Development of an ecliptic safety system with a torsion spring

ing. A. Kragten

February 2009
reviewed May 2016

KD 409

engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

Contains page

1 Introduction

Windmills with fixed rotors can be protected against too high forces and too high rotational speeds by turning the rotor out of the wind. This can be done around a vertical and around an horizontal axis. All present VIRYA windmills developed by Kragten Design turn out of the wind around a vertical axis and make use of the so called hinged side vane safety system.

Safety systems for water pumping windmills are described in report R 999 D (ref. 1). Water pumping windmills normally have fixed rotors and all safety systems are working by turning the rotor out of the wind. However, electricity generating windmills can also be protected by turning the rotor out of the wind. In chapter 2 of R 999 D, the reasons are given why a safety system is necessary. These reasons are:

1 Limitation of the axial force or thrust on the rotor to limit the load on the rotor blades, the tower and the foundation.

2 Limitation of the rotational speed of the rotor to limit the centrifugal force in the blades, imbalance forces, high gyroscopic moments in the blades and the rotor shaft, to prevent flutter for blades with low torsion stiffness and to prevent too high rotational speeds of the load which is relevant for limitation of heat dissipation in a generator or for limitation of shock forces in the transmission to a piston pump.

3 Limitation of the yawing speed to limit high gyroscopic moments in the blades and the rotor shaft.

Almost all known systems are described shortly in chapters 3 and 4 of R 999 D. The three most generally used systems, the ecliptic system, the inclined hinge main vane system and the hinged side vane system are described in detail in chapter 7 of report R 999 D. Because report R 999 D is no longer available, the hinged side vane system is also described in several KD-reports. This system is described for the VIRYA-4.2 windmill in report KD 213 (ref. 2).

Every safety system has certain advantages and disadvantages. The main advantages of the hinged side vane safety system are:

1) It is simple and cheap.
2) It has a δ-V curve which is lying close to the ideal δ-V curve (see chapter 2).
3) The hinge axis is loaded only lightly and therefore simple door hinges can be used.
4) The vane blade is situated in the undisturbed wind and therefore a relatively small vane blade area is required to generate a certain aerodynamic force.
5) The moment of inertia of the head is large resulting in low yawing speeds and so large gyroscopic moments at high wind speeds are prevented.

The main disadvantages of the hinged side vane system are:

1) There must be a certain ratio in between the vane area and the vane weight if a certain rated wind speed is wanted. Therefore it appears to be difficult to make a large vane blade stiff enough. The hinged safety system is therefore limited to windmills with a maximum rotor diameter of about 5 m.
2) The system is sensible to flutter of the vane blade, if the vane blade and the vane arm is not made stiff enough. Flutter is suppressed effectively using a vane blade stop at the almost horizontal position of the vane blade
3) It is difficult to turn the head out of the wind permanently by placing the vane blade in the horizontal position because this vane blade is positioned far form the tower and far from the ground.

In report KD 377 (ref. 3) a safety system is described with which the rotor is turned out of the wind around an horizontal axis. This system has rather good characteristics which can easily be determined. However, this system needs an extra horizontal axis and it requires rather heavy balancing weights. It will be investigated if it is possible to realise acceptable characteristics for an ecliptic system equipped with a torsion spring. In report KD 408 (ref. 4) an ecliptic safety system is described for which the eccentricity is chosen so large that the contribution of M_{so} and $F_{s\delta}$ to M_{rotor} can be neglected. This results in a simple equation for M_{rotor}. However, a large eccentricity results in a very large vane blade which is impractical.

2 The ideal δ-V curve

Generally it is wanted that the windmill rotor is perpendicular to the wind up to the rated wind speed V_{rated}, and that the rotor turns out of the wind such that the rotational speed, the rotor thrust, the torque and the power stay constant above V_{rated}. It appears to be that the component of the wind speed perpendicular to the rotor plane determines these four quantities. The yaw angle δ is the angle in between the wind direction and the rotor axis. The component of the wind speed perpendicular to the rotor plane is therefore V cosδ. The formulas for a yawing rotor for the rotational speed n_δ, the rotor thrust $F_{t\delta}$, the torque Q_δ and the power P_δ are given in chapter 7 of report KD 35 (ref. 5). These formulas are copied as formula 1, 2, 3 and 4.

$$n_\delta = 30 * \lambda * \cos\delta * V / \pi R \qquad \text{(rpm)} \qquad (1)$$

$$F_{t\delta} = C_t * \cos^2\delta * ½\rho V^2 * \pi R^2 \qquad \text{(N)} \qquad (2)$$

$$Q_\delta = C_q * \cos^2\delta * ½\rho V^2 * \pi R^3 \qquad \text{(Nm)} \qquad (3)$$

$$P_\delta = C_p * \cos^3\delta * ½\rho V^3 * \pi R^2 \qquad \text{(W)} \qquad (4)$$

These four quantities stay constant above V_{rated} if the component of the wind speed perpendicular to the rotor plane is kept constant above V_{rated}. So in formula:

$$V \cos\delta = V_{rated} \qquad \text{(for } V > V_{rated}\text{)} \qquad (5)$$

It is assumed that the rotor is loaded such that it runs at the design tip speed ratio λ_d. If the wind speed is in between 0 m/s and V_{rated}, the n-V curve is a straight line through the origin. The F_t-V and the Q-V curves are then parabolic lines and the P-n curve is a cubic line.

Formula 5 can be written as:

$$\delta = \arccos (V_{rated} / V) \qquad (°) \qquad (6)$$

This formula is given as a graph in figure 1 for different value of V / V_{rated}. The value of δ has been calculated for V / V_{rated} is respectively 1, 1.01, 1.05, 1.1, 1.25, 1.5, 2, 2.5, 3, 4, 5 and 6.

The rated wind speed V_{rated} is chosen on the basis of the maximum thrust and the maximum rotational speed which is allowed for a certain rotor and a certain generator. Mostly V_{rated} is chosen about 10 m/s. For the chosen value of V_{rated}, figure 1 can be transformed into the δ-V curve for which V (in m/s) is given on the x-axis. If it is chosen that V_{rated} = 10 m/s, figure 1 becomes the δ-V curve if all values on the x-axis are multiplied by a factor 10.

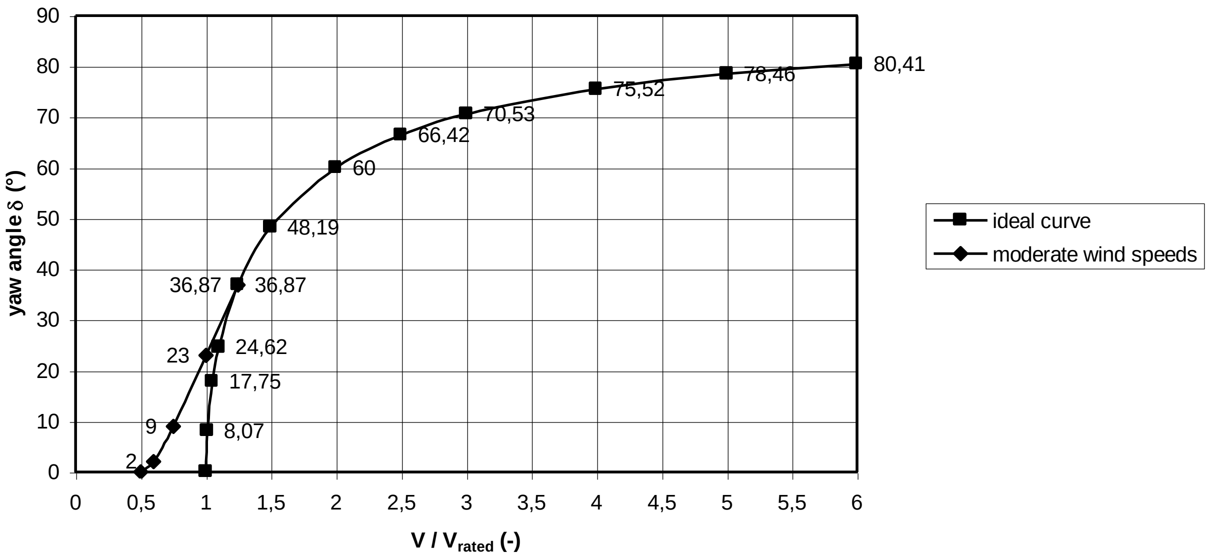

fig. 1 the δ-V/V_{rated} curve for the ideal safety system

In figure 1 it can be seen that the rotor is perpendicular to the wind for (V / V_{rated}) < 1 but that the required change in δ is very sudden if V / V_{rated} is a very little higher than 1. So even if one would have a safety system which theoretically has the ideal δ-V curve, in practice this curve will not be followed because the inertia of the system prevents sudden changes of δ around V / V_{rated} = 1. So the system will turn out of the wind less than according to the ideal δ-V curve. This will result in a certain overshoot of the rotational speed and the thrust.

For high values of V / V_{rated}, a certain increase of V, and therefore a certain increase of V / V_{rated}, requires only a relatively small increase of δ. It is therefore much easier to follow the theoretical δ-V curve at high wind speeds.

Because of this effect, it is practically impossible to follow the ideal δ-V curve for wind speeds lower than about 1.25 * V_{rated} and the practical δ-V curve must therefore start increasing already at a much lower wind speed than the theoretical rated wind speed. An example of a practical δ-V curve for moderate wind speeds is also given in figure 1. Even for this practical curve for moderate wind speeds and for the ideal curve for values of V / V_{rated} > 1.25, there will be a certain overshoot of n and F_t because of inertia effects.

3 Description of the normal ecliptic safety system

The ecliptic safety system is widely used in old fashioned water pumping windmills. The name of the system probably comes from the windmill of manufacture Eclipse which is equipped with this system. The ecliptic system is described in general in chapter 4.4 and in detail in chapter 7.4 of report R999D (ref. 1). The ecliptic system can be used in combination with an eccentrically placed rotor or with a centrally placed rotor and an auxiliary vane. Only the use in combination with an eccentrically placed rotor will be taken into account.

The main feature of a normal ecliptic safety system is that the main vane is turning around a vertical axis and that the vane arm it is pulled against a stop by a tension spring. The geometry of the rotor, the head and the vane are chosen such that the rotor is perpendicular to the wind direction as long as the vane arm makes contact with the stop. The pulling force in the spring exerts a certain moment M_{spring} around the vane axis. M_{spring} depends on the distance in between the hart of the spring and the vane axis and so on the position of the vane arm. The pulling force in the spring depends on the spring characteristics.

The vane arm is touching the stop as long as M_{spring} is larger than the moment M_{vane} exerted by the aerodynamic force on the vane blade around the vane axis. At a certain critical wind speed called V_{crit}, M_{vane} becomes larger than M_{spring} and the vane turns away.

The rotor exerts a certain rotor moment M_{rotor} around the tower axis. This rotor moment is mainly determined by the rotor thrust $F_{t\delta}$ and the eccentricity e but the side force on the rotor $F_{s\delta}$ in combination with the distance f in between the rotor plane and the tower axis and the so called self orientating moment M_{so} also have a certain influence. If M_{rotor} becomes larger than the moment of the vane around the tower axis, the rotor starts turning out of the wind. This is the case for wind speeds higher than V_{crit} when the vane arm is no longer in contact with the stop.

How the rotor turns out of the wind as a function of the wind speed is difficult to determine, especially if the vane blade is in the rotor shadow where the wind speed is not well known. Another disadvantage of the ecliptic system is that, if the rotor is turned out of the wind a lot and if the wind speed suddenly decreases, the vane arm will move back to its zero position. It will hit the stop with a large force if the stop is not elastic. To prevent that the vane arm can touch the rotor at high wind speeds, another stop is needed at a position where the vane arm is about parallel to the rotor plane.

4 Description of the ecliptic system with torsion spring

The new ecliptic system will have some special differences if compared to the normal system. The differences are:

a) A torsion spring will be used. The spring moment M_{spring} will therefore increase linear to the angle γ over which the vane arm turns.

b) The vane arm will point upwards with an angle of 45° and will be so long that the vane blade is in the undisturbed wind speed V. The vane blade will be square and will be positioned such that two sides are horizontal. The angle in between the vane blade and the wind direction is called α.

c) There will be an elastic stop at the zero position of the vane arm for $\gamma = 0°$ and a second elastic stop at a position for $\gamma = 100°$. So the shock forces are limited if the vane arm hits one of these stops and the vane arm can never touch the rotor. However, the elasticity of the stop at zero position is neglected for the determination of γ, so it is assumed that $\gamma = 0°$ as long as the vane arm touches this stop.

d) The position of the zero line of the vane arm is chosen such that there is an angle $\varepsilon = 20°$ in between this zero line and the rotor axis.

e) The geometry of rotor, head and vane are chosen such that the rotor axis for a rotating rotor is perpendicular to the wind for $\gamma = 0°$. The left hand angle in between the rotor axis and the wind direction is called δ. So $\delta = 0°$ and $\alpha = \varepsilon = 20°$ for this condition.

f) The torsion moment at $\gamma = 0°$ is called $M_{spring0}$. The spring constant of the torsion spring is chosen such that the torsion moment for $\gamma = 100°$, $M_{spring100}$, is a factor 1.5 higher than $M_{spring0}$. This results in a total twist of the spring of 300° from the unstressed position.

g) The eccentricity e in between the rotor axis and the tower axis will be taken rather large with respect to the rotor radius R (e = 0.2 R). The contribution of the side force $F_{s\delta}$ and the self orientating moment M_{so} to the rotor moment M_{rotor} will therefore be rather small. However, they can't be neglected for this ratio in between e and R.

h) The position of the vane axis is chosen such that it coincides with the tower axis. This has as advantage that the vane moment around the vane axis is the same as around the tower axis and this simplifies the moment equations.

In point e it is said that the rotor axis is perpendicular to the wind for $\gamma = 0°$. However, this is only true for a rotating rotor which turns about with the design tip speed ratio. The thrust coefficient for a non rotating rotor is much lower than for a rotating rotor which means that the thrust force and so also M_{rotor}, will be much lower too. This means that the rotor axis will have a negative yaw angle δ when the rotor is not rotating at low wind speeds.

The wind speed for which M_{rotor} is the same as M_{spring} for $\gamma = 0°$, is called the design wind speed V_d. It is chosen that $V_d = 8$ m/s. The rotor will be perpendicular to the wind for wind speeds lower than V_d (as long as the rotor is rotating at a about the design tip speed ratio). This situation for $V = V_d = 8$ m/s is given in figure 2 for a top view of the head.

The wind speed for which the rotational speed, the thrust and the power have a maximum, is called the rated wind speed V_{rated}. V_{rated} is determined in chapter 6 and it appears that V_{rated} is rather high for the chosen characteristics of the torsion spring. For very high wind speeds, the angle α in between the wind direction and the vane blade will be very small and the yaw angle δ will therefore be almost 80° for $\gamma = 100°$.

The rotor will turn out of the wind for wind speeds higher than V_d. The yaw angle δ depends on the undisturbed wind speed V. The situation for a wind speed V = 11.339 m/s (see table 3) is given in figure 3 for a top view of the head. In table 3 it can be seen that $\delta = 30°$, $\alpha = 9.96°$ and $\gamma = 40.04°$ for V = 11.339 m/s.

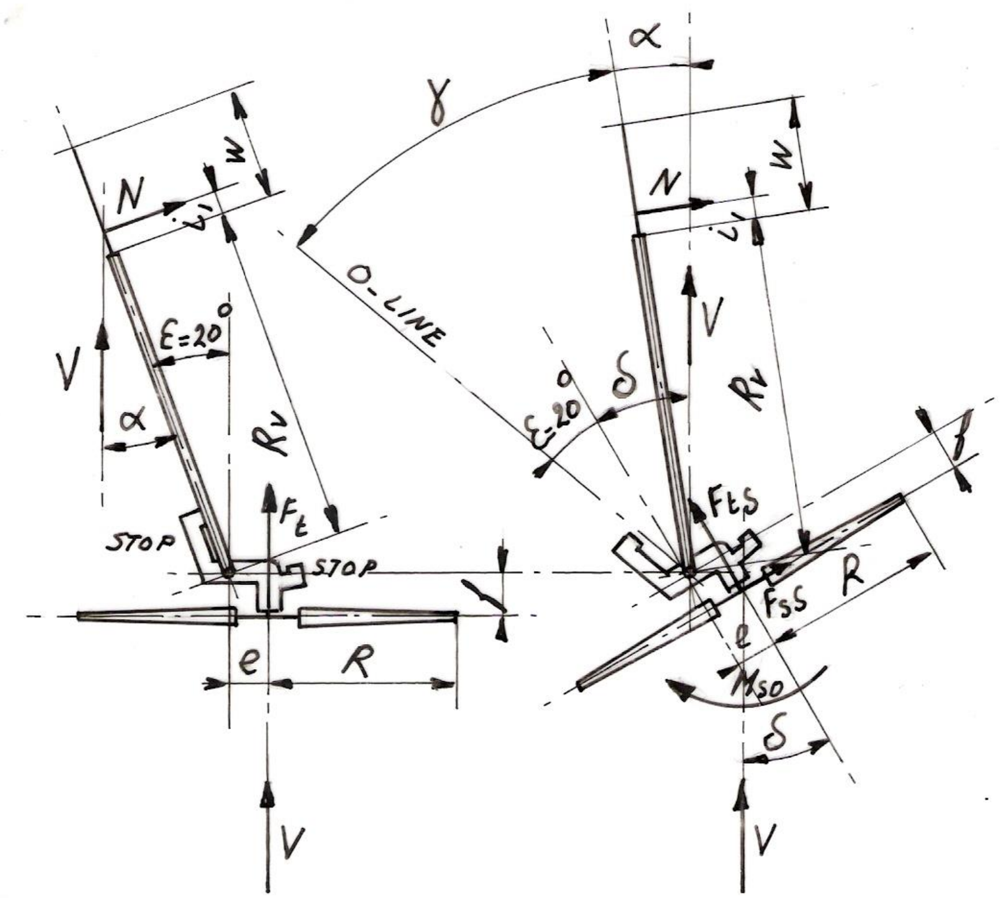

fig. 2 Situation for $V = V_d = 8$ m/s

fig. 3 Situation for V = 11.339 m/s

In figure 3 it can be seen that:

$$\delta = \gamma + \alpha - \varepsilon \quad (°) \tag{7}$$

5 The moment equations

The moment produced by the aerodynamic normal force N which is working on the vane blade is called M_{vane}. Now it is assumed that the system is functioning quasi-stationary. So no moments are needed for acceleration of the system from one position into the other. This means that:

$$M_{rotor} = M_{vane} \quad (\text{for } V \leq V_d) \tag{8}$$

For $V > V_d$, the vane arm is no longer touching the stop at zero position. The force at the stop is also zero for $V = V_d$. So in both cases it is valid that:

$$M_{rotor} = M_{spring} \quad (\text{for } V \geq V_d) \tag{9}$$

For $V < V_d$, a part of M_{spring} is taken by the stop and another part is taken by the vane. Which part depends on the elasticity of the stop and this results in a small variation of γ, but this aspect is not taken into account.

For the determination of the δ-V curve, it is necessary to determine the formulas for M_{rotor}, M_{spring} and M_{vane}.

5.1 Determination of M_{rotor}

M_{rotor} is caused by the influence of the thrust force $F_{t\delta}$, the side force $F_{s\delta}$ and the so called self orientating moment M_{so}. $F_{t\delta}$ results in a moment $M_{Ft\delta}$. $F_{s\delta}$ results in a moment $M_{Fs\delta}$. Both $M_{Ft\delta}$ and $M_{Fs\delta}$ have a left hand direction which tends to increase δ. However, M_{so} has a right hand direction such that δ is decreased. M_{rotor} is positive if it is left hand and is therefore given by:

$$M_{rotor} = M_{Ft\delta} + M_{Fs\delta} - M_{so} \quad (\text{Nm}) \tag{10}$$

$$M_{Ft\delta} = F_{t\delta} * e \quad (\text{Nm}) \tag{11}$$

(2) + (11) gives:

$$M_{Ft\delta} = C_t * \cos^2\delta * \tfrac{1}{2}\rho V^2 * \pi R^2 * e \quad (\text{Nm}) \tag{12}$$

$$M_{Fs\delta} = F_{s\delta} * f \quad (\text{Nm}) \tag{13}$$

The distance in between the rotor plane and the tower centre is called f. For the side force on the rotor $F_{s\delta}$, no formula is given in report KD 35 (ref. 5). If one would calculate $F_{s\delta}$ with the component of the wind speed in the rotor plane, V sinδ, the side force would be proportional to $\sin^2\delta$. However, from measurements (see figure 23, report R 999 D) it is found that $F_{s\delta}$ increases much faster than a $\sin^2\delta$ function for small values of δ. A sinδ function gives a better approximation.

For very large angles δ, the tip speed of the rotor is only little with respect to the wind speed. The side area of the rotor A_s, then can be seen as a drag area with a drag coefficient C_d. The ratio i in be between A_s and the swept rotor area $\pi * R^2$ depends on the type of rotor. For fast running rotors as used in the VIRYA windmills, A_s is very small with respect to the swept rotor area because the chord, the airfoil thickness and the blade angles are small. In report KD 213 (ref. 2), the two bladed VIRYA-4.2 rotor is taken which has a design tip speed ratio of 8. For this rotor it is determined that $i = A_s / (\pi * R^2) = 0.01$. The drag coefficient C_d depends on the airfoil and is rather low if an aerodynamic airfoil is used.

The yaw angle δ is large at very high wind speeds and the lower blade sees a much larger relative wind speed than the upper blade. It is assumed that the average C_d value for the whole rotor is 1. The side force $F_{s\delta}$ for a yawing rotor is now given by:

$$F_{s\delta} = C_d * \sin\delta * ½\rho V^2 * i * \pi R^2 \qquad \text{(N)} \qquad (14)$$

(13) + (14) gives:

$$M_{Fs\delta} = C_d * f * i * \sin\delta * ½\rho V^2 * \pi R^2 \qquad \text{(Nm)} \qquad (15)$$

In KD 35 (ref. 5) no formula is given for the self orientating moment M_{so}. M_{so} is created because the exertion point of the thrust doesn't coincide with the hart of the rotor. There is only little known about M_{so} and only some very rough measurements have been performed which are given in report R 344 D (ref. 6, in Dutch). For these measurement an unloaded two bladed rotor was used with a design tip speed ratio of 5 and provided with a curved sheet airfoil. Practical experience with the VIRYA windmills using a Gö 623 airfoil indicate that M_{so} is much lower for this airfoil. Recently I have made a model of a two bladed rotor with a diameter of 0.8 m with a design tip speed ratio of about 6.5 and using a Gö 623 airfoil. The maximum eccentricity which was possible for which the rotor doesn't turn out of the wind completely, was about 0.027 m. From this measurement it is derived that the maximum self orientating moment for a certain wind speed is about half the value as for the same diameter rotor with a curved sheet airfoil.

M_{so} is given by:

$$M_{so} = C_{so} * ½\rho V^2 * \pi R^3 \qquad \text{(Nm)} \qquad (16)$$

C_{so} depends on the yaw angle δ and appears to have a maximum for $\delta = 30°$. The estimated C_{so}-δ curve for a rotor with a Gö 623 or similar airfoil can be approximated by two goniometric functions, one function for $0° \leq \delta \leq 40°$ and one function for $40° \leq \delta \leq 90°$. These functions are:

$$C_{so} = 0.0225 \sin 3\delta \qquad (-) \qquad (\text{for } 0° \leq \delta \leq 40°) \qquad (17)$$

$$C_{so} = 0.0332 \cos^2\delta \qquad (-) \qquad (\text{for } 40° \leq \delta \leq 90°) \qquad (18)$$

If the direction of the moment for a negative value of δ is taken the same as for a positive value of δ, formula 17 can also be used for $-40° \leq \delta \leq 0°$. The path of both curves is given in figure 4.

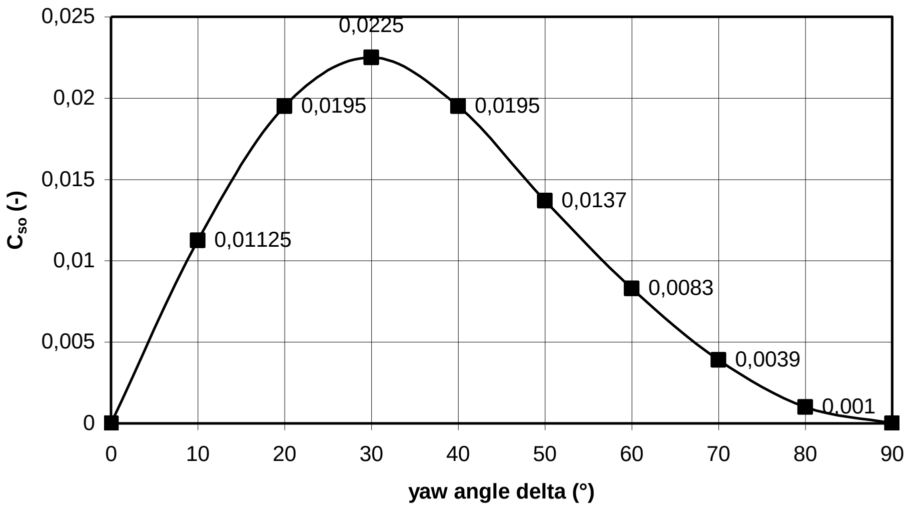

figure 4 Path of C_{so} as a function of the yaw angle δ

(16) + (17) gives:

$M_{so} = 0.0225 \sin 3\delta * ½\rho V^2 * \pi R^3$ (Nm) (for 0° ≤ δ ≤ 40°) (19)

(16) + (18) gives:

$M_{so} = 0.0332 \cos^2\delta * ½\rho V^2 * \pi R^3$ (Nm) (for 40° ≤ δ ≤ 90°) (20)

(10) + (12) + (15) + (19) gives:

$M_{rotor} = C_t * e * \cos^2\delta * ½\rho V^2 * \pi R^2 + C_d * f * i * \sin\delta * ½\rho V^2 * \pi R^2 –$
$0.0225 \sin 3\delta * ½\rho V^2 * \pi R^3$ or

$M_{rotor} = ½\rho V^2 * \pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta – 0.0225 * \sin 3\delta)$
(Nm) (for 0° ≤ δ ≤ 40°) (21)

(10) + (12) + (15) + (20) gives:

$M_{rotor} = C_t * e * \cos^2\delta * ½\rho V^2 * \pi R^2 + C_d * f * i * \sin\delta * ½\rho V^2 * \pi R^2 –$
$0.0332 \cos^2\delta * ½\rho V^2 * \pi R^3$ or

$M_{rotor} = ½\rho V^2 * \pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta – 0.0332 * \cos^2\delta)$
(Nm) (for 40° ≤ δ ≤ 90°) (22)

To get an impression of the contribution of $M_{Ft\delta}$, $M_{Fs\delta}$ and M_{so} to M_{rotor}, the moments are made dimensionless by dividing by $½\rho V^2 * \pi R^3$. The formulas 10, 12, 15, 19 and 20 for M_{rotor}, $M_{Ft\delta}$, $M_{Fs\delta}$ and M_{so} change into 23, 24, 25, 17 and 18 for C_{Mrotor}, $C_{MFt\delta}$, $C_{MFs\delta}$, and C_{so}.

$C_{Mrotor} = C_{MFt\delta} + C_{MFs\delta} – C_{so}$ (-) (23)

$C_{MFt\delta} = C_t * e/R * \cos^2\delta$ (-) (24)

$C_{MFs\delta} = C_d * f/R * i * \sin\delta$ (-) (25)

C_{so} is given by formula 17 and 18.

Now the path of $C_{MFt\delta}$, $C_{MFs\delta}$, C_{so} and C_{Mrotor} is determined as a function of δ for the VIRYA-4.2 rotor and it is assumed that this rotor is now combined with the ecliptic safety system with a torsion spring. For this rotor it is valid that R = 2.1 m. It is assumed that e = 0.42 m and that f = 0.48 m. So e/R = 0.2 and f/R = 0.2286. It was assumed earlier that i = 0.01. The theoretical thrust coefficient 8/9 = 0.89 for $\lambda = \lambda_d$. However in practice it is a lot lower because the inner part of the rotor is not effective and because a part of the thrust is lost by tip and root losses. Assume $C_t = 0.7$. For the drag coefficient it was earlier assumed that $C_d = 1$. Substitution of these values in formula 24 and 25 gives:

$C_{MFt\delta} = 0.14 \cos^2\delta$ (-) (26)

$C_{MFs\delta} = 0.00229 \sin\delta$ (-) (27)

The moment coefficients are calculated for values of δ in between δ = -40° and δ = 90° rising with 10°. The results of the calculations are given in table 1 and figure 5. If the direction of moments for negative values of δ is taken the same as for positive values of δ, formulas 17, 26 and 27 can also be used for negative values of δ.

δ (°)	$C_{MFt\delta}$ (-)	$C_{MFs\delta}$ (-)	C_{so} (-)	C_{Mrotor} (-)
-40	0.08216	-0.00147	-0.01949	0.10018
-30	0.10500	-0.00115	-0.02250	0.12635
-20	0.12362	-0.00078	-0.01949	0.14233
-10	0.13578	-0.00040	-0.01125	0.14663
0	0.14	0	0	0.14
10	0.13578	0.00040	0.01125	0.12493
20	0.12362	0.00078	0.01949	0.10491
30	0.10500	0.00115	0.02250	0.08365
40	0.08216	0.00147	0.01949	0.06414
50	0.05784	0.00175	0.01372	0.04587
60	0.03500	0.00198	0.00830	0.02868
70	0.01638	0.00215	0.00388	0.01465
80	0.00422	0.00226	0.00100	0.00548
90	0	0.00229	0	0.00229

table 1 Calculated values for $C_{MFt\delta}$, $C_{MFs\delta}$, C_{so} and C_{Mrotor} for the VIRYA-4.2 rotor

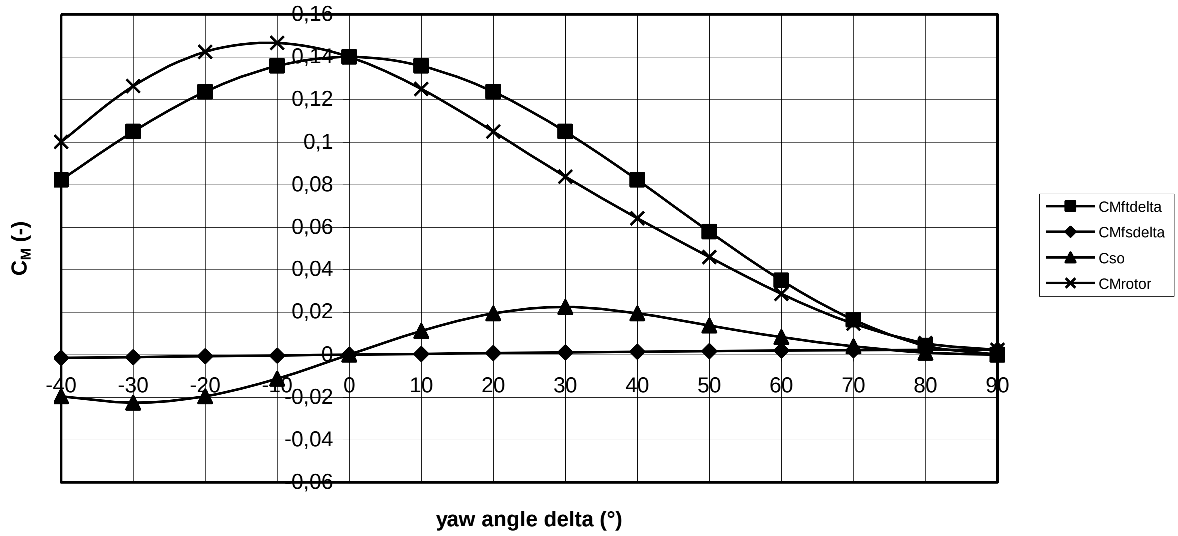

figure 5 Path of $C_{MFt\delta}$, $C_{MFs\delta}$, C_{so} and C_{Mrotor} for the VIRYA-4.2 rotor and head geometry

In figure 5 it can be seen that the contribution of $C_{MFs\delta}$ to C_{Mrotor} can be neglected except for very large angles δ. The contribution of C_{Mso} to C_{Mrotor} can not be neglected and causes that the decrease of the C_{Mrotor}-δ curve at increasing δ is much faster than for the $C_{MFt\delta}$-δ curve. For angles δ in between 25° and 60°, C_{Mrotor} is about a factor 0.8 van $C_{MFt\delta}$. C_{Mrotor} has a maximum at about δ = -13°.

The path found in figure 5 for the dimensionless moment coefficients is also valid for the real moments for a certain wind speed.

5.2 Determination of M_{vane}

$$M_{vane} = N * (R_v + i_1) \quad \text{(Nm)} \qquad (28)$$

N is the aerodynamic normal force on the vane blade. R_v is the length of the vane arm in the horizontal plane. i_1 is the distance in between N and the leading edge of the vane blade. This distance is called i_1 in analogy to the name which is used in report KD 551 (ref. 7). i_1 depends on the vane blade shape, on the vane blade width w and on the angle of attack α. The square plate has originally been measured by Flachsbart and the measuring points of these measurements are used to determine the ratio i_1 / w and the C_n-α curve. The ratio i_1 / w for a square vane blade is given as a function of α in figure 6 of report KD 551 (ref. 7). This figure is copied as figure 6.

For a constant wind direction, α will vary in between 20° for wind speeds below V_d (and a rotating rotor) and almost 0° for very high wind speeds. So the average value will be about 10°. This corresponds to a ratio i_1 / w = 0.27. As i_1 is only small with respect to R_v, it is acceptable to use this constant value i_1 / w = 0.27. As the vane blade is square, the height h will be the same as the width w.

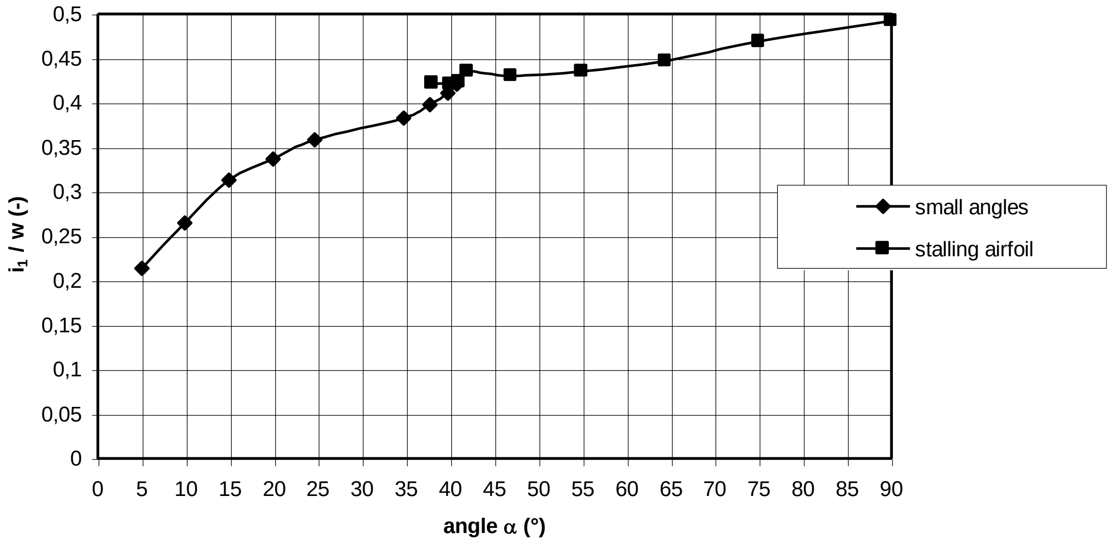

fig. 6 Path of i_1 / w as a function of α using N for a square plate

The angle α will not only vary because of fluctuations in the wind speed but also because of fluctuations in the wind direction. The normal force N is given by:

$N = C_n * ½\rho V^2 * h * w$ (N)   (29)

C_n is the normal force coefficient. The C_n-α curve for a square plate is given in figure 5 of KD 551 (ref. 7). This figure is copied as figure 7.

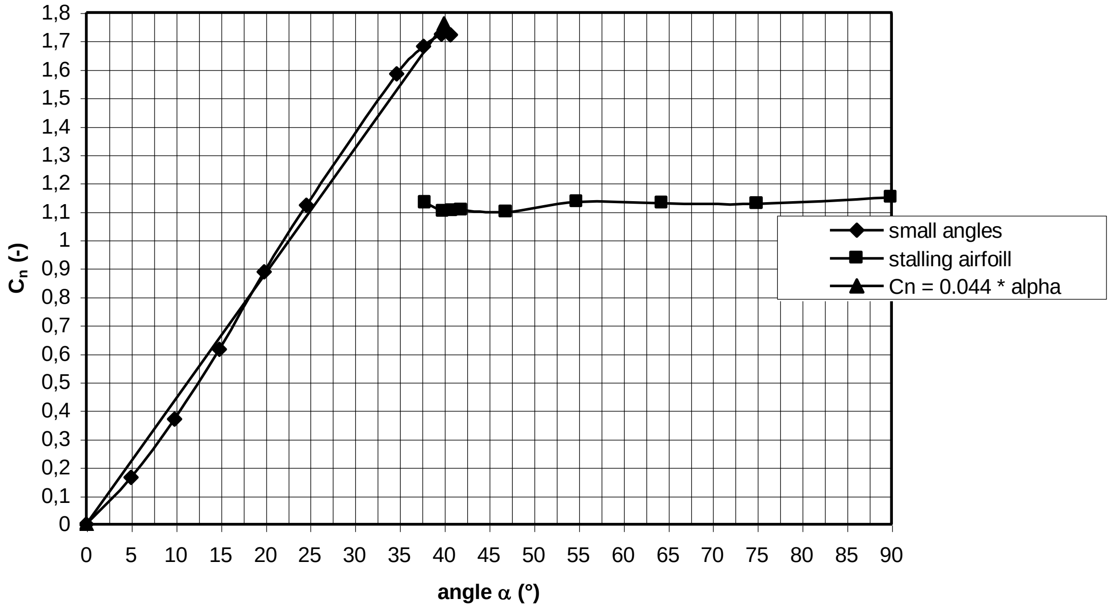

fig. 7 C_n-α curve for a square plate

The C_n-α curve is about a straight line for 0° ≤ α ≤ 40°. The C_n-α curve for 0° ≤ α ≤ 40° can be replaced by the function:

$C_n = 0.044 * \alpha$ (-)   (0° ≤ α ≤ 40°)   (30)

This function is also given in figure 7. The angle α is 20° for V = 8 m/s or smaller. This means that sudden variations of the wind direction with a maximum deviation of 20° in both directions result in variation of α in between 0° and 40° with corresponding values of C_n varying in between 0 and 1.76. So the vane will work properly to keep the rotor perpendicular to the wind.

(29) + (30) gives:

$$N = 0.044 * \alpha * ½\rho V^2 * h * w \quad (N) \qquad (31)$$

(28) + (31) gives:

$$M_{vane} = 0.044 * \alpha * ½\rho V^2 * h * w * (R_v + i_1) \quad (Nm) \qquad (32)$$

5.3 Determination of M_{spring}

In point f of chapter 4 it was decided that $M_{spring100}$ is a factor 1.5 larger than $M_{spring0}$. This means that:

$$M_{spring} = M_{spring0} + 1/200\ \gamma * M_{spring0} \quad \text{or}$$

$$M_{spring} = (1 + 1/200\ \gamma) * M_{spring0} \quad (Nm) \qquad (33)$$

M_{spring} will be zero for γ = -200° but this situation can only occur if the stop at zero position is removed. The geometry of the torsion spring has to be chosen such that $M_{spring} = M_{spring0}$ for γ = 0°. Determination of the required torsion spring geometry for which this is realised, is out of the scope of this report. The ratio $i_s = M_{spring} / M_{spring0}$ as a function of γ is given in figure 8.

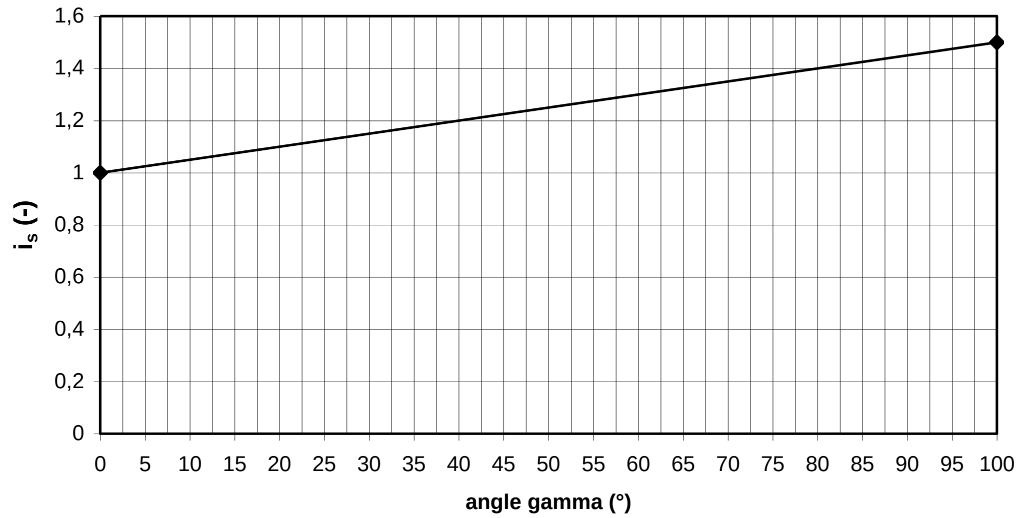

fig. 8 Variation of $i_s = M_{spring} / M_{sprin0}$ as a function of γ

5.4 Determination of the moment equations

(8) + (21) + (32) gives:

$\pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta - 0.0225 * \sin 3\delta) = 0.044 * \alpha * h * w * (R_v + i_1)$
(for $0° \leq \delta \leq 40°$) (34)

(8) + (22) + (32) gives:

$\pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta - 0.0332 * \cos^2\delta) = 0.044 * \alpha * h * w * (R_v + i_1)$
(for $40° \leq \delta \leq 90°$) (35)

Formula 7 can be written as:

$\gamma = \varepsilon + \delta - \alpha$ (°) (36)

(9) + (21) + (33) + (36) and $\varepsilon = 20°$ gives:

$½\rho V^2 * \pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta - 0.0225 * \sin 3\delta) =$
$\{1 + 1/200 (20 + \delta - \alpha)\} * M_{spring0}$ (for $0° \leq \delta \leq 40°$) (37)

(9) + (22) + (35) + (38) and $\varepsilon = 20°$ gives:

$½\rho V^2 * \pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta - 0.0332 * \cos^2\delta) =$
$\{1 + 1/200 (20 + \delta - \alpha)\} * M_{spring0}$ (for $40° \leq \delta \leq 90°$) (38)

Formulas 34, 35, 37 and 38 are the moment equations. The design wind speed V_d, is the highest wind speed for which the vane arm makes contact with the zero line stop. It is chosen that $V_d = 8$ m/s. So $\delta = 0°$, $\gamma = 0°$ and $\alpha = \varepsilon = 20°$ for $V_d = 8$ m/s (see figure 2). Substitution of $\delta = 0°$ and $\alpha = 20°$ in formula 37 gives:

$M_{spring0} = C_t * ½\rho V^2 * \pi R^2 * e$ (Nm) (for $V = V_d$) (39)

It is assumed that $C_t = 0.7$ (-). The air density $\rho = 1.2$ kg/m^3 for a temperature of 20 °C. $V = V_d = 8$ m/s. Substitution of these values in formula 39 gives:

$M_{spring0} = 26.88 * \pi R^2 * e$ (Nm) (40)

(37) + (40) gives:

$½\rho V^2 * (C_t * \cos^2\delta + C_d * f/e * i * \sin\delta - 0.0225 * R/e * \sin 3\delta) =$
$26.88 * \{1 + 1/200 (20 + \delta - \alpha)\}$ (for $0° \leq \delta \leq 40°$) (41)

Suppose we take the rotor and head geometry of the VIRYA-4.2 rotor which is also used in figure 5. Substitution of $\rho = 1.2$ kg/m^3, $C_t = 0.7$, $C_d = 1$, $f/e = 0.48 / 0.42 = 1.1429$, $i = 0.01$ and $R/e = 2.1 / 0.42 = 5$. Substitution of these values in formula 41 gives:

$V^2 * (0.7 * \cos^2\delta + 0.01143 * \sin\delta - 0.1125 * \sin 3\delta) = 44.8 * \{1 + 1/200 (20 + \delta - \alpha)\}$
(for $0° \leq \delta \leq 40°$) (42)

Formula 42 can be written as:

$$V = \sqrt{\frac{44.8 * \{1 + 1/200\,(20 + \delta - \alpha)\}}{(0.7 * \cos^2\delta + 0.01143 * \sin\delta - 0.1125 * \sin 3\delta)}} \quad \text{(m/s)} \quad (\text{for } 0° \le \delta \le 40°) \qquad (43)$$

(38) + (40) gives:

$$½\rho V^2 * (C_t * \cos^2\delta + C_d * f/e * i * \sin\delta - 0.0332 * R/e * \cos^2\delta) =$$
$$26.88 * \{1 + 1/200\,(20 + \delta - \alpha)\} \quad (\text{for } 40° \le \delta \le 90°) \qquad (44)$$

Suppose we take the rotor and head geometry of the VIRYA-4.2 rotor which is also used in figure 5. Substitution of ρ = 1.2 kg/m^3, C_t = 0.7, C_d = 1, f/e = 0.48 / 0.42 = 1.1429, i = 0.01 and R/e = 2.1 / 0.42 = 5. Substitution of these values in formula 46 gives:

$$V^2 * (0.7 * \cos^2\delta + 0.01143 * \sin\delta - 0.166 * \cos^2\delta) = 44.8 * \{1 + 1/200\,(20 + \delta - \alpha)\}$$
$$(\text{for } 40° \le \delta \le 90°) \qquad (45)$$

Formula 45 can be written as:

$$V = \sqrt{\frac{44.8 * \{1 + 1/200\,(20 + \delta - \alpha)\}}{(0.534 * \cos^2\delta + 0.01143 * \sin\delta)}} \quad \text{(m/s)} \quad (\text{for } 40° \le \delta \le 90°) \qquad (46)$$

Formula 43 and 46 give the relation in between δ and V for the two δ ranges for 0° ≤ δ ≤ 40° and 40° ≤ δ ≤ 90°. However, a problem with these formulas is that they contain α and that α is a function of V. In figure 2 it can be seen that α = 20° for V = V_d = 8 m/s. Substitution of these values and ρ = 1.2 kg/m^{3}in formula 34 gives:

$$M_{vane} = 33.792 * h * w * (R_v + i) \quad \text{(Nm)} \qquad (47)$$

Formula 47 can be written as:

$$h * w * (R_v + i) = M_{vane} / 33.792 \quad (\text{m}^3) \qquad (48)$$

(32) + (48) gives:

$$V = \sqrt{\{33.792 / (0.044 * \alpha * ½\rho)\}} \qquad (49)$$

Substitution of ρ = 1.2 kg/m^3 in formula 49 gives:

$$V = \sqrt{(1280 / \alpha)} \quad \text{(m/s)} \qquad (50)$$

Formula 50 can also be written as:

$$\alpha = 1280 / V^2 \quad (°) \qquad (51)$$

Next it will be checked how V is influenced by α. Substitution of α = 20° in formula 50 gives V = 8 m/s, so formula 50 is correct. Substitution of α = 1° in formula 50 gives V = 35.8 m/s. So α becomes very small for high wind speeds and it is allowed to neglect α for high wind speeds.

If α is neglected, formula 43 changes into:

$$V = \sqrt{\frac{44.8 * \{1 + 1/200\,(20 + \delta)\}}{(0.7 * \cos^2\delta + 0.01143 * \sin\delta - 0.1125 * \sin 3\delta)}} \text{ (m/s)} \quad (\text{for } 0° \le \delta \le 40°) \; (\text{for } \alpha = 0°) \qquad (52)$$

If α is neglected, formula 46 changes into:

$$V = \sqrt{\frac{44.8 * \{1 + 1/200\,(20 + \delta)\}}{(0.534 * \cos^2\delta + 0.01143 * \sin\delta)}} \text{ (m/s)} \quad (\text{for } 40° \le \delta \le 90°) \; (\text{for } \alpha = 0°) \qquad (53)$$

So formulas 52 and 53 are only valid for high wind speeds when it is allowed to neglect α. If it is not allowed to neglect α, one has to use formula 43 and 46.

6 Determination of the δ-V curve for V_d = 8 m/s

It is wanted to determine the δ-V curve for values of δ starting at δ = 0° and increasing with 10° up to a maximum value δ = 80°. The value δ = 58° is added too because it appeared that the rotational speed, the thrust and the power have a maximum for δ = 58°. In chapter 5.5 it is explained that the problem of formulas 43 and 46 is that they contain α and that the problem of formula 52 and 53 is that it is only allowed to use them if α can be neglected. This problem is solved by iteration which means that the correct combination of δ and V is approached in some rounds. Five rounds appear to be enough. One has to use the formulas which are valid for a certain δ range so formula 43 and 52 for 0° ≤ δ ≤ 40° and formula 46 and 53 for 40° < δ ≤ 90°. Formula 51 is valid for the whole δ range. The procedure of iteration is explained for the δ range 0° ≤ δ ≤ 40° but it is similar for the other δ range. The following is done:

Round 1
First V is determined for a certain value of δ, using formula 52.
Next α is calculated using formula 51 for the value of V which was found in round 1.
Round 2
Next V is determined for the same value of δ and the angle α from round 1, using formula 43.
Next α is calculated again for the value of V which was found in round 2.
Round 3
Next V is determined for the same value of δ and the angle α from round 2, using formula 43.
Next α is calculated again for the value of V which was found in round 3.
Round 4
Next V is determined for the same value of δ and the angle α from round 3, using formula 43.
Next α is calculated again for the value of V which was found in round 4.
Round 5
Next V is determined for the same value of δ and the angle α from round 4, using formula 43.
Next α is calculated again for the value of V which was found in round 5.

For every new round, the correct combination of δ and V and α is closer approached. The result of the calculations for five rounds is given in table 2. For large angles δ it is even not necessary to use all five rounds because α or V become constant before round 5 is reached.

round 1			round 2			round 3			round 4			round 5		
δ (°)	V(ms)	α (°)	δ (°)	V(ms)	α (°)	δ (°)	V(ms)	α (°)	δ (°)	V(ms)	α (°)	δ (°)	V(ms)	α (°)
0	8	20												
10	9.082	15.52	10	8.770	16.64	10	8.747	16.73	10	8.745	16.74	10	8.745	16.74
20	10.123	12.49	20	9.856	13.18	20	9.841	13.22	20	9.840	13.22			
30	11.572	9.56	30	11.348	9.94	30	11.339	9.96	30	11.339	9.96			
40	13.476	7.05	40	13.292	7.24	40	13.287	7.25	40	13.287	7.25			
50	16.237	4.85	50	16.091	4.94	50	16.088	4.95	50	16.088	4.95			
58	19.75	3.28	58	19.633	3.32	58	19.632	3.32	58	19.632	3.32			
60	20.914	2.93	60	20.804	2.96	60	20.803	2.96	60	20.803	2.96			
70	29.788	1.44	70	29.714	1.45	70	29.714	1.45						
80	49.561	0.52	80	49.518	0.52	80	49.518	0.52						

table 2 Calculated relation in between δ and V for V_d = 8 m/s

The combination of δ, V and α found in the highest round is copied in table 3. The corresponding value of γ is calculated using formula 36 and is also given in table 3. The values for wind speeds in between 0 and 8 m/s are also given in table 3. In table 3, the values for cosδ, $\cos^2\delta$, $\cos^3\delta$, V * cosδ, $V^2 * \cos^2\delta$ and $V^3 * \cos^3\delta$ are also given. V * cosδ is an indication for the increase of the rotational speed (see formula 1). $V^2 * \cos^2\delta$ is an indication for the increase of the thrust and the torque (see formula 2 and 3). $V^3 * \cos^3\delta$ is an indication for the increase of the power (see formula 4).

δ (°)	α (°)	γ (°)	V (m/s)	cosδ	$\cos^2\delta$	$\cos^3\delta$	V * cosδ	$V^2 * \cos^2\delta$	$V^3 * \cos^3\delta$
0	20	0	0	1	1	1	0	0	0
0	20	0	1	1	1	1	1	1	1
0	20	0	2	1	1	1	2	4	8
0	20	0	3	1	1	1	3	9	27
0	20	0	4	1	1	1	4	16	64
0	20	0	5	1	1	1	5	25	125
0	20	0	6	1	1	1	6	36	216
0	20	0	7	1	1	1	7	49	343
0	20	0	8	1	1	1	8	64	512
10	16.74	13.26	8.745	0.9848	0.9698	0.9551	8.612	74.135	638.746
20	13.22	26.78	9.840	0.9397	0.8830	0.8298	9.247	85.497	790.603
30	9.96	40.04	11.339	0.8660	0.75	0.6495	9.820	96.430	946.898
40	7.25	52.75	13.287	0.7660	0.5868	0.4495	10.178	103.596	1054.412
50	4.95	65.05	16.088	0.6428	0.4132	0.2656	10.341	106.946	1105.947
58	3.32	74.68	19.632	0.5299	0.2808	0.1488	10.403	108.225	1125.892
60	2.96	77.04	20.803	0.5	0.25	0.125	10.402	108.191	1125.351
70	1.45	88.55	29.714	0.3420	0.1170	0.0400	10.162	103.302	1049.406
80	0.52	99.48	49.518	0.1736	0.0302	0.0052	8.596	74.051	631.383

table 3 Calculated relation in between δ, α, γ and V for V_d = 8 m/s

In table 3 it can be seen that the maximum values are calculated for δ = 58° and not at δ = 80° where M_{spring} has the maximum value. This is mainly caused by $M_{Fs\delta}$ which becomes important at large yaw angles (see figure 5).

For all values of δ out of table 3 it is assumed that the rotor is loaded such that it rotates with the design tip speed ratio λ_d. For very low wind speeds this is not realistic because the rotor may stand still if it has not yet started. If the generator is charging a battery, the matching in between rotor and generator is normally good for wind speeds above about 4 m/s but for lower wind speeds the rotor is mostly turning at a higher tip speed ratio than λ_d (once the rotor has started). So table 3 is not accurate for wind speeds below about 4 m/s but these wind speeds are not important if the functioning of a safety system is observed.

The calculated values for δ as a function of V are given as the δ-V curve of figure 9.

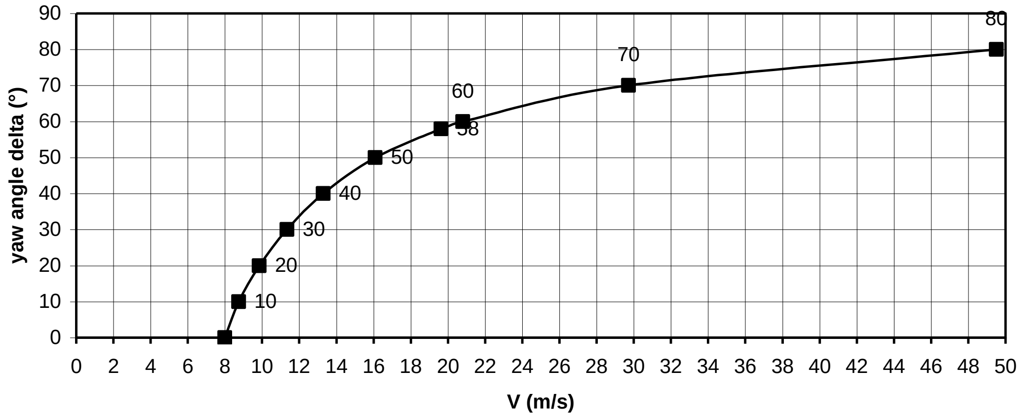

fig. 9 Calculated δ-V curve for the ecliptic safety system with torsion spring for V_d = 8 m/s

If figure 9 is compared to the ideal curve of figure 1, it can be seen that the δ-V curve makes an angle with the V-axis which is smaller than 90°. So the overshoot of the rotational speed and thrust which will happen if the wind varies around V_d = 8 m/s, will be less than for the ideal curve, which is favourable. But the rest of the curve has about the same shape as the ideal curve.

The calculated values of V * cosδ as a function of V are given in figure 10. This curve is an indication of the variation of the rotational speed.

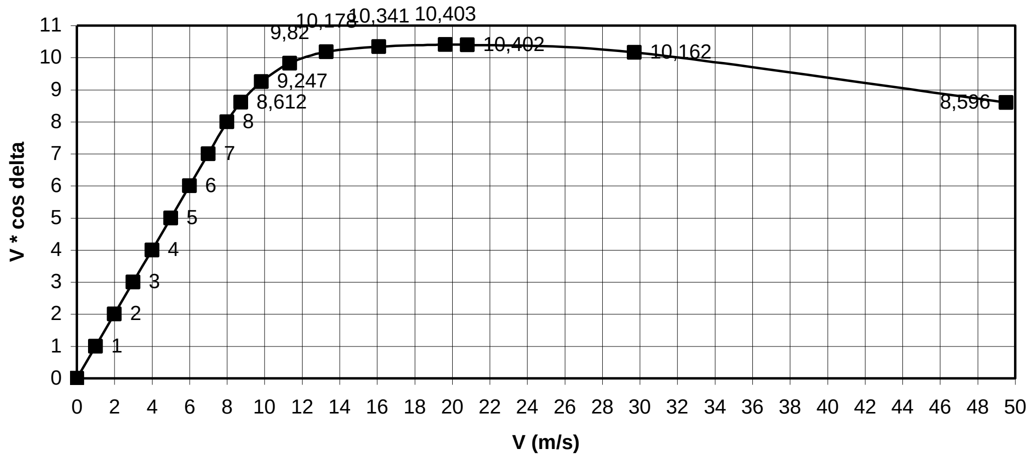

fig. 10 V * cosδ as a function of V for V_d = 8 m/s

In figure 10 it can be seen that the rotational speed is sharply limited and has a maximum at V = 19.632 m/s for δ = 58°. This wind speed is called the rated wind speed V_{rated}, so V_{rated} = 19.632 m/s. The corresponding rotational speed is called n_{rated}. The rotational speed at the design wind speed V_d = 8 m/s is called n_d. The ratio n_{rated} / n_d = 10.403 / 8 = 1.30 which is an acceptable value for V_{rated} / V_d = 19.632 / 8 = 2.454.

The calculated values of $V^2 * \cos^2\delta$ as a function of V are given in figure 11. This curve is an indication of the variation of the thrust and the torque.

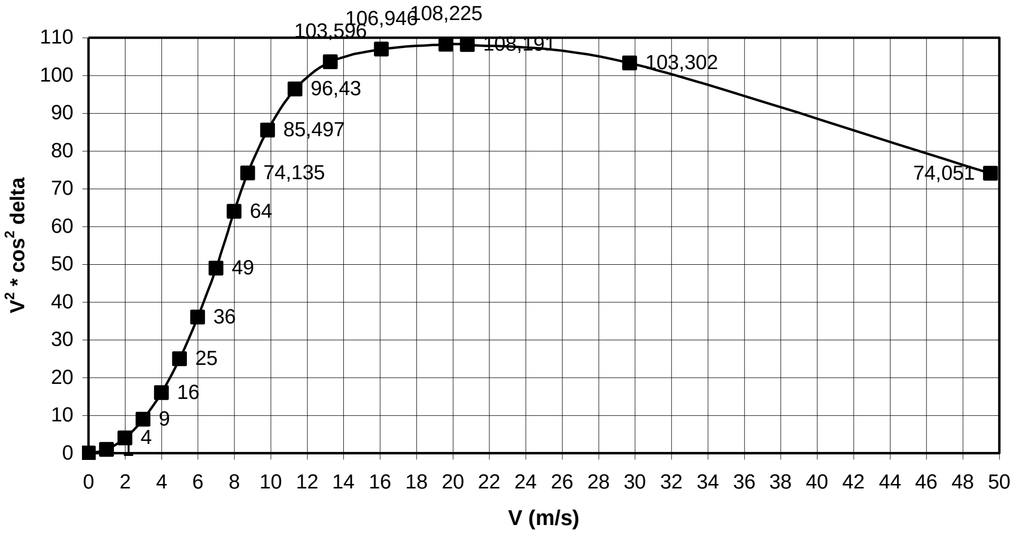

fig. 11 $V^2 * \cos^2\delta$ as a function of V for V_d = 8 m/s

In figure 11 it can be seen that the thrust and the torque are sharply limited and have a maximum at V_{rated} = 19.632 m/s. The ratio in between the rated thrust and the design thrust or in between the rated torque and the design torque is 108.225 / 64 = 1.691. The rotor strength has to be calculated for V_{rated} = 19.632 m/s and δ = 58°.

The calculated values of $V^3 * \cos^3\delta$ as a function of V are given in figure 12. This curve is an indication of the variation of the power.

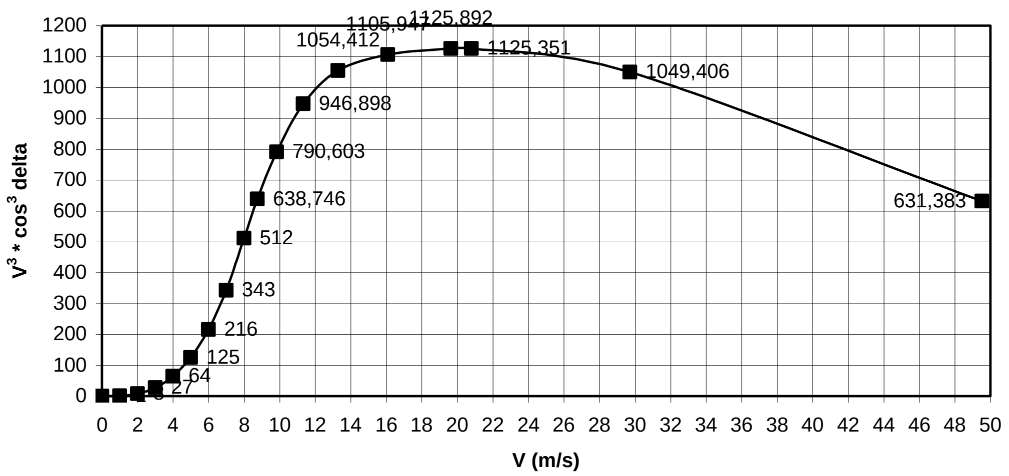

fig. 12 $V^3 * \cos^3\delta$ as a function of V for V_d = 8 m/s

In figure 12 it can be seen that the power is sharply limited and has a maximum at V_{rated} = 19.632 m/s. The ratio in between the rated power and the design power is 1125.892 / 512 = 2.199. The power is the mechanical power supplied by the rotor shaft. For the electrical power, the generator efficiency has to be taken into account.

7 Realisation of a certain design wind speed

In chapter 6 it has been shown that a design wind speed V_d = 8 m/s is a good first choice. For this wind speed, $\delta = 0°$ and $\alpha = 20°$. Substitution of these values in formula 34 gives:

$$C_t * \pi R^2 * e = 0.88 * h * w * (R_v + i_1) \qquad (54)$$

Assume $C_t = 0.7$. Assume it is chosen that e = 0.2 R. Assume a square vane blade is chosen, so h = w. The angle α in between the vane blade and the wind direction is 20° if the rotor is perpendicular to the wind direction and if the vane arm hits the stop. In figure 6 it can be seen that i_1 / w = 0.34 for $\alpha = 20°$, so i_1 = 0.34 w. Substitution of these values in formula 54 gives:

$$R^3 = 2.0008 * w^2 * (R_v + 0.34\ w) \qquad (m^3) \qquad (55)$$

Normally the rotor radius R is chosen first. Next one chooses a square sheet with a side w such that the sheet can be made out of material with standard dimensions such that no or only a little waste material is produced. Next one has to determine R_v such that formula 55 is fulfilled.

R_v is the horizontal length of the vane arm in between the vane axis and the front edge of the vane blade. If the vane arm makes an angle of 45° with the horizon, the real length is a factor √ 2 longer. Next one has to make a composite drawing and check if the vane blade juts above the rotor shadow for the given dimensions of rotor, vane arm and vane blade. If not, one has to increase the length of the vane arm and decrease the width w of the vane blade such that formula 55 is fulfilled.

Once the geometry is OK, one has to determine the construction of the vane hinge and the stops of the vane arm at $\gamma = 0°$ and at $\gamma = 100°$. One also has to determine a torsion spring which has the required characteristics and which supplies $M_{spring0}$ at $\gamma = 0°$. The relation in between $M_{spring0}$ and the rotor parameters is given by formula 40. Assume e = 0.2 R. Substitution of this value in formula 40 gives:

$$M_{spring0} = 16.889 * R^3 \qquad (Nm) \qquad (\text{for } V = V_d = 8 \text{ m/s and } e = 0.2\ R) \qquad (56)$$

The torsion spring looks about the same as a clothes-peg. So it has about five full windings and two legs. The winding is mounted around the vane arm pin. One leg is connected to the head frame and one leg is connected to the vane arm. In figure 8 it can be seen that the spring moment increase by a factor 1.5 for a vane rotation $\gamma = 100°$. So the twist of the spring is 200° from the unstressed position up to $\gamma = 0°$ and 300° from the unstressed position up to $\gamma = 100°$. The determination of the exact geometry of the torsion spring is out of the scope of this report.

8 Alternative with a constant spring moment

In figure 10, 11 and 12 it can be seen hat the maximum rotational speed, the maximum thrust and the maximum power are considerably higher than the values at the design wind speed of 8 m/s. The main reason is that the spring moment is increasing at increasing γ (see figure 8). A second reason is the self orientating moment which makes that the rotor moment is decreasing faster at increasing yaw angle δ than if the rotor moment was only caused by the rotor thrust (see figure 5). The influence of the self orientating moment becomes smaller if the eccentricity is taken larger but it was chosen that e = 0.2 R and this is already a rather large value. So the influence of the self orientating moment can’t be reduced for acceptable head geometry. But it might be possible to realise a constant or almost constant spring moment.

The increase of the spring moment can be reduced by choosing a weak torsion spring. This means that the angle, over which the spring has to be turned until the moment $M_{spring0}$ is realised, is much larger. This requires a spring with more windings and so the spring will use more space. Another disadvantage is that mounting of the spring is much more difficult because one leg of the spring has to be rotated some revolutions until it is connected to the vane arm. So using a weaker spring seems a difficult solution.

The same effect as an infinitive weak torsion spring can be realised if a weight is lifted and if the displacement of the weight is linear to the angle γ over which the vane arm is turning. The weight can be the vane arm itself. The head frame should be provided with a curved cam and the vane arm should have a cam roller running over the curved cam. At this moment it is not yet decided how a constant spring moment is realised but it is good to know how the system works for a constant spring moment and therefore this will be investigated. A constant spring moment makes that certain formulas are changing. Formula 33 changes into:

$$M_{spring} = M_{spring0} \quad \text{(Nm)} \qquad (57)$$

Formula 37 changes into:

$$\tfrac{1}{2}\rho V^2 * \pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta - 0.0225 * \sin 3\delta) = M_{spring0}$$
$$(\text{for } 0° \le \delta \le 40°) \qquad (58)$$

Formula 38 changes into:

$$\tfrac{1}{2}\rho V^2 * \pi R^3 (C_t * e/R * \cos^2\delta + C_d * f/R * i * \sin\delta - 0.0332 * \cos^2\delta) = M_{spring0}$$
$$(\text{for } 40° \le \delta \le 90°) \qquad (59)$$

Formula 43 (for V_d = 8 m/s) changes into:

$$V = \sqrt{\frac{44.8}{(0.7 * \cos^2\delta + 0.01143 * \sin\delta - 0.1125 * \sin 3\delta)}} \quad \text{(m/s)} \quad (\text{for } 0° \le \delta \le 40°) \qquad (60)$$

Formula 46 for (V_d = 8 m/s) changes into:

$$V = \sqrt{\frac{44.8}{(0.534 * \cos^2\delta + 0.01143 * \sin\delta)}} \quad \text{(m/s)} \quad (\text{for } 40° \le \delta \le 90°) \qquad (61)$$

The advantage of a constant vane moment is that now α is not found in the formulas for V and therefore it isn't necessary to follow an iteration process to find the δ-V curve. Table 3 is now copied as table 4 but the value of V is directly calculated with formula 61 or 62. α is calculated with formula 51 and γ is calculated with formula 36 (for ε = 20°).

δ (°)	α (°)	γ (°)	V (m/s)	cosδ	$cos^2δ$	$cos^3δ$	V * cosδ	$V^2 * cos^2δ$	$V^3 * cos^3δ$
0	20	0	0	1	1	1	0	0	0
0	20	0	1	1	1	1	1	1	1
0	20	0	2	1	1	1	2	4	8
0	20	0	3	1	1	1	3	9	27
0	20	0	4	1	1	1	4	16	64
0	20	0	5	1	1	1	5	25	125
0	20	0	6	1	1	1	6	36	216
0	20	0	7	1	1	1	7	49	343
0	20	0	8	1	1	1	8	64	512
10	17.85	12.15	8.469	0.9848	0.9698	0.9551	8.340	69.558	580.157
20	14.99	25.01	9.241	0.9397	0.8830	0.8298	8.667	75.405	654.833
30	11.95	38.05	10.350	0.8660	0.75	0.6495	8.963	80.342	720.112
38	9.68	48.32	11.497	0.7880	0.6210	0.4893	9.060	82.084	743.582
40	9.16	50.84	11.819	0.7660	0.5868	0.4495	9.053	81.969	742.116
50	6.55	63.45	13.975	0.6428	0.4132	0.2656	8.983	80.698	724.909
60	4.10	75.90	17.675	0.5	0.25	0.125	8.838	78.101	690.221
70	2.09	87.91	24.738	0.3420	0.1170	0.0400	8.460	71.60	605.555
80	0.78	99.22	40.466	0.1736	0.0302	0.0052	7.025	49.452	344.567

table 4 Calculated relation in between δ, α, γ and V for V_d = 8 m/s

In table 4 it can be seen that the maximum values are calculated for δ = 38° which is lower than the value δ = 58° which was found in chapter 6 for a torsion spring which has a spring moment at γ = 100° which is a factor 1.5 higher than at γ = 0°. The rated wind speed V_{rated} = 11.497 m/s for δ = 38°. This is also much lower than the rated wind speed of 19.632 m/s which was found in chapter 6. So using a constant spring moment seems a good idea if it can be realised technically. It might even be allowed to choose a higher design wind speed of for instance 9 m/s but this results in change of formula 51, 60 and 61.

The calculated values for δ as a function of V are given as the δ-V curve of figure 13.

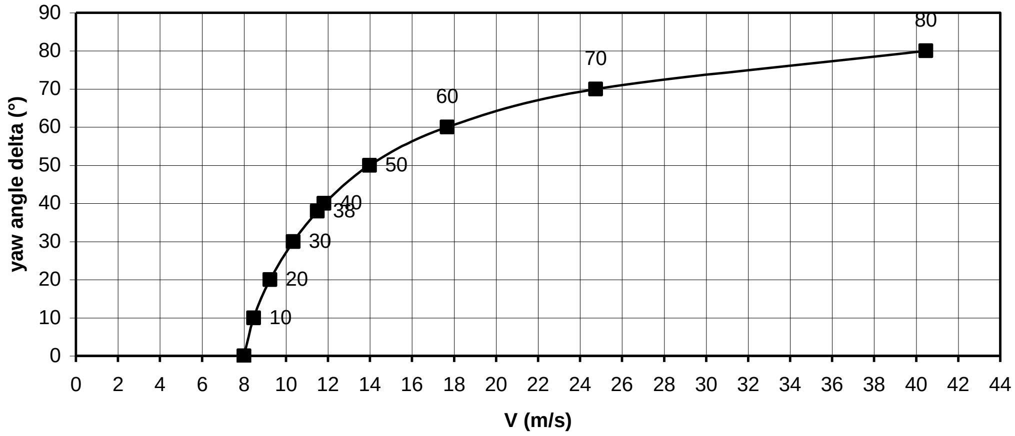

fig. 13 Calculated δ-V curve for the ecliptic safety system with torsion spring for V_d = 8 m/s

If figure 13 is compared to the ideal curve of figure 1, it can be seen that the δ-V curve makes an angle with the V-axis which is smaller than 90°. So the overshoot of the rotational speed and thrust which will happen if the wind varies around V_d = 8 m/s, will be less than for the ideal curve, which is favourable. But the rest of the curve has about the same shape as the ideal curve.

The calculated values of V * cosδ as a function of V are given in figure 14. This curve is an indication of the variation of the rotational speed.

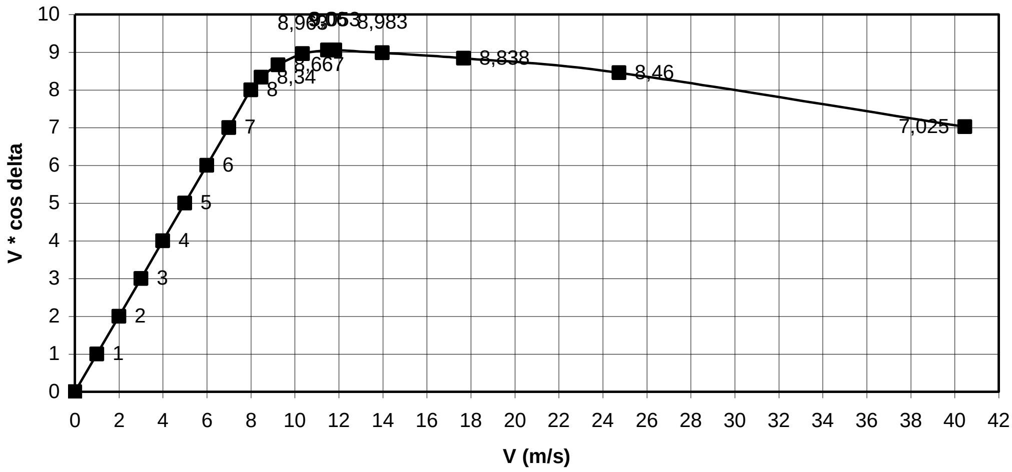

fig. 14 V * cosδ as a function of V for V_d = 8 m/s

In figure 14 it can be seen that the rotational speed is sharply limited and has a maximum at V = 11.497 m/s for δ = 38°. This wind speed is called the rated wind speed V_{rated}, so V_{rated} = 11.497 m/s. The corresponding rotational speed is called n_{rated}. The rotational speed at the design wind speed V_d = 8 m/s is called n_d. The ratio n_{rated} / n_d = 9.06 / 8 = 1.133 which is an acceptable value for V_{rated} / V_d = 11.497 / 8 = 1.437.

The calculated values of V^2 * $\cos^2\delta$ as a function of V are given in figure 15. This curve is an indication of the variation of the thrust and the torque.

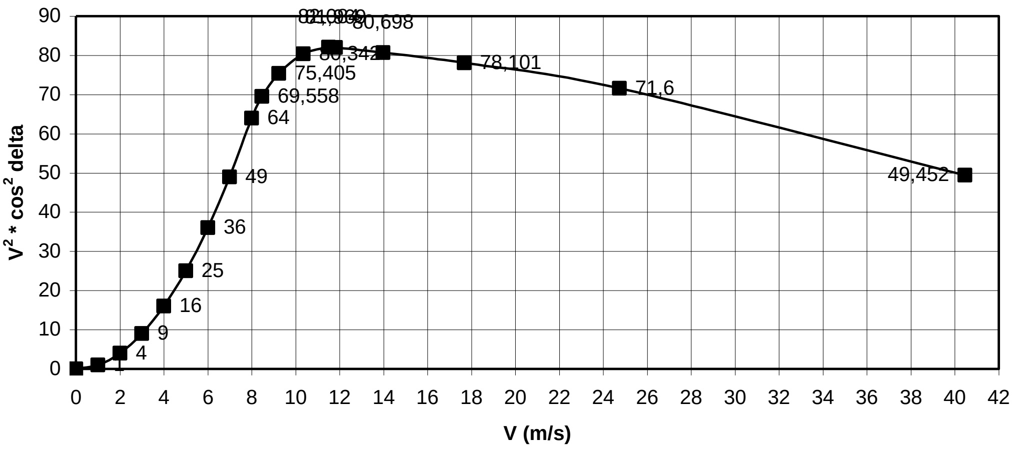

fig. 15 V^2 * $\cos^2\delta$ as a function of V for V_d = 8 m/s

In figure 15 it can be seen that the thrust and the torque are sharply limited and have a maximum at V_{rated} = 11.497 m/s. The ratio in between the rated thrust and the design thrust or in between the rated torque and the design torque is 82.084 / 64 = 1.283. The rotor strength has to be calculated for V_{rated} = 11.497 m/s and δ = 38°.

The calculated values of $V^3 * \cos^3\delta$ as a function of V are given in figure 16. This curve is an indication of the variation of the power.

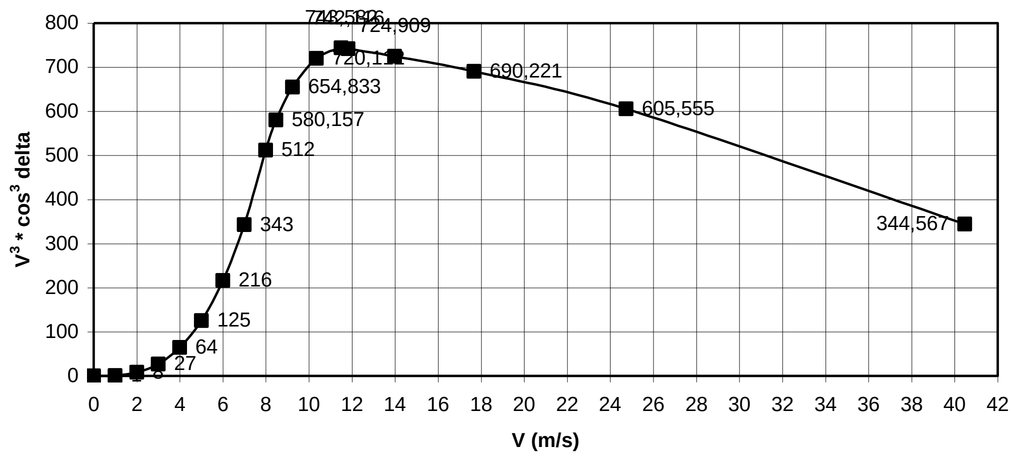

fig. 16 $V^3 * \cos^3\delta$ as a function of V for V_d = 8 m/s

In figure 16 it can be seen that the power is sharply limited and has a maximum at V_{rated} = 11.497 m/s. The ratio in between the rated power and the design power is 743.582 / 512 = 1.511. The power is the mechanical power supplied by the rotor shaft. For the electrical power, the generator efficiency has to be taken into account.

If figures 14, 15 and 16 are compared to figures 10, 11 and 12 it can be seen that the maximum values for a constant spring moment are much lower than for an increasing spring moment. So I think that it is better to design the safety system such that the spring moment is constant or increasing minimal. Further design of this safety system is out of the scope of this report.

9 References

1 Kragten A. Safety systems for water pumping windmills, report R 999 D, April 1989, (former) Wind Energy Group, Faculty of Fluid Dynamics, Department of Physics, University of Technology Eindhoven, The Netherlands (no longer supplied by the TU-Eindhoven but a scan can be found on the Internet by typing the title in Google).

2 Kragten A. Method to check the estimated δ-V curve of the hinged side vane system and checking of the δ-V curve of the VIRY-4.2 windmill, December 2004, free public report KD 213, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Development of a tornado proof pendulum safety system fort a medium size wind turbine which turns the rotor out of the wind along an horizontal axis, April 2008, free public report KD 377, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Development of an ecliptic safety system with a torsion spring and with an eccentricity chosen so large, that the contribution of M_{so} and $F_{s\delta}$ to M_{rotor} can be neglected, January 2009, report KD 408, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Rotor design and marching for horizontal axis wind turbines, July 1999, free public report KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

6 Kragten A. Windtunnelmetingen aan het kantelrotormechanisme ter beveiliging van windmolens (in Dutch), report R 344 D, July 1978, (former) Wind Energy Group, Faculty of Fluid Dynamics, Department of Physics, University of Technology Eindhoven, The Netherlands (probably no longer available).

7 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.