Project Summary Report
Design of a Low Wind Velocity Wind Turbine For Powering Communications After A Natural Disaster

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During periods of mass displacement of persons it is often difficult to maintain communications between neighbouring communities and family members. A portable and self sufficient method of producing electrical power could solve this problem. A method of analysing the power output of a straight bladed vertical axis wind turbine was programmed. This was used to analyse the effect of the turbine radius, blade chord length and blade incidence angle on the power output. It was discovered that the published method for accounting for the velocity loss across the turbine was incorrect for a range of turbine dimensions. A wind tunnel test rig and data logger was also developed to experimentally test the output of a model wind turbine in a low turbulence wind tunnel. The ‘spin down’ method was used to calculate the turbine power coefficient, resulting in the full scale turbine (designed with the flawed analysis code) outputting sufficient power to charge one smart phone at a time. A full scale version of this turbine in 4m/s wind velocity would produce $3.38 \pm 0.52$ Watts. Developing an accurate method for accounting for the velocity loss across the turbine would enable the process followed in this project to be effective as a vertical axis wind turbine design tool.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>Turbine sweep area [m$^2$]</td>
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<tr>
<td>$a$</td>
<td>Induction factor [-]</td>
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<tr>
<td>$AR$</td>
<td>Aspect ratio of turbine [-]</td>
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<td>$B$</td>
<td>Number of blades [-]</td>
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<td>$c$</td>
<td>Blade chord length [m]</td>
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<tr>
<td>$C_{D0}$</td>
<td>Zero lift drag coefficient [-]</td>
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<tr>
<td>$C_{l,a}$</td>
<td>Aerofoil lift line slope [-]</td>
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<tr>
<td>$C_P$</td>
<td>Power coefficient [-]</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of turbine [m]</td>
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<tr>
<td>$H$</td>
<td>Turbine blade height [m]</td>
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<tr>
<td>$I$</td>
<td>Mass moment of inertia [kg/m$^2$]</td>
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<tr>
<td>$P$</td>
<td>Power [watts]</td>
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<tr>
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<td>Radius of turbine [m]</td>
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<tr>
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<td>Reynolds number [-]</td>
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<td>$T$</td>
<td>Torque [Nm]</td>
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<td>Wind velocity [m/s]</td>
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<tr>
<td>$\alpha$</td>
<td>Angle of attack [radians]</td>
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<tr>
<td>$\lambda$</td>
<td>Tip speed ratio [-]</td>
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<td>$\xi$</td>
<td>Angular acceleration [rad/s$^2$]</td>
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<td>$\rho$</td>
<td>Air density [kg/m$^3$]</td>
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<tr>
<td>$\sigma$</td>
<td>Rotor solidity $\sigma = \frac{Bc}{R}$ [-]</td>
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<td>$\phi$</td>
<td>Angular location of blade in cycle [radians]</td>
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<tr>
<td>$\omega$</td>
<td>Angular velocity [rad/s]</td>
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Subscript

$B$ Blade
$\text{res}$ Resistance
$T$ Turbine
$\infty$ Free stream value

I. Introduction

Periods of mass displacement of persons can result in significant strain on state and non-government organisations and their capacity to deal with the ongoing consequences of these situations. These situations can arise as a result of a natural disaster or conflict. Fourteen per cent of the estimated 65.3 million

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people who are currently displaced are in the Asia-Pacific region.\textsuperscript{1} During these periods of mass displacement, communications can be difficult to maintain. Frequently either the electricity infrastructure has been damaged or did not exist previously. For example, often the United Nations High Commission for Refugees will set up temporary accommodation facilities to house the displaced persons while waiting for a permanent solution. These camps are often assembled as cheaply and quickly as possible and aimed to provide the basic needs of its inhabitants. This often leads to a lack of communications systems to help the camp members reconnect with their families.\textsuperscript{1} A portable power source that can operate without the requirement to be resupplied with fuel (i.e. a petrochemical generator) would greatly assist the displaced persons in helping re-establish communication with family and community members and allow them the capacity to be proactive in sourcing their own solutions to housing and supply issues.

Such a device could enable mobile phones to be charged or could power a two-way radio. This set up could also allow remote villages to communicate back to larger centres with relevant situation reports or requests for assistance. Access to mobile phone charging facilities was recently identified as a priority area for the Australian Governments Department of Foreign Affairs and Trades (DFAT) emergency response capability.\textsuperscript{2}

Research was conducted to determine if there was a wind turbine that was suitable for this task. It was found that there were very few designs that were portable. Of these designs it was deemed that they were either too cumbersome to readily transport or were unsuitable for the likely wind conditions. Often the turbines needed stronger than locally expected wind velocities to produce their rated power. It was discovered that there was a definite need for a wind turbine that was capable of operating in low wind conditions. This research project is therefore dedicated to developing a portable and renewable source of electrical power for charging mobile phones or operating a two-way radio.

II. Project Outline

II.A. Aim

The aim of this project is to design, manufacture and test a portable wind turbine that is suitable for use in areas of low wind speed. The turbine needs to be designed specifically with low cost and portability in mind. During this design process mathematical analysis and then testing of concepts was carried out to determine the suitability of the design.

II.B. Power generation requirement

A typical modern ‘smart phone’ mobile phone charger requires 1 Ampere and 5 volts. This gives a required power output of 5 Watts. Assuming the overall performance of the turbine is 30\% efficient, a turbine projected area of 1\text{m}^2 and a wind velocity of 4 \text{m/s}, the turbine could concurrently charge two smart phones (turbine output being \approx 12 \text{Watt}). Modern smart phones also have large battery capacities resulting in a longer charge time. Non smart phone batteries have around half the capacity of a smart phone and hence will take less time to charge. Anecdotal evidence suggests it would be reasonable to assume that in the countries where this turbine is intended to be used the mobile phone users will have a higher proportion of non smart phones.

If the unit is being used to power a two way radio then the approximate 12 Watt output would be sufficient for all consumer grade two way radios researched.

In order to charge eight smart phones concurrently a power output of 48 Watts would be sufficient. As the analysis method employed does not account for system losses (such as bearing friction), a factor of 1.2 was applied to arrive at a final power output of 58 Watts.

II.C. Methodology

This is a design and test project. During the initial stages of the project significant research was conducted into the desirable characteristics of a small scale, portable wind turbine. It was then decided that some of the design parameters needed to be fixed in order to satisfy aerodynamic and portability requirements (for example blade height). The dimension variables of chord length and turbine radius were then analysed using a mathematical model. Based on the results of the modelling, a scale model of the turbine was produced using a rapid prototyping (3D printing) system before it was tested in UNSW Canberras low turbulence wind tunnel to verify aspects of the analysis as well as the experimental set up.
III. Literature review

An extensive review of the current literature on the topic of vertical axis wind turbines (VAWT) has been carried out to determine the suitable design parameters that will meet the requirements of this project.

III.A. Horizontal or vertical axis wind turbine

Wind turbines can have either a vertical or horizontal axis of rotation. Each orientation has its own set of advantages and disadvantages. Traditionally horizontal axis wind turbines have been developed for use in large-scale grid power generation systems. Horizontal axis machines require a yawing mechanism to keep the blades oriented towards the free stream flow. Their blade designs have complex twisted shapes to achieve optimum efficiency. This results in a time consuming and costly manufacturing processes. This is opposed to a Darrieus style, straight bladed vertical axis wind turbine (SB-VAWT), as shown in figure 1(a). This style utilises a simple constant chord, untwisted blade that requires no yawing mechanism. The ability for the turbine to operate without a yawing mechanism means that it is suitable for use in turbulent air flows, such as urban environments or close to the ground. The simple design enables the turbine to be packed down for transportation. The theoretical maximum coefficient of power that a wind turbine can extract from the airflow is known as the Betz limit. A VAWT has the same Betz limit as a horizontal axis wind turbine (HAWT). This shows that theoretically a VAWT can be as efficient as a HAWT.

These features make a VAWT a suitable design choice for a small-scale human portable turbine for rapid deployment in a humanitarian assistance and disaster relief (HADR) situation. It also allows for the flexibility of having a small sized turbine that can be dismantled and carried in a backpack then set up on a small pole. The same turbine could also be placed on a tall telescoping mast that places it into the higher energy flows further off the ground.

III.B. Wind speed

The 10m above ground level reference wind speed for use during the design process was conservatively estimated to be 5m/s using ocean wind data produced by the Remote Sensing Systems company using microwave sensing satellites. The assumption that the ocean wind velocity is suitable for the design of this onshore turbine is being made based on the Pacific Islands being relatively small and that the majority of applications for this turbine are in coastal areas.

Using the 10m wind velocity and the IEC61400-2 standard the wind velocity distribution was calculated as shown in figure 2(a). From this distribution the 4m above ground level (AGL) wind velocity is calculated as 4.1m/s. It can be seen that to gain 0.9m/s requires a significant hub height increase of 6m. This shows that a turbine capable of operating in 4m/s to 5m/s winds would increase its portability due to it requiring a smaller, easier to transport support structure.

Several wind velocities at different heights AGL were selected from the above distribution. These were then

![Diagram](image)

**Figure 1.** (a) The terminology associated with a vertical axis wind turbine components and (b) a schematic of the wind turbine set up for mathematical analysis showing the single stream tube of air (dashed line). Note the reduction in velocity after the turbine is a result of the induction factor \((a)\) as described in section IV.
analysed using a cumulative distribution function to determine the probability of the wind velocity at those particular heights, as shown in Figure 2(b). This distribution is based on the wind being modelled using a Rayleigh distribution. For clarity a reference line at 4 m/s has been added. At a hub height of 10m there is a 60% probability that the wind speed will be greater than 4 m/s. This diminishes to 48% at 4 m hub height. This is still deemed a suitable probability given the intended short-term use of the turbine and the fact that it will be connected to a battery system and is not designed to provide continuous power. It is therefore determined that the wind turbine design will be based around operating in a minimum wind speed of 4 m/s.

III.C. Aerofoil Selection

The selection of an appropriate aerofoil is an important part of the design process. The type of aerofoil chosen will affect the turbine’s ability to self-start in low wind speeds as well as the power it produces while operating. There are two main characteristics of the aerofoil that are important for the turbine design, the thickness and camber percentage. Early studies into aerofoils were predominantly focused around the NACA 4-digit series of symmetrical aerofoils, probably due to the prevalence of tabulated performance figures. A significant consideration for the design of a SB-VAWT is its ability to self-start. The turbine is required to operate in a wide range of locations as the HADR situation requires as well as be installed by unskilled labour. This is likely to result in situations where it is installed in a location where the average wind speed is low. This dictates that it requires good self-starting properties in low wind conditions. At lower tip speed ratios \( \lambda = \frac{R\omega}{U_\infty} \), the blade angle of attack (\( \alpha \)) often exceeds the stall angle for a large portion of the circular blade path, with two of the blades being in a stalled condition for much of the revolution. This condition can result in a negative torque causing the net work per revolution to be negative. Investigations into the use of symmetrical aerofoils have determined that thicker profiles perform better in lower Re flows due to their resistance to stall. This is in contrast to Hameed et al. who claim that NACA0015 would be more suitable than NACA0018. This study makes no mention of the Reynolds number but does specify that it was considering \( U = 8m/s \).

The support arm of the blade also needs to be considered. An aerofoil shape has approximately ten times less drag than a similar sized circular support arm. The support arm aerofoil will be operating at close to \( \alpha = 0^\circ \) for the entire revolution of the turbine. An aerofoil profile that has a low \( C_{D0} \) at \( \alpha = 0^\circ \) and shows a lack of sensitivity to surface roughness would be suitable. In this project, a NACA0015 symmetrical aerofoil is deemed suitable for this purpose. At low angles of attack its \( C_{D0} \) actually decreases slightly. This study will therefore focus on the performance of a NACA0018 profile blade and a NACA0015 profile support arm.
III.D. Solidity

The solidity can be varied by either altering the number of blades or the blades chord length. Two blades produce a higher $C_p$ and are best suited for higher wind velocity areas, while a 5 blade turbine is most suited to a lower wind velocity area (albeit producing a slightly lower $C_p$). This being said, there is no significant benefit to increasing the number of blades beyond three for the target wind conditions of this turbine. Utilising three support arms also makes the turbine structurally non-directional, resulting in reduced stress compared to a two-bladed turbine of the same chord length.

A study into the solidity of a VAWT by altering the chord of the blades determined that a higher solidity (out of the two studied) resulted in better performance. The performance of each of the blades was compared at the same Reynolds number and used the same aerofoil profile of NACA0022. Due to differences in the flow field the solidity of $\sigma = 0.34$ obtained a better $C_p$. The design of this turbine will therefore utilise a solidity of approximately $\sigma \approx 0.34$.

III.E. Aspect Ratio

A higher aspect ratio blade will have reduced induced drag. The bending stresses that each blade experiences depend on the square of $c$; therefore reducing the chord and having a higher aspect ratio blade is preferred for structural considerations. An aspect ratio of no less than 7.5 will be used in this design.

III.F. Rotor sweep area

The rotor sweep area ($A$) is the total area of the turbine projected onto a plane. It is defined as the height of the blades multiplied by the diameter of the turbine. The rotor sweep area dictates the maximum amount of energy that the turbine can extract through the formula:

$$ P = \frac{1}{2} \rho A U^3 \infty C_p $$

This formula shows that the power extracted is proportional to the area of the turbine (assuming a constant $C_p$). The aspect ratio of the turbine projected area is related to the rotor sweep area and is defined as the height of the blades divided by the diameter of the turbine. It has been shown that a $H/D = 1$ gives the best $C_p$, however a $H/D$ of 0.5 to 2 have very similar $C_p - \lambda$ curves to $H/D = 1$. A $H/D$ above one gives the turbine a more compact shape and is recommended for areas with limited room available. The proposed design shall have a $H/D$ ratio of between 0.5 and 2.

III.G. Chosen parameter and boundary conditions

The following is a summary of the chosen parameters for use in the theoretical analysis code:

- AR $> 7.5$
- $B = 3$
- $C_{l,\alpha} = 2\pi$
- $0.5 < H/D < 2$
- $Re \in [100,000, 200,000]$
- Solidity $\approx 0.34$
- $U_\infty = 4 \text{ m/s}$
- Aerofoil Blade: NACA0018, Support arm: NACA0015

IV. Applied Theory

In order to design a wind turbine with a particular power output, the ‘Single Stream Tube’ analysis technique was applied. This technique treats all the air flowing through the turbine as a single stream tube of air (shown in figure 1(b)). The relative wind velocity on the blade at discretised locations around the blade’s revolution is analysed and used to determine the tangential force contribution and thus amount of power produced by the blade using equation 2. The integral part of this equation was numerically solved at numerous blade locations through one rotation of the turbine.

$$ P = \Omega R H \frac{Bc}{4\pi} \rho \int_0^{2\pi} U^2_{rel}(C_l \sin(\alpha) - C_d \cos(\alpha))d\phi $$

A significant assumption in this analysis technique is that a single ‘induction factor’ is assumed for the complete rotation of the blade. The induction factor accounts for the deceleration of the free stream air
after it passes through the upwind face of the turbine. The induction factor range is $0 < a < 0.5$, with 0 meaning the flow is unaffected and 0.5 meaning the flow far downstream was stopped by the turbine blades.\textsuperscript{3} The induction factor is applied in the analysis as an average reduction in power output over the turbine revolution.

The analysis was conducted by keeping all the turbine parameters constant and computing the power output over varying blade chord lengths and turbine radii. The contour plot produced was then overlaid with the constraints selected from the literature review (summarised in section III.G). An example of this plot can be seen in figure 3(b). In an attempt to thwart the self-starting problem associated with SB-VAWTs, the blade incidence angle was adjusted to increase the turbines ability to self start and to increase the turbine power output.\textsuperscript{18} When the blade incidence angle was adjusted by small amounts (2\textdegree-3\textdegree) it was noted that the power contours changed significantly. This lead to the power output analysis code being extended to three dimensions to include blade incidence angle. This was calculated and plotted as an isosurface of power of 58\textdegree (as outlined in section II.B). This is shown in figure 3(a). This analysis showed that increasing the blade incidence angle allowed the turbine dimensions to be more compact. With the portability requirement in mind the incidence (inc) angle 0.16 radians (9\textdegree) was chosen. A contour plot with constraint overlay for $inc = 9\textdegree$ was computed and is shown in figure 3(b). To maximise the power produced in this configuration the dimensions of $R = 0.56$ and $c = 0.13$ were chosen, as shown with the blue dashed line in figure 3(b). To confirm that the highest power output from those particular radius and chord dimensions was being achieved, the integral section of the power formula was recalculated varying the incidence angles from 1\textdegree to 20\textdegree. The results of this are shown in figure 3(c). This analysis indicated that the maximum power output for the blade chord and turbine radius would be at 9\textdegree to 10\textdegree blade incidence. Therefore the parameters chosen from the analysis process were: $R = 0.56m$, $c = 0.13m$ and $inc = 9\textdegree$.

During further analysis into the angle of attack that the blades were experiencing it was noticed that the induction factor (approximated by equation 3) was not within the range suggested in the literature.\textsuperscript{3}

\[
\alpha \approx \frac{1}{16} \frac{BC}{R} C_{l,\alpha} \lambda
\]

(3)

For the purposes of this analysis the number of blades, lift line slope and tip speed ratio remain constant. This results in the remaining parameter of interest being the $\frac{C_l}{\Omega}$ ratio.

It can be seen in figure 3(d) that applying the induction factor considerably reduces the maximum angle of attack experienced by the blade to around the stall angle of $\approx 9\textdegree$ (‘calculated induction factor’ plot). As the rate of increase in drag considerably rises after 11\textdegree,\textsuperscript{19} the analysis code predicts a higher turbine power output due to the lower computed $\alpha$. According to the single stream tube model with a tip speed ratio of 4, the angle of attack should only be between the ‘induction factor = 0’ and ‘induction factor = 0.5’ plots in figure 3(d). This shows that for the turbine dimensions derived earlier and a 9\textdegree incidence angle the turbine will remain largely in the stalled region (above $\alpha \approx 9\textdegree$). The inflated induction factor also caused the relative velocity experienced by the turbine blades (equation 4) to be higher, thus increasing the aerodynamic lift calculated.

\[
U_{rel}^2 = \{\Omega R + (1 + a)V_\infty \sin(\phi))\}^2 + \{(1 - a)U_\infty \cos(\phi)\}^2
\]

(4)

These two factors result in the analysis code overestimating the power output of the turbine. Research was then conducted into commercially available SB-VAWT dimensions. It was found that similar scaled versions of turbines exist that do not give a $\frac{C_l}{\Omega}$ ratio suitable for an induction factor of less than 0.5. For this reason it is decided that this analysis method is not suitable for turbines of these dimensions, however turbines with these approximate dimensions will work. As this was discovered after the wind tunnel model was produced, the physical testing was conducted using potentially inefficient dimensions.

V. Wind tunnel testing

V.A. Wind tunnel model

A mounting system was designed and constructed using aluminium to mount the test piece in the UNSW Canberra Low Turbulence Wind Tunnel (LTWT). The hub, support arm and blades were 3D printed using polylactic acid (PLA) thermoplastic using a quarter scale model. The design incorporated a spacer between the support arm and the blade to enable testing of different blade incidence angles. The dimensions chosen for manufacture were determined using the analysis outlined above.
Figure 3. Plots showing (a) the 3D isosurface of turbine power output for a range of blade incidence angles, chord lengths and turbine radii; (b) the contour plot of turbine power output with the design constraints overlaid; (c) the aerodynamic contribution to the power produced by the turbine during one revolution with varying blade incidence angles and fixed blade geometry (c=0.13m and R=0.56m). 9-10 degrees incidence angle will produce the most power; and (d) the angle of attack experienced by the blade for one rotation with the induction factor theoretical limits applied as well as the value calculated by the analysis code.

V.B. Experimental set-up

A image of the experimental set-up is shown in figure 4. The differential pressure sensor is connected to the total pressure port of the pitot tube (which is upwind of the turbine) and the remaining atmospheric sensors are in the ambient air outside the tunnel. The object reflectance sensor fits into a slot in the side of the support structure under the wind tunnel and faces the VAWT drive shaft. A laptop computer running the ‘Arduino’ program collects the data using the serial monitor. At the completion of each test the data is saved as a .csv file for analysis in Matlab. The data logger was designed and constructed specifically for this project.

V.C. Measurement of turbine performance in low turbulence wind tunnel

The performance of the wind turbine was analysed for suitability in the low turbulence wind tunnel (LTWT) by experimentally determining the power curve of the design. This was be achieved by non dimensionalising the results by calculating the tip speed ratio (\( \lambda \)) and the coefficient of power (\( C_p \)) of the turbine. This is achieved by using the spin down method. The angular velocity of the turbine was measured during the spin down from full speed to zero angular velocity by a microprocessor that logged the time taken to complete each revolution as well as the wind tunnel velocity at the completion of the revolution. This method
initially utilises a spin down test without the blades attached (spun up with an electric motor) to determine the resistive torque of the system \( T_{res} = I_{NoBlades} \xi \). The test is then repeated with the turbine blades attached (spun up using wind velocity) and the torque produced from the blades \( T_B \) was computed using equation 5, where \( I_T \xi \) is for the whole turbine and test rig assembly.

\[
T_B = I_T \xi - T_{res}
\]  

(5)

It can be seen from this formula that it relies on accurately knowing the mass moment of inertia \( I \) of the rig with and without the blades fitted and does not allow for steady state operation of the turbine. The moment of inertia was calculated within the CAD program the turbine was drafted in. The measured weights of the final printed components was used to increase the accuracy of the component density.

VI. Test Results

VI.A. Self starting

One of the significant documented drawbacks of a SB-VAWT is the turbines ability to self start. During the testing of the turbine with a 9° incidence angle the turbine failed to self start. This is due to the turbine moving into a position during the initial very low tunnel wind velocities where two of the three blades are producing a negative torque that balances out the positive torque of the third blade. The turbine was able to start after a small, short duration external torque was applied to the drive shaft to move it out of this position. The turbine then accelerated to a stable operating angular velocity. The turbine was positioned in various starting angles (phi) but self starting was unable to be achieved. Further review into the ability of a SB-VAWT to self start revealed that for the NACA0018 blade profile an incidence angle of 3° gave the fastest acceleration to operating speed.\(^8\) The blade angle was adjusted on the wind tunnel model and then tested in the LTWT. In this configuration the turbine demonstrated reliable self starting ability with various starting angles (phi). The is due to the three degree incidence angle reducing the maximum angle experienced by the turbine to be much closer to the 9° angle of attack where the blade begins to exhibit stall characteristics.

VI.B. Results obtained from wind tunnel testing

The data obtained during the LTWT testing was analysed to determine the power curve of the test VAWT. Each data point consisted of a time interval for that particular revolution as well as a voltage output from the differential pressure sensor that indicates the wind tunnel wind velocity. The uncertainties in these measurements as well the uncertainties from the ambient pressure, temperature and the turbine dimensions was then carried through the remaining calculations using a Monte Carlo simulation with 10,000 normally distributed situations modelled. The mean and standard deviation of each data point was taken. Figure 5(a) shows the mean and standard deviation of each data point for a single test (in blue). A weighted moving average of the mean and standard deviation values was taken and is plotted with the red solid and dashed
Figure 5. Graphs showing (a) the test data obtained from a single test run with the moving mean and standard deviation applied (in red) and (b) the power curves obtained from seven test runs overlaid with their respective uncertainties. The red plots show good agreement with each other, while the blue plots have a slightly lower coefficient.

VI.C. Uncertainty quantification

There are three quantifiable uncertainties associated with this experiment: the uncertainty in the time measurement, the differential pressure measurement (for wind tunnel velocity) and the dimensional uncertainty in the wind turbine size. These uncertainties have been accounted for in the test results shown in figure 5(a) and 5(b). The error bars on the higher tip speed ratio results are larger because of the larger uncertainty in the wind velocity measurement. There is a 2.5% error in the value. The error associated with time also has a larger effect at higher rotational velocities. As the microprocessor measured time in milliseconds a 1 millisecond fluctuation (noise) in the output changed the rotational velocity measured. This is also seen as the increased scatter in the higher TSR points.

There were also several uncertainties that were identified that are much more difficult to account for. These uncertainties are likely to be the reason why the tests shown in blue in figure 5(b) are grouped slightly lower from the main grouping in red. The 3D printed components had uneven mass distributions and slight variations in the blade thickness. The thickness variations cause a slightly different amount of lift to be produced in different areas of the blade. This combined with the large load fluctuations on the blade during each revolution resulted in a significant vibrational mode being excited, which was unable to be absorbed or damped by the horizontal support arms. While the turbine was operating the support arms were oscillating with a stationary node at each end. During a practice wind tunnel run it was noted that the vibrational noise produced by the turbine spontaneously reduced considerably and the turbine was observed to accelerate to a much higher angular velocity. This condition was unable to be replicated in future test runs. From this observation it is believed that a more rigid model would be capable of rotating closer to the design tip speed ratio of 4, as opposed to the approximate maximum value of 1.2 demonstrated in the LTWT testing.

It should also be noted that at high angular velocities the turbine blades bent outwards, this would also effect the aerodynamic performance of the turbine.

VI.D. Power Output

The analysis of the power curve for the VAWT enables the calculation of the power output the turbine is capable of. The mean maximum power coefficient is \( C_P = 0.084 \pm 0.012 \). This results in a model turbine power output of 13.5 ± 1.97 Watts. A full scale version of this turbine in 4m/s wind velocity would produce 3.38 ± 0.52 Watts. This power output would be sufficient to charge one smart phone at a time. This is a
much lower value than what was desired due to the design being based on the flawed analysis code, as well as the excessive vibration.

VII. Future work

VII.A. Development of a suitable analysis code

It has been outlined in section IV above how the single stream tube method utilised does not apply to turbines of dimensions similar to the turbine tested, although such turbines do exist. This is because the current method of defining an induction factor does not produce a value between the required range for turbines with similar dimensions to those desired of this design. Due to this, further work needs to be conducted to determine a suitable method for accounting for the free stream airflow velocity loss across the turbine that allows for a wider range of turbine dimensions to be analysed. This would enable the single stream tube method to be applied more broadly to SB-VAWT design.

VII.B. Increased fidelity of angular velocity measurement

Increasing the fidelity of the microprocessor readings would result in a more accurate acceleration reading during slow speed operation of the turbine. The wind turbine LTWT model drive shaft could have more vertical lines on the shaft to trigger the interrupt on the microprocessor several times during each revolution. This would also require the microprocessor code to be modified slightly. Reducing the time scale used on the microprocessor to be smaller than milliseconds will also increase the accuracy of the readings and reduce the scatter of results seen at higher tip speed ratios.

VII.C. Improved Wind Tunnel Model

A more rigid wind tunnel model could potentially reduce the unquantifiable uncertainties associated with the experiment. This would allow a more accurate comparison between the wind tunnel results obtained and the theoretical analysis code.

VII.D. Comparison of Different Blade Profiles

A comparison of different blade cross sectional profiles could allow for a more economical manufacturing process. If a more simplistic design was able to provide the required power output then manufacturing cost and complexity could be reduced.

VIII. Summary

Significant progress has been made in designing a VAWT that is suitable for powering communication devices in low wind velocities. Desirable design constraints have been developed and an analysis code programmed. Further improvement to the calculation of the induction factor is required to enable accurate VAWT performance predictions. A wind tunnel test rig and data acquisition system has also successfully been implemented, allowing future research to be conducted into VAWT design. In spite of the erroneous power prediction code, a SB-VAWT was manufactured and successfully tested in a LTWT that is capable of charging a single smart phone with an output of $3.38 \pm 0.52$ Watts on a full scale version.

Acknowledgements

I would like to acknowledge the significant guidance I have received from my project supervisor, Mr Charles Hoke. Mr Hoke’s ability to visualise and troubleshoot my aerodynamic roadblocks and his insight into the research and design process helped me immensely during the course of my project. Mr Geno Ewyk and Mr Darryl Budarick’s assistance was invaluable in the programming and manufacturing of the data logger. I would also like to acknowledge the considerable assistance that Dr Murat Tahtali gave me during the CAD modelling and 3D printing of the model. Finally, I would like to thank Dr Jouke De Baar who greatly helped me with the uncertainty quantification in the experiment and with my results analysis in Matlab.
References