has been taken into account by making the new C_q-λ curve which is corrected for wind tunnel blockage.

Next it is assumed that the unloaded tip speed ratio λ_{unl} is a factor 1.85 * λ_{opt}, so $\lambda_{unl} = 1.85 * 2 = 3.7$. Next it is assumed that the C_q-λ curve is a straight line in between the points $C_q = 0.18$, $\lambda = 2$ and $C_q = 0$, $\lambda = 3.7$. It is assumed that the C_q-λ curve is a line which is slightly curved in between $\lambda = 0$ and λ_{opt}.

In figure 2 it can be seen that the starting torque hasn't been measured for $\lambda = 0$ but by interpolation it is about found that $C_{qstart} = 0.42$ for $\delta = 0°$. Next it is assumed that the starting torque coefficient is reduced by the same factor as the optimum torque coefficient. The reduction factor for the optimum torque coefficient is 0.18 / 0.2136 = 0.84. So the new starting torque coefficient C_{qstart} becomes 0.84 * 0.42 = 0.35. The new C_q-λ curve has been drawn such $C_{qstart} = 0.35$. The C_p-λ curve is found from the C_q-λ curve by multiplying each value of C_q by the corresponding value of λ. The new C_p-λ curve for $\delta = 0°$ is given in figure 3. The new C_q-λ curve for $\delta = 0°$ is given in figure 4.

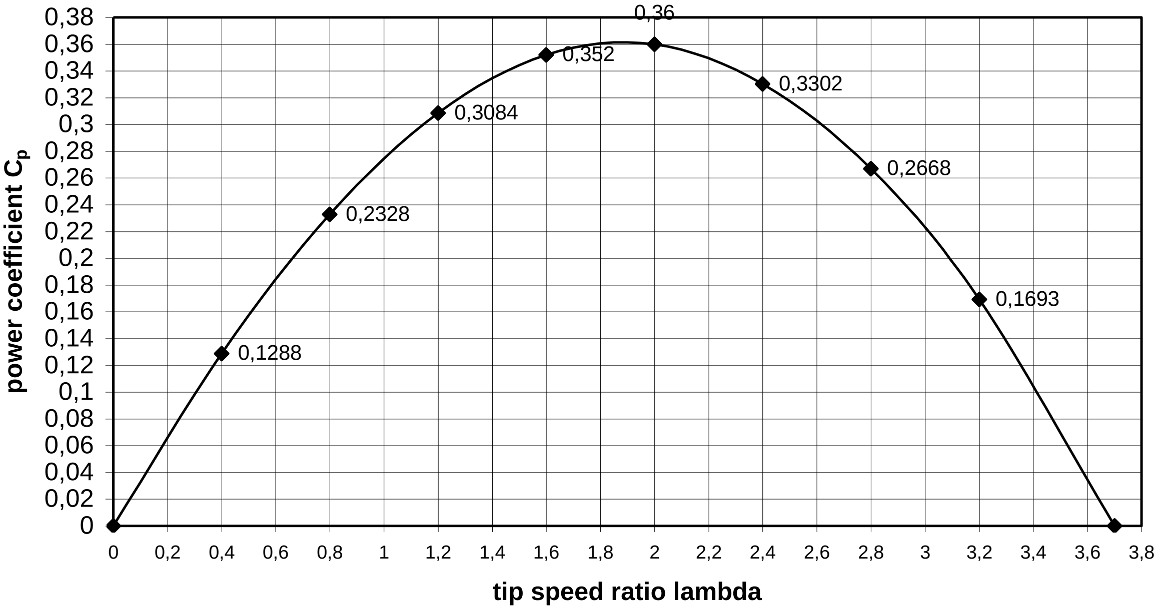

fig. 3 Estimated C_p-λ curve, corrected for tunnel blockage for wind servo (β = 30°, δ = 0°)

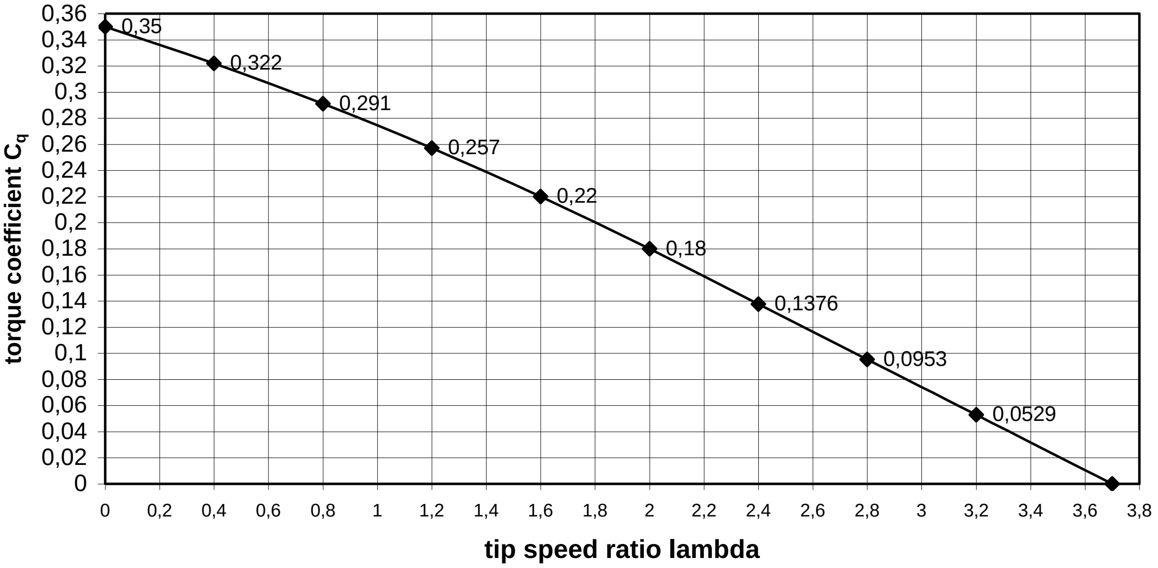

fig. 4 Estimated C_q-λ curve, corrected for tunnel blockage for wind servo (β = 30°, δ = 0°)

5 Ideas about the VIRYA-2B8

The C_q-λ curve of figure 4 has a very favourable shape if the load has a high starting torque. The ratio in between the starting torque and the optimum torque is 0.35 / 0.18 = 1.944 which is even higher than for traditional multi bladed windmill rotors. So it seems possible to use a similar rotor as the wind servo to drive a grinding mill or a positive displacement pump. However, a rotor diameter of only 0.8 m will be much too small to get a substantial output.

An advantage of using flat plates is that now it is possible to make the blades from waterproof plywood (with a good protection against the weather by epoxy and aluminium paint). Assume a standard sheet size 1.22 m * 2.44 m with a thickness of 6 mm is sawn into eight pieces of 0.61 * 0.61 m. This means that the scale factor with respect to the wind servo is 0.61 / 0.25 = 2.44 resulting in a rotor diameter of 2.44 * 0.8 = 1.952 m. Assume a rotor diameter of 2 m is chosen and the windmill with this rotor is called the VIRYA-2B8 (B8 because it has eight blades).

Assume that the spokes are made of a 6 m long steel strip size 60 * 10 mm sawn into eight 0.75 m long spokes. Assume the rotor is turning right hand and so a spoke is twisted 60° left hand and welded to a 60 mm hub with the welds in parallel to the axis of the hub. So the free blade length is 1000 - (750 + 30) = 220 mm. The overlap in between a blade and a spoke is 610 - 220 = 390 mm. A blade can be connected to a spoke by three bolts M8, six nuts M8 and three big washers to protect the wood. All eight blades are mounted at the front side of the spokes to prevent a strong point load on the wood at the outer bolt.

Assume that the windmill is coupled to a standard hose pump. A hose pump has as advantage above a rope pump that it can have a positive pressure height and so the water can be pumped above the level of the pump. A hose pump has a high starting torque but this is no problem as the windmill rotor has a high starting torque coefficient. Assume that the windmill is provided with a vertical shaft which is running in the centre of the tower and that the hose pump is directly coupled to the vertical shaft. So a transmission is needed from the horizontal rotor shaft to the vertical pump shaft.

The windmill must be provided with a safety system which limits the maximum rotational speed and thrust. I prefere the hinged side vane safety system which is used in all my VIRYA windmills. As the rotor is mounted eccentrically from the tower axis, a transmission is needed which bridges the eccentricity e in between the rotor shaft and the vertical shaft. Such a transmission, using a round string, is described in report KD 320 (ref. 5) for the VIRYA-2.8B4 rotor driving a rope pump. It has a 12 mm Polycord string, an accelerating gear ratio i = 2.5 and an eccentricity e = 0.295 m. It is assumed that a 10 mm string is strong enough for the VIRYA-2B8 and if all dimensions of the transmission would be reduced by a factor 10/12 = 0.8333, the eccentricity would become about 0.246 m. This is large enough to make that the influence of the reaction torque of the vertical shaft is small enough with respect to the moment which turns the head out of the wind.

The Q-n curves of the rotor for different wind speeds can be derived from the C_q-λ curve as given in figure 4 and the δ-V curve of the safety system using the formulas for n_δ and Q_δ as given in chapter 7 of KD 35 (ref. 2). If the gear ratio i and the transmission efficiency η_{tr} are taken into account, it is also possible to derive the Q_v-n_v curves as seen on the vertical shaft. Further development of the VIRYA-2B8 is out of the scope of this report.

6 References

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4 Kragten A. Aerodynamic characteristics of rectangular flat plates with aspect ratios 5 : 1, 2 : 1, 1 : 1, 1 : 2 and 1 : 5 for use as windmill vane blades, March 2014, reviewed April 2016, free public report KD 551, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Development of the VIRYA-2.8B4, a windmill with a Polycord transmission in between the rotor shaft and the vertical shaft to drive a rope pump or an Archimedian screw pump, February 2007, free public report KD 320, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

7 Appendix 1 Technical drawing of the wind servo
(be alert, this rotor is turning left hand)