# Development and Analysis of a Novel Vertical Axis Wind Turbine

Paul Cooper and Oliver Kennedy
School of Mechanical, Materials and Mechatronic Engineering
University of Wollongong, Wollongong, NSW 2522,
AUSTRALIA
E-mail: pcooper@uow.edu.au

*Abstract*

*This paper describes the development of a novel vertical axis wind turbine used for teaching and research purposes. The device is designed to operate at low tip speed ratios and features blades that are symmetric about the mid-chord plane. The blades are actively pitched by means of a mechanical system so that the chord of each blade rotates by 180º for every revolution of the main rotor. One of the attractions of the device is that it is self-starting and produces relatively high torque. A multiple streamtube analysis of the device has been developed and numerical predictions for the performance of the device are presented. Commissioning and field tests of a prototype are described and some preliminary performance results are presented and discussed.*

## 1.INTRODUCTION

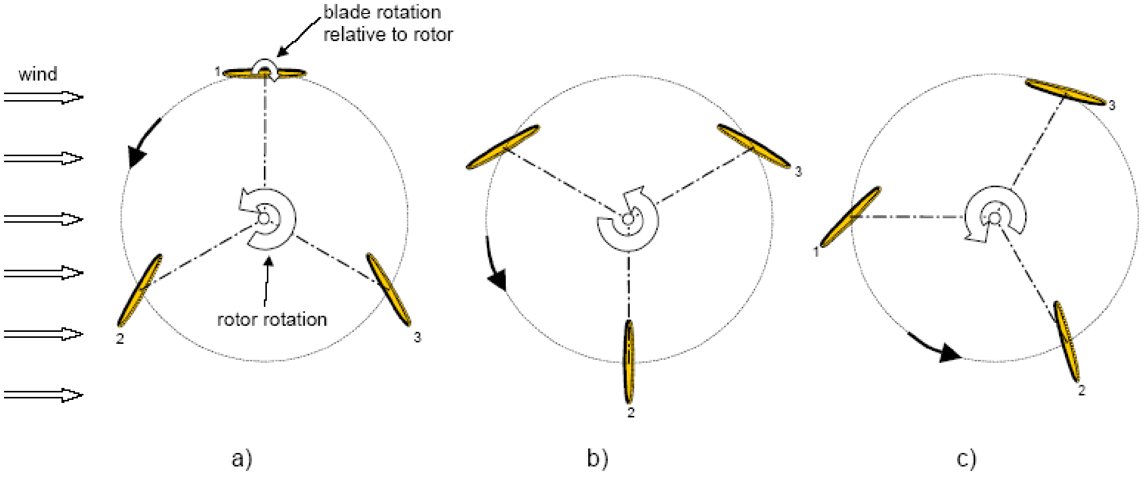
Wind energy is rapidly emerging as one of the most cost-effective forms of renewable energy with very significant increases in annual installed capacity being reported around the world. The favoured form of turbines used for electricity generation purposes is the Horizontal Axis Wind Turbine (HAWT) with low solidity ratio (ratio of blade area to swept area) and high tip speed ratio, $\lambda = \Omega R/V\text{wind}$, where $R$ is the radius of the blades and $V$wind is the wind velocity. This type of turbine has a high efficiency or coefficient of performance, $C$p, but relatively low torque. By contrast, the traditional "American Windmill" or "Southern Cross", used throughout Australia and the USA for water pumping purposes, is a high solidity, low tip speed ratio device that produces a high torque suitable for direct drive of relatively simple mechanical pump systems. The second major group of wind turbine types are the Vertical Axis Wind Turbines (VAWTs). A wide variety of VAWT configurations have been proposed, dating from the Persian VAWTs used for milling grain over a thousand years ago, through to the Darrieus turbine, invented in 1926 by Georges Darrieus, which has been used extensively for power generation. In fact one of the largest turbines ever built was the 96m high 64m diameter Éole Darrieus built near, Quebec, Canada, with a rated power output of 3.8MW and a rotor weighing 100tonnes. Other VAWT configurations include the Savonius VAWT, which is popular because of the simplicity of manufacture, and the straight bladed VAWTs. The latter include the Musgrove turbine that was developed culminating in successful testing of a 500kW device at Carmarthen Bay in the UK (Peace, 2004).

In Australia, Kirke (1998) reported on his extensive testing and analysis of a number of "giromill" type VAWTs with the blade pitch controlled so as to optimise the aerodynamic angle of attack on the blade aerofoils on both the upwind and downwind blade passes. Kirke's work culminated in the development and field-testing of two devices used for electricity generation. In New Zealand, Solwind Ltd have developed and are marketing a number of VAWTs for electricity generation. HAWTs have come to dominate the market for electricity generation for several reasons including low cost. However, VAWTs do have several inherent advantages over HAWTs including: VAWTs do not have to have a means of "yawing" (rotating about a vertical axis) to follow the changing wind direction; the generator (or other power takeoff device) can be located at ground level, reducing the structural requirements of the support tower. However, a disadvantage of most VAWT configurations is the fact that they have either low or insignificant starting torque, so that in the case of Darrieus devices, for example, the rotor must be brought up to speed either by using the generator as a motor or by means of a small secondary rotor, such as a Savonius, mounted on the Darrieus main shaft.

The present work was originally devised as a student project to examine the possibility of developing a small scale, high torque, self-starting VAWT for applications such as water pumping. In the following we outline the development of the concept of the novel turbine; the development of a theoretical model of the device; and the design, manufacture, commissioning and preliminary testing of the device

## 2. CONCEPTUAL DEVELOPMENT OF THE NOVEL TURBINE

The development of the “Wollongong Turbine” was initiated when a local inventor, Mr John Boothman, approached the present authors with a concept for a wind turbine and a working model with a swept area of approximately 0.25m2. The working model had a horizontal axis and a rotor with three blades with their axes held parallel to the main rotor axis. The blades were simple flat plates, the pitch of which was controlled by means of a chain and sprocket arrangement so that the blades rotated about their own longitudinal axes by only 180º for each full revolution of the main rotor. The motion of the blades is shown schematically in figure 1. Subsequent to the initial approach by Boothman a literature search revealed that a similar concept (with chain driven blade pitch control) had been mentioned by Golding (1976) but no evidence could be found of such a device having been theoretically modelled in detail or built



a) b) c)

**Figure 1. Plan view schematic of the orientation of blades and rotor of the novel VAWT.**

While at first sight this device appears to be a “drag” device where Blade 2 in figure 1a is clearly acting effectively as a plate perpendicular to the undisturbed flow of wind, it is also clear that liftforces on all three blades have the potential to act to generate positive torque throughout a complete revolution of the rotor. The working model of the horizontal axis device was tested in a wind tunnel and in the field by Riggall (1999). The results were promising given the relatively crude construction of the model, with coefficients of performance (efficiency) measured between 0.2 and 0.3. It was therefore decided to investigate the concept further with a view to providing an interesting research project for final year honours engineering students and a study of a fundamental aerodynamic problem.

The original proposal for the rotor axis to be located horizontally by Boothman was clearly not ideal for a working device since the machine would have to be made to yaw into the wind by some means, which would be both costly and structurally difficult. Two major design innovations were devised to bring the concept to a workable configuration. Firstly, the rotor axis was brought to a vertical orientation with a wind vane mounted on a control shaft to orientate the blades with changing wind direction. Secondly, Boston (2000) devised a system of bevel gears to replace the chains on the original working model that controlled the pitching of the blades. Thus, the configuration of the device was transformed to a VAWT with wind vane for orientation of the blade pitch mechanism as shown in figures 2 and 3a.

## 3. PRACTICAL IMPLEMENTATION

A practical implementation of the device outlined above was developed as a design exercise and as a demonstration of the concept for use in the Sustainable Energy Technology education program in the Faculty of Engineering, University of Wollongong. The major dimensions of the rotor/blade system were as follows: blade length, *L* = 2.4m; blade chord, *c* = 0.56m; rotor radius (to shaft supporting the blade), *R* = 1.0m; number of blades, n =3. One of the original concepts behind the configuration of the device was that the blades could be of relatively simple construction. However, since the blades rotate a full 360° relative to the wind during the blade profile chosen must symmetrical about the mid-chord plane. Although this meant that a flat plate could be used it was decided that for structural and aerodynamic reasons to use a more aerodynamically appropriate blade profile. The three blades were made from a skin of 0.8mm aluminium sheet formed over spars mounted a hollow aluminium bar running through the centre of the blade. The blade profile, shown in Figure 3b, was essentially the upstream half of a NACA 0010 – 65 section reflected about the mid-chord.

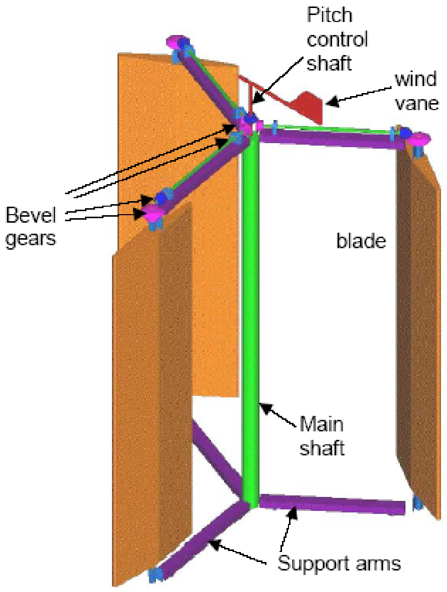


**Figure 2. Schematic of wind turbine design.**

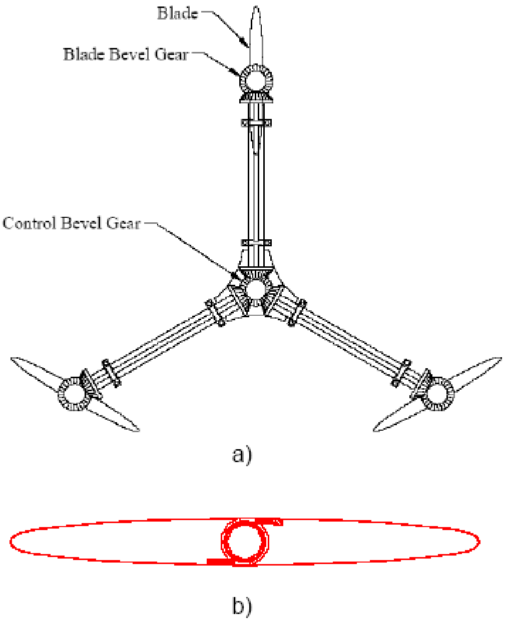


**Figure 3. a) Plan view of the pitch control mechanism mounted on the upper support arms. b) Cross section through a blade.**

The blades were suspended between the upper and lower support arms, which, in turn were mounted on a 139mm OD "main shaft" with two concentric inner shafts. The wind vane was mounted on the innermost "wind direction" shaft. This was mechanically locked with the "intermediate shaft" on which was mounted the "control bevel gear" to activate the blade pitch mechanism. The relative orientation of the wind direction and intermediate shafts design that they could be adjusted through 90º to bring the blades into a "furled" position so as to provide a means of reducing the torque output of the rotor to zero as shown in Figure 4.

The entire rotor system was mounted on a substantial 3m high steel lattice tower which could be tilted by means of hydraulic rams to allow easy access to the rotor assembly and so that the turbine could be lowered when not undergoing field tests. For reasons of security the arrangement was located on top of a multi-storey car park approximately 10m high. The torque from the main rotor shaft was taken via a two-stage 14:1 belt drive to a specially built three-phase, 240v, permanent magnet ac generator. A purpose-built control system was connected between the generator and a resistive load whereby the control system could be set to maintain an approximately constant rotational speed of the turbine with varying wind speed. The ac output from the generator was converted to dc, which was then fed to the resistive load via pulse width modulation of thyristors. Mechanical power output from the rotor was measured by mounting the generator on trunnion bearings so that the torque transmitted to the generator shaft could be measured by means of a torque arm and load cell. Angular velocity of the shaft was measured by means of an encoder. A DataTaker 50 data acquisition system was used to monitor the following parameters: the torque and rpm of the generator; the orientation of the turbine wind vane; and the wind speed/direction and air temperature from a weather station located approximately 5m from the turbine. The sample rate for these measurements was 1Hz, however, higher speed data acquisition utilizing a Sony PC 208AX Dat Recorder at a speed of 100Hz was also carried out.

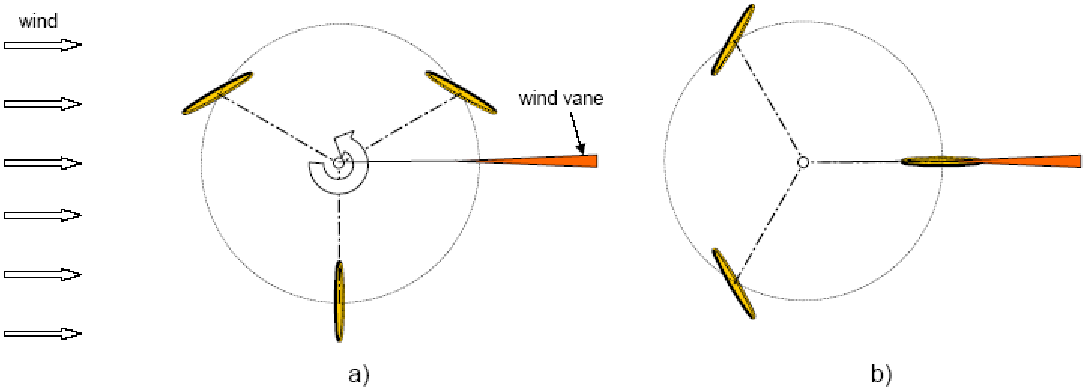


**Figure 4. a) Wind vane alignment for power production. b) Vane set for blades in "furled" position.**

## 4. THEORETICAL ANALYSIS

The multiple-streamtube model is a well established technique for prediction of the performance of VAWTs and is similar in many ways to that used for HAWTs. The objective of this type of analysis is to simultaneously determine the forces acting on the blades of the turbine by "blade element analysis" and the slowing of the wind that occurs due to the energy extracted from the air flow by the turbine through "actuator strip" theory (Sharpe, 1990). As the rotor of the VAWT revolves, the blades trace the path of a vertical cylinder known as the "actuator cylinder". As the wind intersects this cylinder so it must slow and any given streamtube of rectangular cross section must expand horizontally as shown schematically in Figure 5.

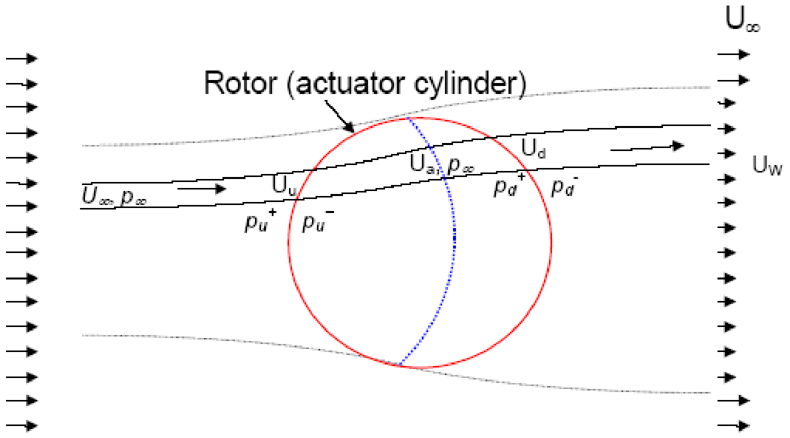


**Figure 5. Plan view of the "actuator cylinder" used to analyse VAWTs (after Sharpe, 1990).**

The multiple-streamtube analysis is relatively straightforward conceptually, but somewhat complex to implement, requiring many iterative calculations even for VAWTs with fixed blades. In the case of the "Wollongong Turbine" the trigonometry and resulting formulation of the blade element and actuator cylinder analyses was complicated further by the fact that the blades rotate relative to the rotor radius. However, Whitten (2002), developed a system of tracking the major geometric parameters for a single blade rotating about the rotor axis as shown schematically in Figures 6 and 7 so that the lift and drag forces, $L$ and $D$, respectively, could be determined and hence the torque, power output and mechanical efficiency of the rotor could be determined. Here the symbol $\beta$ represents blade azimuth angle, $\varphi$ the angle between resultant wind velocity, $W$, and blade velocity ($\Omega R$), $\alpha$ is angle of attack, $\gamma$ is the blade pitch angle and $\theta$ is the angle between the streamtube and the rotor radius.

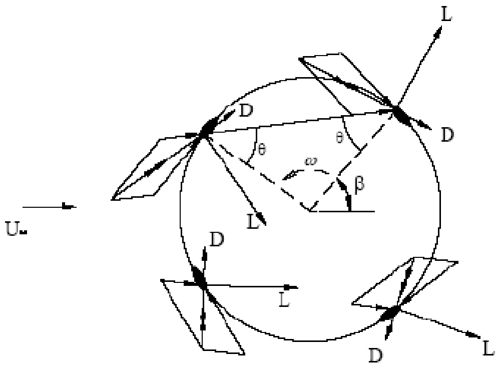


**Figure 6. Lift and drag forces acting on a blade of a VAWT.**

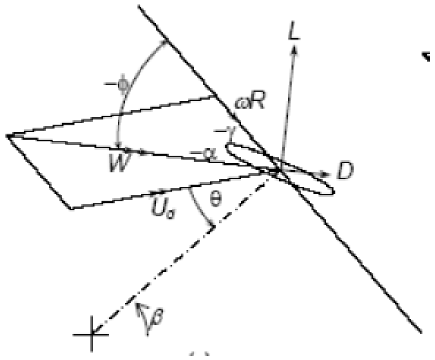


**Figure 7. Nomenclature used to represent the geometry of the variable pitch blade for the Wollongong Turbine (upper right quadrant).**

The analysis carried out by Whitten (2002) must be viewed as preliminary for a number of reasons, including the fact that lift and drag data were not available for the symmetric blade profile used in practice. As a starting point Whitten used lift and drag data for the NACA0012H blade (Sheldahl and Klimas, 1981) and interpolated for both angle of attack and Reynolds number. Other limitations of his analysis include the fact that no tip losses were included.

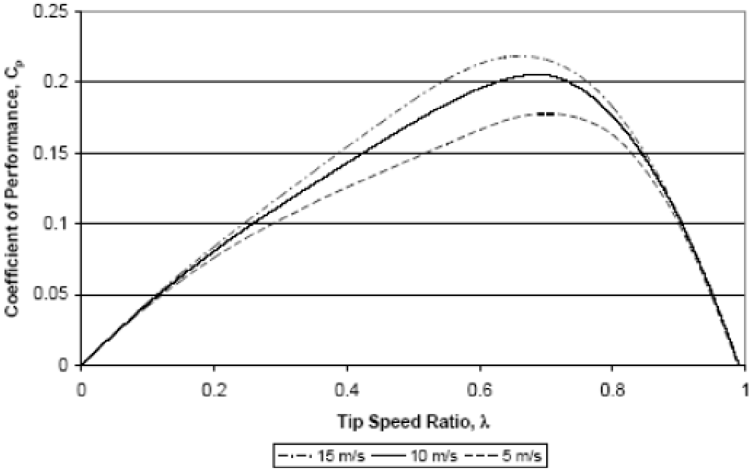


**Figure 8. Performance of the Wollongong Turbine predicted for three wind speeds, assuming blade lift and drag data can be approximated by that for NACA0012H (Whitten, 2002).**

The coefficient of performance of the turbine rotor predicted by Whitten's analysis is presented in Figure 8 which shows $C_p$ as a function of tip speed ratio, $\lambda$ , for a three-bladed rotor with dimensions of the rotor as built (but with lift and drag data for NACA0012H blade profile). Three wind speeds are given to show the relatively strong influence of blade Reynolds number on turbine performance. It should be noted that these performance predictions do not include aerodynamic losses (eg from windage losses on the non-streamlined support arms) or other frictional losses. Whitten estimates that these would further decrease the performance to $C_{p,max} \sim 0.15$.

As one might expect, the device is predicted to produce useful power output only for low tip speed ratios ($\lambda < 1.0$) since large losses would arise otherwise (eg for $\lambda > 1.0$ Blade 2 in Figure 1b would be moving faster than the undisturbed wind). The maximum efficiency is approximately 0.2 at $\lambda \sim 0.65$, which is rather low compared with published data for other configurations and is only equivalent to that of the Savonius rotor (eg Ackermann and Söder, 2002). Nevertheless, the Wollongong Turbine is predicted to have a high starting torque due to the active pitching of the blades

**Figure 9. The practical implementation of the novel VAWT.**

## 5. FIELD TESTS

The prototype of the Wollongong Turbine was installed at the University of Wollongong Engineering Innovation and Education Centre and is shown in Figure 9. A number of preliminary tests have been carried out on the device, which has operated successfully. In particular, the device has a very strong torque characteristic at low tip speed ratio, which means it is self-starting and may lend itself to applications such as water pumping. In addition, the rotor generates very little aerodynamic noise due to the low blade tip speeds. However, difficulties with commissioning of the torque measurement and control systems have delayed the acquisition of definitive test data to date. In addition, the test the wind regime at the test site is far from ideal since the presence of buildings and other topographic features nearby result in a high degree of turbulence, which has made steady state performance tests very difficult.

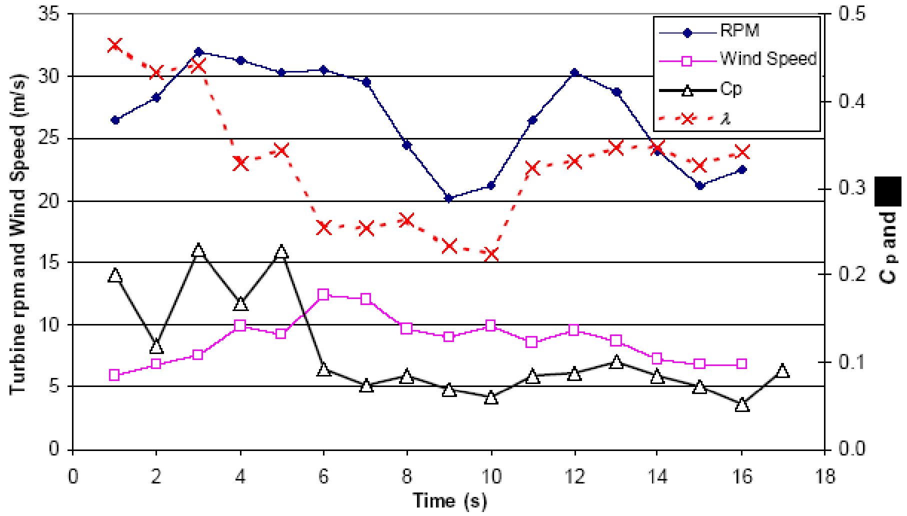


Figure 10. Example of preliminary results from field testing of the turbine.

The data presented in Figure 10 is an example of the preliminary performance data that have been derived from raw wind and torque/speed data from the turbine collected by Parker (2003). The numerical values of $C_p$ shown in Figure 10 have been calculated from the raw wind speed, torque and rotational velocity data accounting for changes in the turbine rotational speed with time and hence stored rotational kinetic energy. *In situ* experiments were conducted to determine the substantial moment of inertia, $I_{rotor}$, of the rotor and generator system ($I_{rotor} \approx$ 105kg-m$^2$). To determine the angular acceleration of the turbine was calculated from the raw data using the Douglas-Avakian numerical differentiation scheme. A plot of rotor efficiency, $C_p$, versus tip speed ratio, λ, is shown in figure 11. There is a large scatter in the data due to in part the turbulent wind regime at the test site, however, the turbine is shown to be operating in the approximately the region shown predicted by the multiple streamtube analysis.

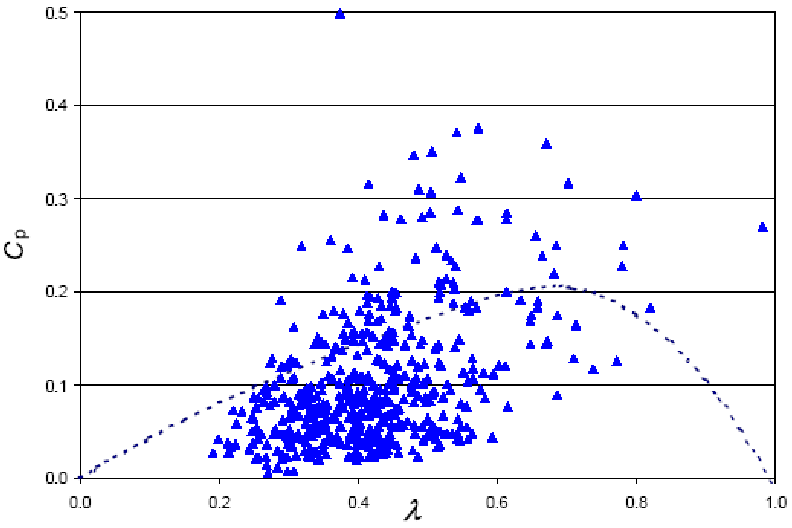


**Figure 11. Preliminary results from field testing of the turbine where $C_p$ is the coefficient of performance and λ is the tip speed ratio. The dashed line is the predicted efficiency of the turbine at 10m/s from the multiple streamtube analysis of Whitten (2002).**

The project has proven to be a very useful tool for education of senior Mechanical Engineering students interested in careers in Sustainable Energy Technologies. Indeed, one of the students involved in commissioning of the demonstration device has subsequently gone on to project manage one of the largest wind farm developments in Australia.

## 6. CONCLUSIONS

The concept of a novel vertical axis wind turbine has been developed and practically demonstrated. The blades of the turbine rotor are symmetric about their mid-chord and rotate 180º about this point for every complete revolution of the rotor. A theoretical analysis of the concept has been performed using a multiple streamtube/blade element analysis, which has shown that the device is likely to have only a modest maximum efficiency with $C_p$ of order 0.25. However, the device has been shown to have a high startup torque, which may be suitable for applications such as pumping.

A practical demonstration of the device has been designed and built by students. Preliminary tests have confirmed that device does indeed self-start with a high torque and generates useful power in a tip speed range of between 0.2 and 0.8. Further testing is required to confirm these initial tests. The project has proven to provide very successful training in wind energy for engineering undergraduate students.

## 7. ACKNOWLEDGMENTS

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