Measurements of Savonius rotors available on the Internet

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Contains page

1 Introduction

This report KD 599 was originally available as KD technical note dated 30-12-2009. However, the original digital version was lost because of a computer crash. The note was typed again but now as free public report KD 599. It was also slightly reviewed.

To propel the blades of a windmill, one can use the aerodynamic lift force or the aerodynamic drag force. The lift force L is the force (in N) which is generated on an airfoil perpendicular to the relative wind speed W. The drag force D is the force (in N) which is generated on a drag body in the direction of the relative wind speed W. The relative wind speed W is the wind speed (in m/s) which is felt by the airfoil or by the drag body. Modern horizontal axis wind turbines make use of the lift force and the blades move in a direction perpendicular to the undisturbed wind speed V (in m/s). Information about horizontal axis windmills can be found in my report KD 35: Rotor design and matching for horizontal axis wind turbines (ref. 1).

Vertical axis wind turbines can make use of lift, drag or a combination of lift and drag. A vertical axis wind turbine using lift is the Darrieus rotor (ref. 2). This type of windmill has only a few advantages but many disadvantages. A common type of a drag machine is a cup anemometer which is normally used for measuring wind speeds. In my report KD 416: Windmills using aerodynamic drag as propelling force; a hopeless concept (ref. 3), I strongly discourage people to develop cup anemometer like windmills because the maximum power coefficient is very low (about 0.05), because the optimum tip speed ratio λ_{opt} is very low (about 0.15) and because a lot of material is needed. A less common vertical axis wind turbine is the so called rotating blade, vertical axis wind turbine which is described in report KD 417 (ref. 4). This machine is mainly using lift if it is running at the optimum tip speed ratio of about 2/3. The $C_{p\ max}$ which can be realised has never been measured.

The Savonius rotor is partly a drag machine but also partly a lift machine and therefore a higher $C_{p\ max}$ and a higher λ_{opt} can be realised than for a pure drag machine. The first research to Savonius rotors has been done by Mr. Savonius himself in between 1922 and 1931. He reports a very high value $C_{p\ max} = 0.31$ but this high value could not be measured by most of the later researchers.

I did some research on the Internet through Google in 2009 to see if reliable measurements on the Savonius rotor can be found. Typing Savonius rotor or Savonius wind turbine results in thousands of hits but only very few hits give wind tunnel measurements. Many reports, in which wind tunnel measurements on Savonius rotors are described, are only available after paying fees of at least € 25. I have mentioned only those reports which can be copied for free from the Internet.

Most people agree with the fact that the $C_{p\ max}$ of a Savonius rotor is much lower that the $C_{p\ max}$ of a well designed horizontal axis wind turbine. However, very often it is claimed that a Savonius rotor might be a good solution for developing countries because of its simplicity. I have serious doubts about this claim after having seen many pictures of Savonius rotors which have really been built. Making a Savonius rotor from new material is not simple and the required tower is complicated because a Savonius rotor has to be supported at the upper and at the lower side. Generation of electricity requires a large accelerating gearing.

Another argument which is often used, is that a Savonius rotor has a high starting torque and that therefore it can be used to drive a load like a pump or a grinding mill. However, measurements on a 1-phase Savonius rotor show that the starting torque coefficient $C_{q\ start}$ is very fluctuating as a function of the position of the rotor with respect to the wind direction. At a certain angle it is almost zero. An acceptable starting torque can be realised if two Savonius rotors are combined which differ 90° in position. This kind of Savonius rotor is called a 2-phase Savonius rotor. Another option is to twist the blades 90°.

For measuring of a scale model of a windmill rotor, one should use an open wind tunnel because only for an open wind tunnel the wake around the rotor can expand like this also happens in real wind. I have measured many horizontal axis windmill rotors in the open wind tunnel of the University of Delft in the years 1975 -1990. The disadvantage of an open wind tunnel is that it consumes a lot of energy because all energy in the air flow which is generated, is lost. Measuring of a scale model in a closed wind tunnel results in too high C_p values if the wind speed is not corrected for tunnel blockage. The blockage is larger as the swept area of the windmill is larger with respect to the cross sectional area of the measuring section of the wind tunnel. For most closed wind tunnels it is possible to remove the wind tunnel walls for the measuring section but this is not good enough to realise full expansion of the wake around the scale model. None of the measurements on Savonius rotors which I have found on the Internet, have been measured in an open wind tunnel!

2 Reports and articles found on the Internet

Typing Savonius rotor in Google gives e.g. the hit:

2.1 Savonius rotor

On this site, many pictures of Savonius rotors can be found. One picture called ”info about Savonius rotors” gives the abstract of a very interesting report: ”On the performance of the Savonius wind Turbine”. In this abstract it is clearly explained why Mr. Savonius has measured a too high C_p value. The Internet address of this abstract is: www.southcom.co.au/~windmill/info.htm. The complete report is not freely available

Typing Savonius rotor performance in Google gives e.g. the hits:

2.2 Wind Tunnel Performances Data for Two- and Three-bucket Savonius rotors

Internet address: www.greenenergywindturbine.com/download/vawt/760131.pdf
This is one of the best reports I have found. The used wind tunnel section was very large with respect to the size of the scale model and the wind speed has been corrected for blockage. So these measurements are very reliable. A conclusion is that a Savonius rotor must have two and not three buckets, if a high maximum C_p value is wanted. One has measured $C_{p\ max} = 0.24$ for $\lambda_{opt} = 0.9$. The unloaded tip speed ratio is about 1.8. The buckets should have an overlap of 10 % to 15 % of the bucket diameter. In the end of the report many measured characteristics are given for the static torque coefficient as a function of the angle of rotation and for the C_p-λ and C_q-λ curves. Anyone who wants to design a Savonius rotor should study this report (105 pages) in detail.

2.3 Performance of Double-step Savonius Rotor for Environmental Friendly Hydraulic Turbine

Internet address: www.jstage.jst.go.jp/article/jfst/3/3/410_pdf
This article describes the use of a Savonius rotor with a horizontal axis as a water turbine. Unfortunately the size of the Savonius rotor was rather large with respect to the size of the measuring section of the water tunnel and the measurements were not corrected for blockage. The measured C_p values are therefore certainly too high. But one did nice research to the flow pattern by injection of ink in the water. One also compared 1-phase and 2-phase rotors and showed the flow pattern. One found that a 2-phase rotor result in about 10 % increase of the C_p value because of the so called meandering effect. This report shows very nice coloured pictures and gives a good insight in what happens with the flow.

2.4 Turn, turn, turn Performance of Savonius rotor as a water current turbine

Internet address:
www.journalofoceantechnology.com/getFile.asp?file=TurnTurnTurn.pdf&article=True&vol=4&issue=2
This article also deals about measurements of a Savonius rotor as a water turbine but for these measurements the turbine axis was taken vertical. The maximum C_p which has been measured was only 0.05 but to my opinion the C_p is defined incorrectly. Correct definition of C_p results in a maximum C_p of 0.2 which seems realistic as the size of the water tunnel was very large in respect to the size of the scale model. I have reported the mistake in C_p to the authors but never got a reaction.

2.5 mformarlce Test of a Savonius rotor Technical Report

Internet address: www.fastonline.org/CD3WD_40/JF/JF_VE/SMALL/21-481.pdf
This report describes measurements on a Savonius rotor made of halve oil drums. The maximum C_p was only 0.14 at a tip speed ratio $\lambda = 0.8$. Many existing Savonius rotors are made this way. It is unclear to me why the results are so much worse than for other measurements. An important remark in this report is that old oil drums may explode if you grind or flame cut them in two halves because of absorbed oil in the material.

Typing optimum geometry Savonius rotor in Google gives e.g. the hits:

2.6 Increase in the Savonius Rotors efficiency via a parametric …….

Internet address: www.2004ewec.info/files/23_1400_jeanlucmenet_01.pdf
In this article one has researched e.g. the influence of the ratio e / d in between the overlap e and the bucket diameter d on the C_q value. A first optimum value of 0.29 is found for e / d = 0.129 and a second optimum value of 0.33 is found for e / d = 0.242. The first value was also about found for research given in point 2.1. The second higher value is new. However, one should realise that increase of the ratio e /d results in decrease of the rotor diameter D for a certain bucket diameter d and so in decrease of the swept area A. So a higher optimum C_q value may result in a higher maximum C_p value but the power produced at a certain wind speed may still be less because of the smaller swept area.

2.7 150

Internet address:
http://www4.gu.edu.au:8080/adt-root/uploads/approved/adt-QGU20050916.120408/public/09main.pdf
This is a part of a report about aerofoil data from page 150. It is a report about the Darrieus rotor but sometimes Savonius rotors are used to make a Darrieus rotor self starting. The part about the Savonius rotor starts at page 159. Very interesting remarks are given about the report as mentioned in point 2.1. It is said that: The measured maximum C_p for a Savonius rotor is very much influenced by tunnel blockage. Increase of the blockage from 5 % to 20 % results in increase of the measured C_p by 70 %!

A Savonius rotor may be much more sensible for wind tunnel blockage than a horizontal axis wind turbine because apart from the thrust in the wind direction, there is a large force working perpendicular to the wind direction. This effect has been measured and is reported in the report given at point 2.2.

3 Some formulas, definitions and conclusions

The formulas for horizontal axis wind turbines are given in my report KD 35 (ref. 1). Not all formulas can be used for vertical axis wind turbines because the swept area is not a circle but equal to 2 R * H. So hereby I give the main formulas for a Savonius rotor.

$P = C_p * \rho V^3 * R * H$ (W) (1)

$Q = C_q * \rho V^2 * R^2 * H$ (Nm) (2)

$n = 30 * \lambda * V / (\pi * R)$ (rpm) (3)

$C_p = C_q / \lambda$ (-) (4)

$\lambda = \Omega * R / V$ (-) (5)

$D = 2 d – e$ (m) (6)

P is the mechanical power (W). Q is the torque (Nm). n is the rotational speed (rpm). Ω is the angular velocity (rad/s). D is the rotor diameter at the outside of the buckets (m) (so it is not the diameter of the end plates). R is half the rotor diameter D (m). H is the height of the rotor (m). d is the bucket diameter (m), e is the overlap in between the buckets (m). V is the undisturbed wind speed (m/s). ρ is the air density (is about 1.2 kg/m^3 for air of 20 °C at see level). C_p is the power coefficient (-). C_q is the torque coefficient. λ is the tip speed ratio (-).

The maximum power coefficient $C_{p\ max}$ is generated at the optimum tip speed ratio λ_{opt} which is about 0.9 for the Savonius rotor. The maximum torque coefficient $C_{q\ max}$ is generated at a tip speed ratio of about 0.4. The unloaded tip speed ratio λ_{unl} is about 1.8. The C_q-λ curve is about a straight line for 0.5 < l < 1.8. The C_p-λ curve is about a parabola for 0.5 < λ < 1.8. The average starting torque coefficient $C_{q\ start}$ is considerable lower then the maximum value.

In some reports it is advised to take the diameter of the end plates somewhat larger than the rotor diameter. Sometimes the end plates have the same diameter as the rotor diameter and sometimes the end plates cover only the bucket sides. The total required sheet area of a Savonius rotor depends on these factors and on the H / D and e / d ratios but is always much larger than the swept area 2 R * H.

The total blade area of a horizontal axis wind turbine (HAWT) with an optimum tip speed ratio of about 5 is much smaller than the swept area πR^2. Taking into account the lower maximum C_p value, a Savonius rotor which generates a certain power at a certain wind speed, will therefore be much heavier than a HAWT which generates the same power at the same wind speed, even if this HAWT uses steel sheet for the rotor blades.

4 References

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

2 Kragten A. The Darrieus rotor, a vertical axis wind turbine (VAWT) with only a few advantages and many disadvantages, December 2004, free public report KD 215, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Windmills using aerodynamic drag as propelling force; a hopeless concept, April 2009, free public report KD 416, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. The rotating blade, vertical axis wind turbine, April 2009, reviewed November 2015, free public report KD 417, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.