

Insects Cause Double Stall

- Stall Flag and PV Measurements on the NEG Micon 700/44 Wind Turbine with LM19 Blades -
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Several large commercial wind turbines demonstrate drops in maximum power levels up to 45%, under apparently equal conditions. Earlier studies attempting to explain this effect by technical malfunctioning, aerodynamic instabilities and blade contamination effects estimated with computational fluid dynamics, have not yet yielded a plausible explanation.

A number of hypotheses was formulated, three of which were useful. By performing stall flag measurements, as well as two other experiments, one of the three hypotheses was confirmed: the Insect Hypothesis. Insects only fly in low wind, impacting near the leading edge of the blade. In low wind conditions, the 'insect roughness' has little influence on profile performance and power is not affected. In high winds, however, the flow pattern around the blade has changed, and contamination on the leading edge now has a marked affect, resulting in power drop. In conclusion: the level of contamination changes only in low wind when insects fly and influences the power level in high winds when insects do not fly. As a consequence the power curve displays distinct levels at high wind speeds.

keywords: insect accumulation, double stall, stall flags

1. INTRODUCTION

About 15 years ago the first observations were made that wind turbines apparently could have more than one power level in the same wind. The first publication on the phenomenon was made by Madsen [1]. At several turbine parks in California one noticed different power levels, of which the lowest was about half the design-level, see figure 1. The phenomenon, often referred to as 'Double Stall' or 'Multiple Stall' demonstrates the production losses (up to 25%) that may be involved. Several initiatives were taken to understand and solve the problem, for example the study of Dyrmoose and Hansen [2], the Joule project on Multiple Stall [3] and the analyses published by Risø [4]. Since the cause remained uncertain, we studied a 44m HAT at a Californian site as well [5].

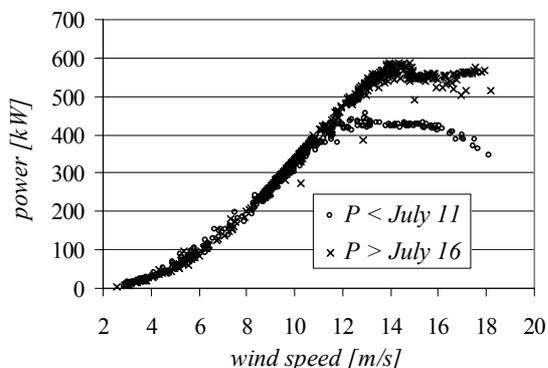


figure 1 This figure shows an example of the power levels measured by Oak Creek Energy on a NEG Micon 700/44. The cause of this behaviour was unknown.

2. HYPOTHESES

The project started with an inventory of existing and new hypotheses, yielding a list of 10 hypotheses. All hypothetical causes were based on events related to stall. We therefore carried out stall flag measurements on a turbine that clearly showed the problem: a NEG Micon 700kW turbine owned by Oak Creek Energy. Our working hypothesis was 'the Tip Commands'[6], a model that seemed to give a good description of what might happen, but at the end of the project we came up with the 'the Insect Hypothesis'. We first explain these hypotheses and then present the experimental results. At different sites and at different moments there can be different causes for multiple power levels. Furthermore, we formulated the first possible cause not related to stall. It is described by the Terrain Concentration Model [7]. An overview over all these aspects is given in [8].

2.1. The Tip Commands Hypothesis [6]

Here the phenomenon is attributed to the stalling of the blade tips. Thus in a strong gust, the blade locks into the full blade stall state and from then on it will produce less power, or in other words, *the tip commands* the flow state on the remainder of the blade. It only switches back to the partly stalled state when the wind speeds greatly decreases. As long as the blade is in the partly stalled state the radial transient from attached to stalled flow shifts from root to tip in a continuous manner with changing inflow angles and thus the blade will not show bi-stable hysteresis. Most airfoil sections tested in a wind tunnel show this bi-stable behaviour in stall. When we turn the section to larger inflow angles until leading edge stall starts, then we have to turn backwards over several degrees before the flow reattaches. In the above model this bi-stable stall cannot occur as long as there are both a

stalled and an attached section on the blade. Therefore we think that the double stall hypothesis that has been put forward in [4], which is based on bi-stable behaviour, cannot be explained without an additional assumption such as ‘the tip commands’. In this hypothesis every blade can have two states, one with the tip attached, one with the tip stalled. For a three-bladed rotor this may explain a maximum of 4 stall levels, one with all blades in the high power state and then three with 1, 2 or 3 blades in the lower power states.

2.2. The Insect Hypothesis [5]

Here the phenomenon is attributed to the weather-dependent flying behaviour of insects. Figure 2 explains the mechanism in a diagram. It is assumed that the contamination of wind turbine blades increases only when insects are flying during turbine operation. Insects mostly fly when there is no rain, little wind and when it is not too cold, at temperatures above 10°C. If the turbine operates under these conditions, insects will increasingly contaminate the blade near the stagnation line¹. Here the flow is insensitive to contamination so that the power is not affected². Above a certain wind speed, when insects rarely fly, the contamination remains constant. At high wind speed, the angle of attack along the blade is large and the suction peak has shifted to the contaminated area³. Now the flow disturbance depends a great deal on the level of contamination, which shows itself as a decrease of the stall angle depending on the level of contamination. The smaller the stall angle, the lower the power level. This can also explain two or more power levels. The design level will be reached again when the blades are cleaned or when it rains during turbine operation.

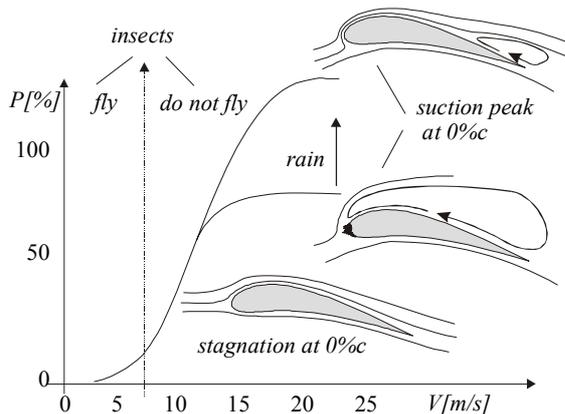


figure 2 The Insect Hypothesis.

¹ Insects, with a mass density much larger than air, follow a straight path when they crash on the airfoil near 0%*c*; at low wind speed (small angles of attack) the stagnation point is also near 0%*c*.

² The flow speed near the stagnation point is low, so that the viscous shear is small, furthermore the negative pressure gradient beyond the stagnation point is stabilising the flow, which means that the flow will be almost independent of contamination.

³ The flow speed in the suction peak is high, so that contamination causes high frictional drag; moreover the positive pressure gradient beyond the suction peak destabilises the flow, which means that the flow will come to a standstill already at smaller angles of attack and thus will sooner stall.

3. VALIDATION

This section presents the experimental validation of the multiple-power-level hypotheses. In fact the above insect hypothesis was made half-way the experiments. It gave rise to further experiments to make sure that it was correct.

In the project with the NEG Micon 700kW turbine several stall flag measurements were performed with three different patterns of vortex generators, stall flags etc. on the rotor. We only present the most important measurements. The corresponding configuration is shown in figure 3. The leading edge of blade 1 was cleaned from root to tip between -20%*c* (pressure side) and 20%*c*. Artificial roughness was applied on blade 2 from root to tip at 0%*c*. For the roughness a zigzag tape (0.5mm period) with a maximum thickness of 1.15mm and

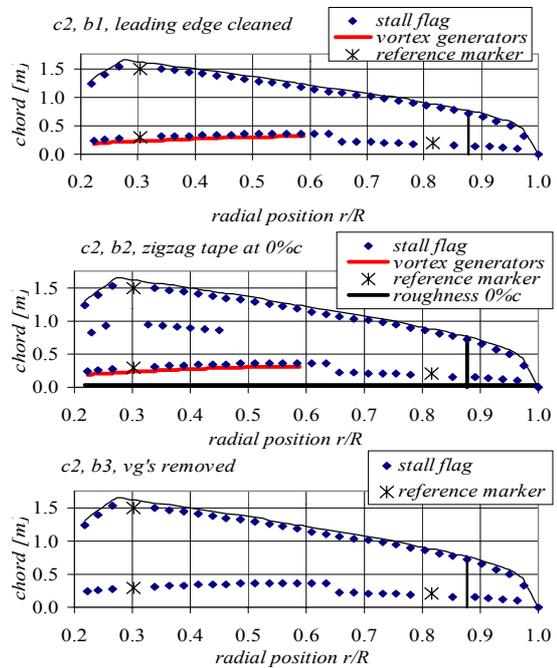


figure 3 Configuration of the second measurement. The leading edge of blade 1 was cleaned. Zigzag tape was put on that of blade 2. The vortex generators of blade 3 were taken off.

surface roughness of 0.8mm was used. The tape was 0.5cm wide between 0.7-1.0*R* and 1.5cm between 0.2-0.7*R*. All vortex generators of blade 3 were removed. This blade was not cleaned. The leading edges of blades 2 and 3 were contaminated with insects to a depth of about 0.3mm. The roughness was about the same over the entire span and was located at chord-wise positions smaller than 5%*c* on both the suction and the pressure side. The density of these disturbances was about 100 insects per square metre.

3.1 Test of 'The Tip Commands' Hypothesis

We took measurements at 18 m/s average wind speed and we even yawed the turbine over 35°. Under these conditions the tip angle of attack varies between about 13° and 18° depending on the azimuth. We followed the precise stall patterns per blade continuously

during many revolutions, but did not see any sign of locking behaviour. The stall pattern ‘continuously’ followed the changing inflow conditions, although there might be some delay. This was the reason to believe that the double stall mechanism suggested by ‘the Tip Commands’ was not responsible for the multiple power levels of practice. In fact the command-mechanism was not yet triggered, since leading edges (0.2c) of the tips remained attached.

But part of the model is confirmed: the blade did not show bi-stable hysteresis but a continuous behaviour as was expected from the model. This implies that the hypothesis in [4], which is based on bi-stable behaviour, is an unlikely candidate.

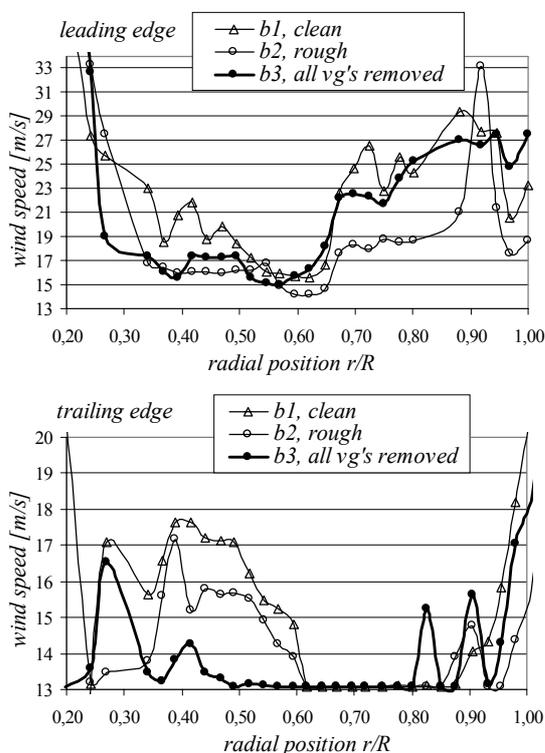


figure 4 Wind speed against radial position. The important observation is the difference of the leading edge signals of blade 2 with roughness, compared to the other blades. Between 0.65R and the tip blade 2 stalls at about 18 m/s while blades 1 and 3 stall at about 25 m/s (neglecting the peak in the signal of blade 2). This advance of leading edge stall corresponds to power losses of tens of percents. The peak at about 0.92R corresponds to the first stall flag radial beyond the tip division. Here there is much influence of the transient or the air-leakage through the slit. The trailing edge signals show the stall delay due to the vortex generators.

3.2 Validation of the Insect Hypothesis

The video with the stall flag signals was analysed with the image processing program. After sorting out the frames on tip speed ratio $\lambda = \Omega R/U$, the λ -value at which the stall flag switched between its two states was statistically determined. The variation of λ was caused by changes of Ω during starting and stopping the turbine. Figure 4 shows plots of the artificial wind speed $\Omega R/\lambda$

versus radial position. *Artificial* since it was not the wind that was changing but the rotation speed.

3.2.1 Stall Flag Results

We see in figure 4 that most stall flags on the leading edge of the rough blade switch over at 17 m/s on average, while those on the clean blade switch over at 21 m/s on average. It follows from this and other figures [5], that the roughness causes a large advance of stall in the wind speed range of 11 m/s to 25 m/s. As the influence extends over the entire span of all blades it can easily affect the power by tens of percentage points. Therefore it can explain the multiple power levels.

3.2.2 Time series of PV-data

Time series of the power P and the wind speed V of four different turbines were studied in detail in order to validate the Insect Hypothesis [5]. The power levels appeared to become lower after each period of low wind speed. This confirms the Insect Hypothesis, since the contamination increases during each period of low wind speed (insects fly) and this progressively reduces the stall level. We also observed one period of no wind, after which the power did increase. However it was discovered that the blades had been cleaned by lots of rain. So in this case the Insect Hypothesis was also confirmed.

3.2.3 Influence of Artificial Roughness on Power

Roughness (the same as before) was applied on the leading edges of all three blades, from 0.55R up to the tip of a turbine numbered 12-12. Another turbine, numbered 12-14, located 50 metres away, was left unchanged. We measured the power to see if different power levels would be obtained above rated wind speed, while the levels would be equal below rated wind speed. The results are shown in figure 5. We started taking measurements on October 8, 1999. On October 12 turbine 12-14 was cleaned, although it was not very

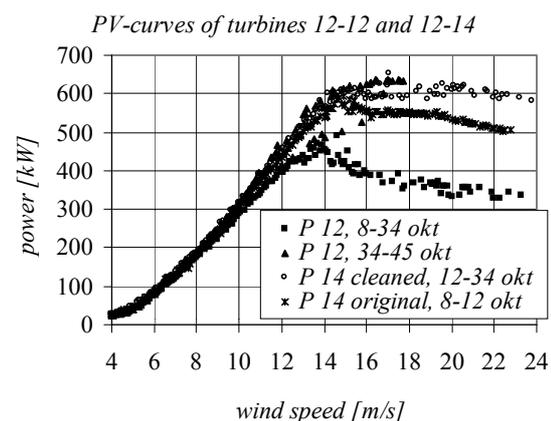


figure 5 Power curves of turbines 12-12 and 12-14. The measurements started on Oct. 8, 1999. Oct. 14 turbine 12-14 was cleaned and the power went up by 50 kW. Oct. 34 the artificial roughness was removed from turbine 12-12 and the blades were cleaned. Then 12-12 produced as 12-14. The power level was clearly roughness dependent, while the power below rated was much less affected. The level of 350 kW agreed with the lowest level measured during operation with lots of bugs on the leading edges.

contaminated. Its power level increased by about 50 kW. Then, on October 34 (we continue on the October scale), the artificial roughness on turbine 12-12 was removed and the blades were cleaned. The power increased by about 250 kW to the same level as turbine 12-14. When comparing figure 5 with the demonstration of the multiple power levels in figure 1 we see that they are similar, which confirms the Insect Hypothesis.

3.2.4 Arguments against the Hypothesis

Can the Insect Hypothesis be refuted? One may argue that contamination is a continuous process and that the stall level would therefore change continuously rather than showing distinct levels. In fact jumps from one power level to another are observed (e.g. the jump in figure 6), and how can this possibly be explained by blade contamination? However, this first argument is not valid, since contamination only occurs when insects fly and they do not fly when the turbine operates at its stall level. The jumps between power levels need not contradict the hypothesis either. They could be explained by 'the Tip Commands', but we have already shown that this model is not satisfactory. Within the Joule project 'MUST'[3] such a jump was observed once. The power jumped down to 75% along with a 20° change of the wind direction and it returned to the initial level when the wind turned back to its initial direction. We therefore

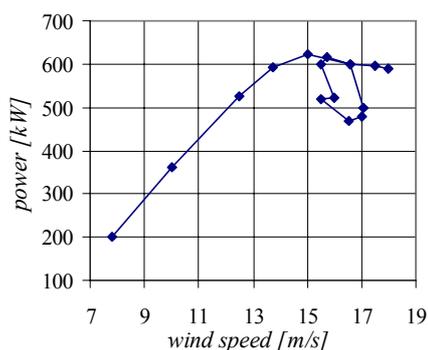


figure 6 A jump between power levels observed by Risø. The wind speed was measured on the nacelle and the points represent 10 minute averaged values. Yaw was not measured (pers. comm. F. Rasmussen), so the jump may be due to a temporal yaw error. Ref.: Madsen, H.A.; Bak, C.; Fuglsang, P.; Rasmussen, F. 'The Phenomenon of Double Stall', EWEC 97, Dublin.

think that this jump was caused by a failure of the yaw mechanism of the turbine. A turbine with a large yaw error should have large power variations. These are approximately proportional to $\cos^3 \theta_y$, θ_y being the yaw error, which gives $(0.94)^3 = 0.83$ for $\theta_y = 20^\circ$ or a reduction of $(0.996/0.906)^3 = 0.75$ for θ_y changing from 5°

to 25° . The wind direction always varies around its average, and this causes power variations that depend on the yaw error. Indeed, the measurement showed that the amplitude of the power variations became much higher after the wind direction change. So the jump could even quantitatively be ascribed to a yaw failure. One more argument against contamination is that wind tunnel experiments [11] have shown that roughness on the blades would not have large effects. But the roughness is often simulated at 5%*c*, while the insects mainly contaminate the airfoils around 0%*c*. This is a more sensitive domain, since it corresponds to the suction peak area at high inflow angles. Thus this argument is not valid either.

4. CONCLUSION ON MULTIPLE POWER LEVELS

The occurrence of multiple power levels can be explained by the 'Insect Hypothesis', which states that these levels correspond to different amounts of contamination caused by spattered insects on the leading edges.

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