Wind Turbine Design Report

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Introduction

WindPac, a manufacturer of wind turbines, intends to develop a low-cost wind turbine to allow remote communities to have access to electricity.

The turbine is to operate in wind speeds from 8 to 14 knots. At the target wind speed of 10 knots, it is expected to provide 3.25 Nm of torque at an angular velocity of 140 RPM.

The diameter of the turbine cannot exceed 1.6m. A generator and hub, with radius 173mm is already available. The hub admits between 3 and 8 (inclusive) aluminium rods at a radial distance of 42mm. The budget for surfacing the blades is NZ$80.

Model Development

BEM

The basis of the design calculations is the Blade Element Momentum (BEM) algorithm. This iterative scheme calculates the loads on the blades, which is used to find the torque and power available from the wind. A required power, efficiency and angular velocity must be provided.

The scheme can be summarised as follows:

1. Known parameters are the airfoil shape (and its coefficients of lift and drag), the number of blades, and the target torque and angular velocity.

2. Calculate the radius, using power required, the upstream wind velocity and the Power Coefficient (power extracted/power available)

3. Divide the blade into a number of cross-sections and calculate the local speed ratios

4. Calculate wind angles and chord lengths at each section using the axial (a) and radial (a') induction factors. Calculate new values of a and a' using the wind angles.

5. Calculate tangential loads at each section. Torque is then calculated by numerically integrating load times radius with respect to radius. The power extracted is then found by multiplying the torque, the number of blades and the design angular velocity.

6. Repeat 4 and 5 until the Power Coefficient converges.

7. Return to step 2 and repeat using the new value of the Power Coefficient. Repeat until the values of Cp from step 6 converge.

The full equations can be found in the Appendix.

The BEM equations and all other calculations for this project were done with MATLAB.

Assumptions of BEM

Pressure differences lead to undesired air flows around the tips of the blades that reduce the lift generated, a phenomenon known as Prandtl tip loss. The calculations for a and a' in step 4 have been corrected to approximately account for this.

Wake rotation occurs when the wind behind the turbine rotates in the opposite direction to the wind in front. The equations for wind angle and chord length in step 4 are adjusted for this.

There are small efficiency losses from having a finite number of blades, leading to wind flowing between turbines and not being used for power generation. These losses are fairly small even when the number of blades is 3, the minimum number available for this project.

Aerodynamic drag is unavoidable. It is also likely that the generator will be subject to mechanical losses. The quality of the surface of the blades is of paramount importance, as a poor surface will increase drag and will not have the expected performance if the shape is flawed.

Airfoil Selection

The software Xfoil was used to select an airfoil shape. When given an airfoil shape, a Reynolds number (Re) and angle(s) of attach, Xfoil returns the coefficients of lift (C_l) and drag (C_d). While it can handle a wide range of airfoil shapes and angles of attack, it is particularly suited for 4 digit NACA airfoils. Additionally, these NACA airfoils have well-defined equations for their shapes and files containing co-ordinate points for their outline are easily accessible. A decision was made to restrict the search for an airfoil to 4 digit NACA airfoils.

The performance of an airfoil is highly dependent on the angle of attack and the Reynolds number. The Reynolds number is dependent on the length of the blade and wind velocity, which varies across the blade.

Therefore, simply maximising the ratio of lift to drag at a single Re is inappropriate. Minor errors of just one or two degrees in the construction of the blades, or a minor change in Re could lead to a very poorly performing wind turbine.

An objective function to quantify in a single number the performance of each airfoil was defined. The C_l/C_d ratio was calculated at two degrees above and below the target angle of attack for higher and lower Re (50,000 and 70,000)- four points in total. From the sum of these values was subjected the absolute difference between each of them and the ratio at the target angle of attack and approximate Re (60,000). Linear extrapolation was used if the lift-to-drag ratio was not known at a particular angle of attack.

Overall Structure/Manufacturing Method

For each blade, a number of profiles will be created by laser cutting acrylic sheets. These shall contain a hole, so that they can be glued to an aluminium rod. Each profile shall contain an angled slot, so that another rod can be inserted, ensuring they are in the correct orientation. A surfacing material shall be wrapped around this structure.

Surface

Besides the budget, the material for the surface of the blades needs to be smooth to minimise drag, and lightweight to minimise energy losses.

The material chosen was Ultracote, a commercially available shrink-wrap adhesive film. Ultracote has the advantage of being water- and weather- proof, an important consideration given the tropical climates the turbine may operate in.

Number of Blades

The number of blades is permitted to be between 3 and 8 inclusive. If the radius is 0.8m, then at 140 RPM the tip speed ratio is about 2.3. This relatively low value suggests a higher number of blades would be better.

The number of blades chosen was 6. This choice of a higher number of blades means a smaller radius, narrower blades, and a reduction in inefficiencies related to the finite number of blades. It should be easier to get a smooth surface on a smaller blade, however more blades results in parts of the assembly and construction taking longer.

Sustainability and Society

From a sustainability perspective, this project is very positive as it establishes a renewable, non-polluting source of energy. In the absence of this project, developing communities may pursue environmentally harmful energy sources such as burning wood or fossil fuels. Access to electricity would allow these communities to have lighting, heating and machinery, permitting economic development and improved living standards. An efficiently and accurately designed wind turbine will maximise these benefits.

A negative aspect of the design is the Ultracote surfacing, whose manufacture is environmentally damaging and if damaged or removed could become litter. This is unavoidable, as it is very difficult to get a smooth surface using materials other than plastics and films.

Design Calculations

Airfoil Selection

Theoretically, there are 10^4 possible 4-digit NACA airfoils. Even if very cambered foils (high 1^{st} digit), awkwardly positioned cambers (high 2^{nd} digit), or very thin or thick foils (low or high $3^{rd}/4^{th}$ digits) are not considered, the number of candidate solutions is still many hundreds. Xfoil takes many seconds, and often over a minute, to evaluate the lift and drag ratios for each airfoil. Some airfoils cause Xfoil to “freeze”. Running Xfoil on every possible foil is not feasible.

Therefore, a Genetic Algorithm metaheuristic was used to maximise the objective function. The 1^{st}, 2^{nd} and $3^{rd}/4^{th}$ digits were considered as discrete units that the algorithm could adjust or mutate. The number of “generations” was set to 20, and the number of “individuals” to 5; all other settings were the MATLAB defaults.

The output from the Genetic Algorithm was not used unquestioned, but the practicality of getting a good quality surfacing was also considered. The graphs of lift/drag at different Re and angles of attack were viewed for each candidate airfoil.

The chosen airfoil was NACA3614. This airfoil has a maximum camber of 3%, which occurs at 60% of the distance from the leading edge to the end of the foil. The maximum thickness is 14% of the chord length. The intended angle of attack is 8°.

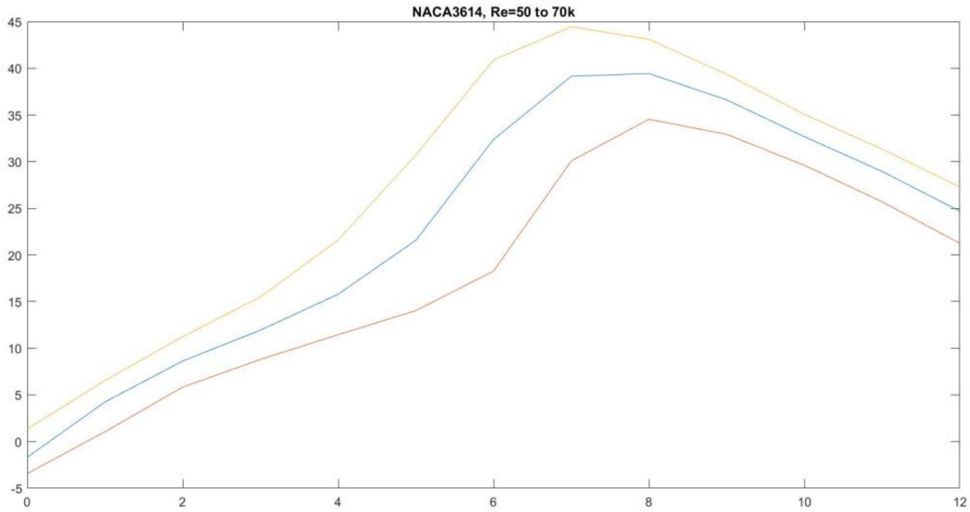

Figure 1: Cl/Cd ratio for NACA3614, plot generated by MATLAB, Re=50,60 and 70 thousand.

Chord Lengths

Once the airfoil and number of blades was determined, BEM could be used to determine chord lengths. Due to the previously mentioned 173mm radius zone in the middle of the turbine that cannot be occupied by blades, there is a 180mm clearance in the center. See the Appendix for the shapes of the blade profiles and an Assembly Drawing.

Distance from Center (m)	Chord Length (m)	Blade Setting Angle(°)
0.180	0.1649	33.9
0.234	0.1742	29.5
0.289	0.1747	25.7
0.343	0.1702	22.4
0.398	0.1632	19.6
0.452	0.1551	17.2
0.507	0.1468	15.1
0.561	0.1386	13.3
0.616	0.1309	11.8
0.670	0.1237	10.4

Performance

While the BEM algorithm was used with a wind speed of 10 knots and an angular velocity of 140 RPM, the wind turbine must also operate at other speeds. BEM was modified, with the radius, chord lengths and blade setting angles (β) now fixed. For wind speeds 8, 10, 12 and 14 knots, at angular velocities from 50 to 250 RPM, the angle of attack (α=φ-β) was calculated at each cross-section, and Xfoil used to find the coefficients of lift and drag at different angles of attack. The equations for the tangential load were used without iteration to find the torque. Changes in Re were not considered.

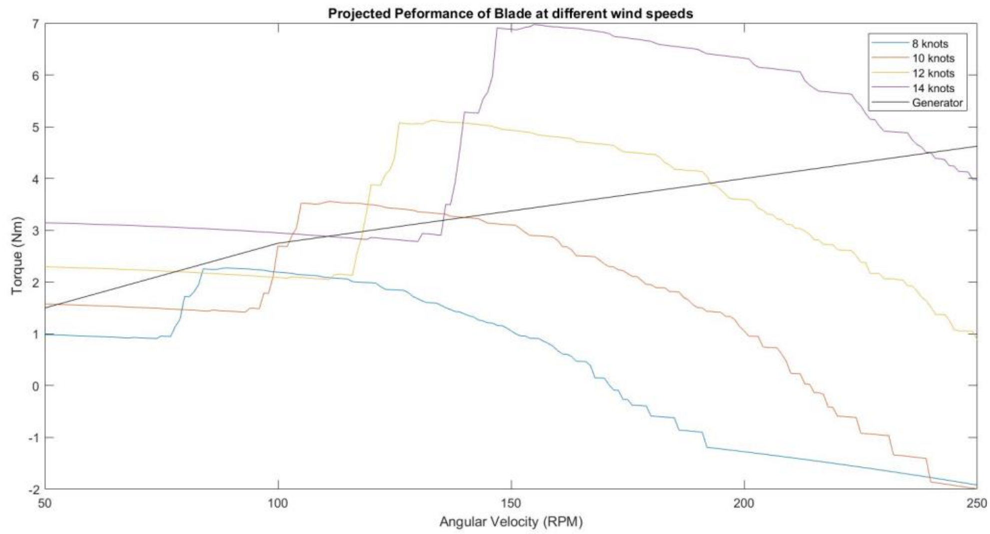

Figure 2: RPM v torque for 4 different wind speeds and the generator

If the turbine is to reach a state of equilibrium when running the generator, it will spin at about 240 RPM at 14 knots, 190 RPM at 12 knots and 140 RPM at 10 knots. At 8 knots, there may be difficulty generating enough torque for the generator. If it spins, a speed of 85-90 RPM is most likely.

Manufacturing costs

The following table details the costs to manufacture a complete turbine:

Material	**Unit Cost**	**Total Cost**
2 0.605x0.4x0.003m Acrylic sheets	$6.36/sheet	$12.72
6 Aluminium rods, 0.7m each	$3.20/m	$13.44
Hub	approx. $150	$150.00
6 Rod-Hub Connectors	$5.71/unit	$34.26
Acrylic Glue	$24.67/tube	$24.67
Ultracote- 1 sheet	$45	$45.00
	TOTAL	**$280.09**

Appendix

BEM equations

In Step 2, we calculate an overall radius R:

$$R = \sqrt{\frac{2P_s}{C_p \mu \rho \pi {v_u}^3}}$$

Where P_s is the required power, C_p the power coefficient, μ the efficiency, ρ the density of air, and v_u the upstream velocity.

In Step 3, we calculate local speed ratios λ_r:

$$\lambda_r = \frac{\Omega r}{v_u}$$

Where Ω is the angular velocity and r is the radius of the cross-section.

We then calculate the local wind angles ϕ. This equation is adjusted for wake rotation.

$$\varphi = \frac{2}{3}\arctan(\frac{1}{\lambda_r})$$

In step 4, we then calculate the chord lengths c at each cross-section:

$$c = \frac{8\pi r}{BC_l}(1 - \cos\varphi)$$

Where B is the number of blades and C_l the coefficient of lift.

To simplify subsequent equations we define:

$$C_n = C_l \cos\varphi + C_d \sin\varphi$$

$$C_t = C_l \sin\varphi - C_d \cos\varphi$$

$$f = \frac{B(R - r)}{2r\sin\varphi}$$

$$F = \frac{2}{\pi}\arccos(e^{-f})$$

$$\sigma' = \frac{Bc}{2\pi r}$$

Where C_d is the coefficient of drag, and σ' is the solidity.

When then calculate the axial induction factor a at each cross-section:

$$a = \frac{\sigma' C_n}{4F\, sin^2\, \varphi + \sigma' C_n}$$

In step 5 ,we then calculate the tangential load p_T:

$$p_T = 0.5\rho \frac{{v_u}^2 (1-a)^2}{sin^2\, \varphi}\; C_t c$$

We can the find the total torque Q, numerically integrating using the trapezium rule:

$$Q = B \int_0^R p_T\, r\, dr$$

The new value of the power coefficient is:

$$C_p = \frac{2Q\Omega}{\rho \pi R^2 {v_u}^3}$$

The denominator being twice the total amount of power in the wind.

Blade Cutting File

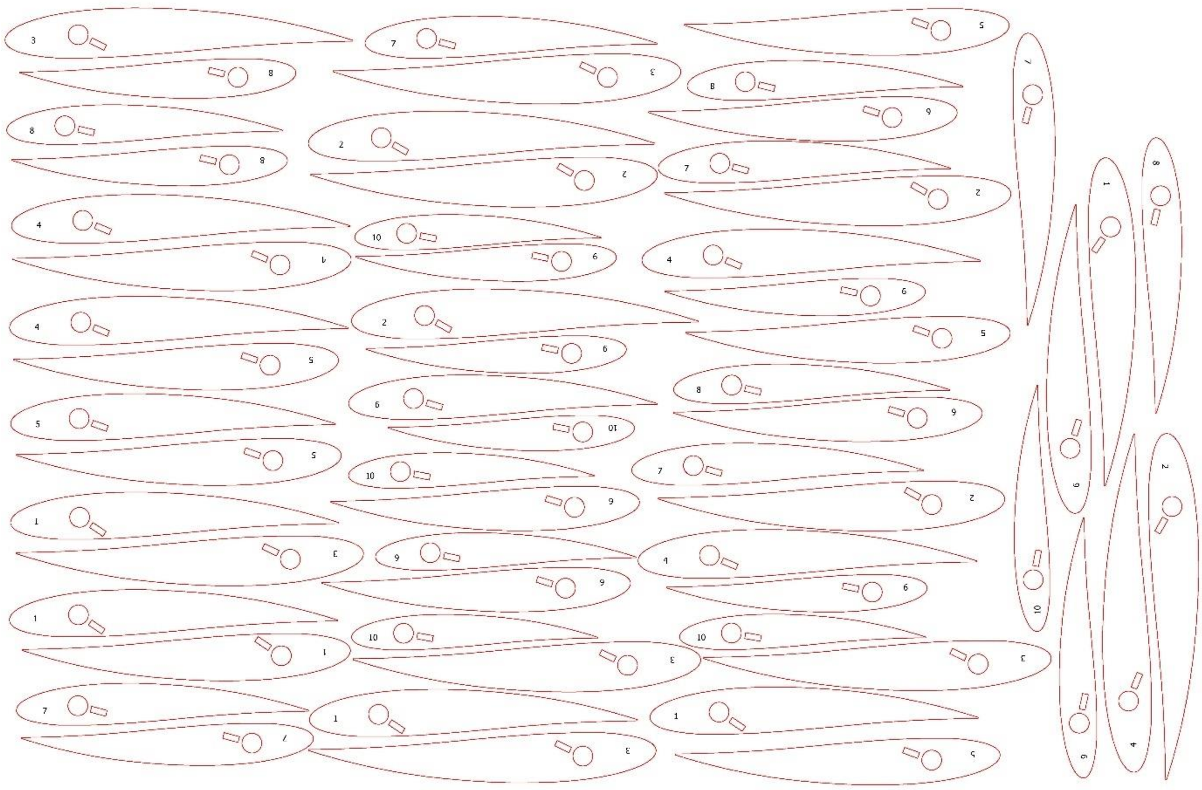

Figure 3: Laser-cut acrylic sheet. Red lines cut, black lines engraved

Assembly Drawing

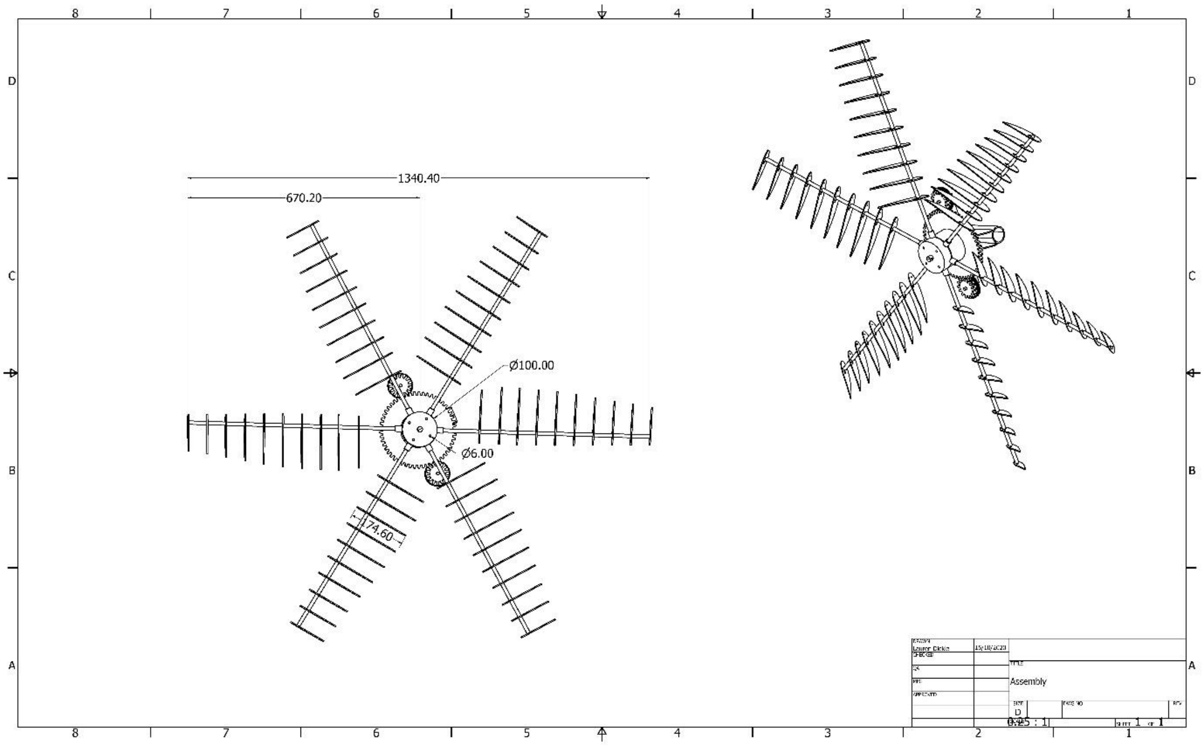

Figure 4: Assembly Drawing. Note blade setting angles not shown