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THE EFFECT OF TURBULENCE ON THE PERFORMANCE OF A SMALL WIND TURBINE

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ABSTRACT

The BEM method is used to predict the power produced by horizontal axis wind turbines. However, turbines produce more power than expected where the BEM method predicts the blades stall. What causes this "delayed stall" effect is difficult to determine. By comparing the performance of a small turbine in a low turbulence wind tunnel environment and in the natural turbulence of a field environment the effect of turbulence was observed. Higher turbulence levels increased performance in a way consistent with "delayed stall". Further work is being undertaken to quantify the effect of turbulence on aerofoil performance.

1. INTRODUCTION

Electricity production is the largest single contributor to greenhouse gas emissions in Australia (Australian Greenhouse Gas Office, 2000). Wind turbines have been adopted worldwide as an alternative to burning fossil fuels, e.g. Lemming & Anderson (1999) showed wind power produced 8.6% (2779 GWh) of Danish electricity supply in 1998. Predicting the aerodynamic performance of wind turbines is important in evaluating the power production of different designs. It also determines the strength and fatigue resistance turbines require to survive their design lifetime.

This paper will only discuss horizontal axis wind turbines (HAWTs), which are far more common than vertical axis designs. The Blade Element Momentum (BEM) method is commonly used to predict the aerodynamic performance of HAWTs; it uses the results of aerofoil section test to predict the aerodynamic performance of a rotating blade element. Due to the blades rotation and the expansion of the wake behind the rotor the angle of attack varies with the wind speed. As the wind speed increases the angle of attack increases.

The BEM method predicts performance well when wind turbines are operating at angles of attack below where the aerofoil sections stall in the wind tunnel and at small yaw errors (where yaw is the angle between the rotational axis of the turbine and the wind direction). Van Grol, Snel & Schepers (1991) (as quoted in Hansen & Butterfield (1993)) found that the BEM method predicts power and annual energy yield to an accuracy of ±8% for such conditions. However the BEM method consistently underpredicts the turbines performance at wind speeds that correspond to angles of attack above stall on the aerofoil section. Even turbines that pitch the blades (change their angle) to avoid stall do not avoid the extra load, as the pitching mechanisms are too slow to avoid stall conditions during wind gusts.

The data shown in Figure 1A is from NREL's 10 m diameter turbine, as reported by Simms *et al.* (1999). Each data point was obtained by selectively averaging data during periods of steady wind and minimal yaw. The averaged data represents less than 1% of the total measurements. In Figure 1B the same data is replotted in the non-dimensional form commonly used to compare the performance of different wind turbines. The power coefficient (C_P) is the ratio of the power produced to the power available in the wind.

$$C_P = \frac{P}{\frac{1}{2}\rho A V^3} \qquad (1)$$

where P is the power output, ρ is the fluid density, A is the rotor area and V is the freestream velocity. The tip speed ratio (λ) is the ratio of the speed of the end of the blades to the freestream velocity.

$$\lambda = \frac{\omega R}{V} \qquad (2)$$

where ω is the rate of rotation and R is the radius of the turbine rotor.

The large scatter at high tip speed ratios in Figure 1B is due to amplification of scatter in the low wind speed data by the unit conversion. Small errors in V are increased by the power in the C_P equation.

The circled areas in Figure 1A and B show where "delayed stall" occurs on a rotating turbine.

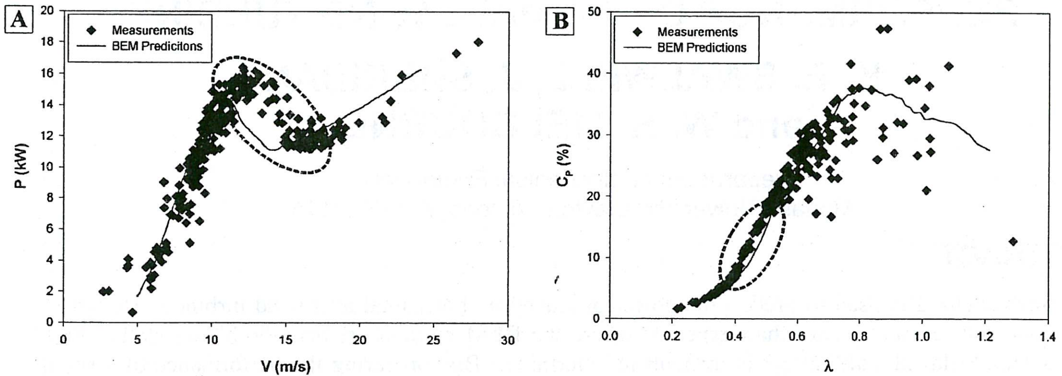

Figure 1 : The "delayed stall" region is circled in A and B which present the same data in dimensional and non-dimensional units respectively (data from the NREL Unsteady Aerodynamics Experiment Simms *et al.*, 1999).

The uncertainty in the loads at high wind speeds due to "delayed stall" means that turbines are frequently over designed to avoid failure. This increases the weight of the turbine and therefore the material cost of the turbine and tower. A better understanding of "delayed stall" could allow designers to make more accurate predictions and therefore minimise material costs. It may even enable designs that maximise the use of the increased power available in this region.

There are numerous theories about the cause of "delayed stall". Full scale experiments in natural wind have had difficulty quantifying the different effects. Madsen & Christensen (1990) examined a 19 m diameter turbine in the field and found "delayed stall" both when the blades were rotating and when they were not, although the maximum lift in the second case was lower. Blade sections tested in wind tunnels with controlled turbulence have also found "delayed stall", as shown in Figure 2.

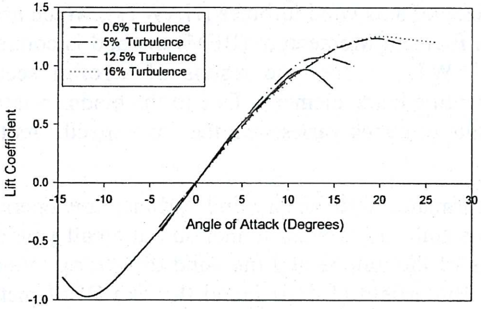

Figure 2 : Performance of a NACA 0006 Aerofoil in Turbulence at $Re_c \sim 2\times10^5$ (Jancauskas, 1983)

However, Simms *et al.*'s (1999) measurements in the low turbulence of the NREL baseline cycles and Clausen *et al.*'s (1987) wind tunnel study of a shrouded turbine also found "delayed stall". This seems to indicate that there are other important effects. Schreck *et al.*'s (2000) investigation found yaw also played an important part in the turbine response.

The current investigation compares the performance of a small turbine operating in low turbulence wind tunnel environment with the results obtained in a natural turbulence field environment to isolate the effect of turbulence on turbine performance.

2. EXPERIMENTAL METHOD

The data analysed in this paper was kindly supplied by Dr. Gholam Riahy Dehkordi (1999) who collected it as part of his doctoral thesis on designing a predictive controller for a wind turbine. He used a Rutland 910 wind turbine that had a variable rotational speed. The manufacturers specify this turbine produces a peak power output of 50 W at a wind speed of 10m/s. The turbine used was identical to that shown in Figure 3 except it had 12 mm wide metal struts between the blades (these were attached 107 mm from the end of the blades). Unfortunately the unusual construction of this turbine (thin blades and bracing between the blades) prevented use of the BEM method to predict performance.

The turbine was tested under different loads in the 450 kW wind tunnel at Monash University. To obtain the power curve the wind speed was held constant at 5.94 m/s and the load was varied resulting in different rotational speeds and therefore different tip speed ratios. The tunnel and turbine were run for 15 minutes to obtain a steady temperature. Then the power output and the resistances of the generator were measured and, by correcting for generator performance, the power from the blades determined. To get measurements near stall a dynamic controller was developed by Riahy & Freere (1997) to ensure the blades remained at an appropriate tip speed ratio.

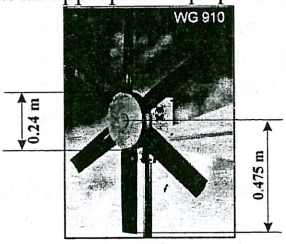

Figure 3 : Rutland WG 910

The field data was obtained using the same wind turbine placed on a tower on the roof. Three anemometers placed around the turbine measured the wind speed. The inertia of the blades caused changes in tip speed and power to lag the changes in wind speed during wind gusts. The field readings were averaged to minimise this effect. Most of the field measurements used were part of the testing of Gholam Dehkordi's load controller. This data was obtained from 24 hour runs with the controller alternately on (the high C_P data) and off (the lower C_P data). The number and size of these runs allowed a long averaging time (780 seconds). There was only a few short runs of data available at high tip speed ratios so this data was averaged over a relatively short time (200 seconds) to provide a reasonable number of data points in this region for the polynomial fit.

3. RESULTS AND DISCUSSION

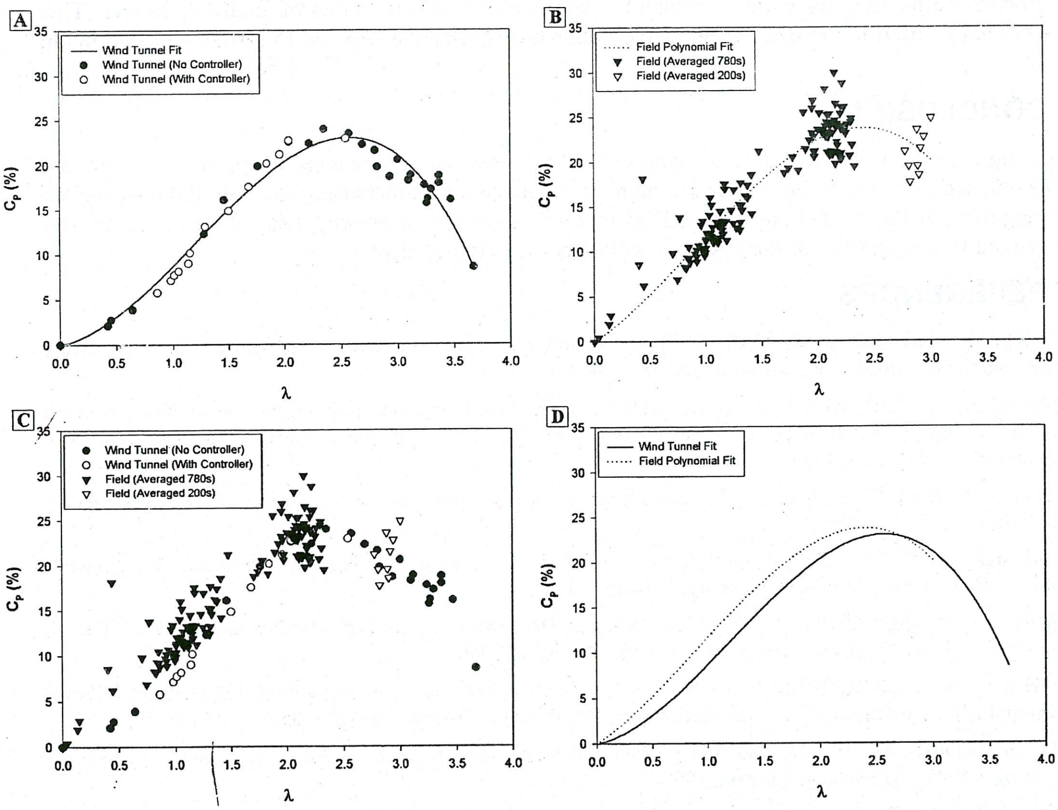

Figure 4 : Wind Tunnel and Field Data. (A and B show the wind tunnel and field data along with their respective fitted curves. C plots all the data points for comparison and D does the same for the fitted curves).

Figure 4A shows the measurements obtained in the wind tunnel. The data taken using the controller to maintain a constant rotational speed is indicated. A third order polynomial, constrained to pass through the origin, was fitted to the data to aid comparison (the equation is given below).

$$C_P = -2.315\lambda^3 + 8.403\lambda^2 + 2.622\lambda \qquad (3)$$

The field data, shown in Figure 4B, was averaged to minimise the effects of the inertia of the rotor on results. The polynomial fit was done in the same way as for the wind tunnel data; the fitted equation is given below.

$$C_P = -1.989\lambda^3 + 5.449\lambda^2 + 8.282\lambda \tag{4}$$

Figure 4C is a combined plot of both the wind tunnel and field data. In the "delayed stall" region the power coefficient for the field data is higher than for the low turbulence wind tunnel data. This can be seen more clearly by comparing the polynomial fits, as shown in Figure 4D. Unfortunately there was no field data at very high tip speed ratios so the effect of turbulence at tip speed ratios above three could not be evaluated.

The wind turbine investigated was an upwind turbine that used a tail vane to angle it into the wind. The placement in the field also had a predominately north-easterly wind whose direction varied little. These factors should ensure that any yaw error was minimal.

The 450 kW wind tunnel has a turbulence intensity of 0.06%, while the average turbulence intensity in the field was 18% (ranging from 9% to 36%). Figure 4 shows the performance in the stall region was altered by the turbulence levels. This change in performance with turbulence is worth further investigation.

4. FURTHER WORK

Turbulence is known to increase the lift and drag of aerofoils at high angles of attack. However there has been surprisingly little research done on the phenomena, presumably because it has little impact on the performance of aircraft aerofoils, whose motion effectively reduces the turbulence intensity encountered. It is planned to measure the effect of turbulence on a thick aerofoil section, similar to those used near the hub of wind turbines, the area of the blade that is predicted to stall first. Experiments are planned for various levels of turbulence over a wide range of angles of attack. This data will then be used in the BEM method and the predicted output compared to results obtained in the field.

5. CONCLUSION

Comparing the performance of a small wind turbine in a low turbulence wind tunnel environment and high turbulence field environment showed higher turbulence levels increased power in the stall region. This suggests that the predictions of the BEM method in the region where "delayed stall" occurs may be improved by accounting for the effects of turbulence on performance.

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