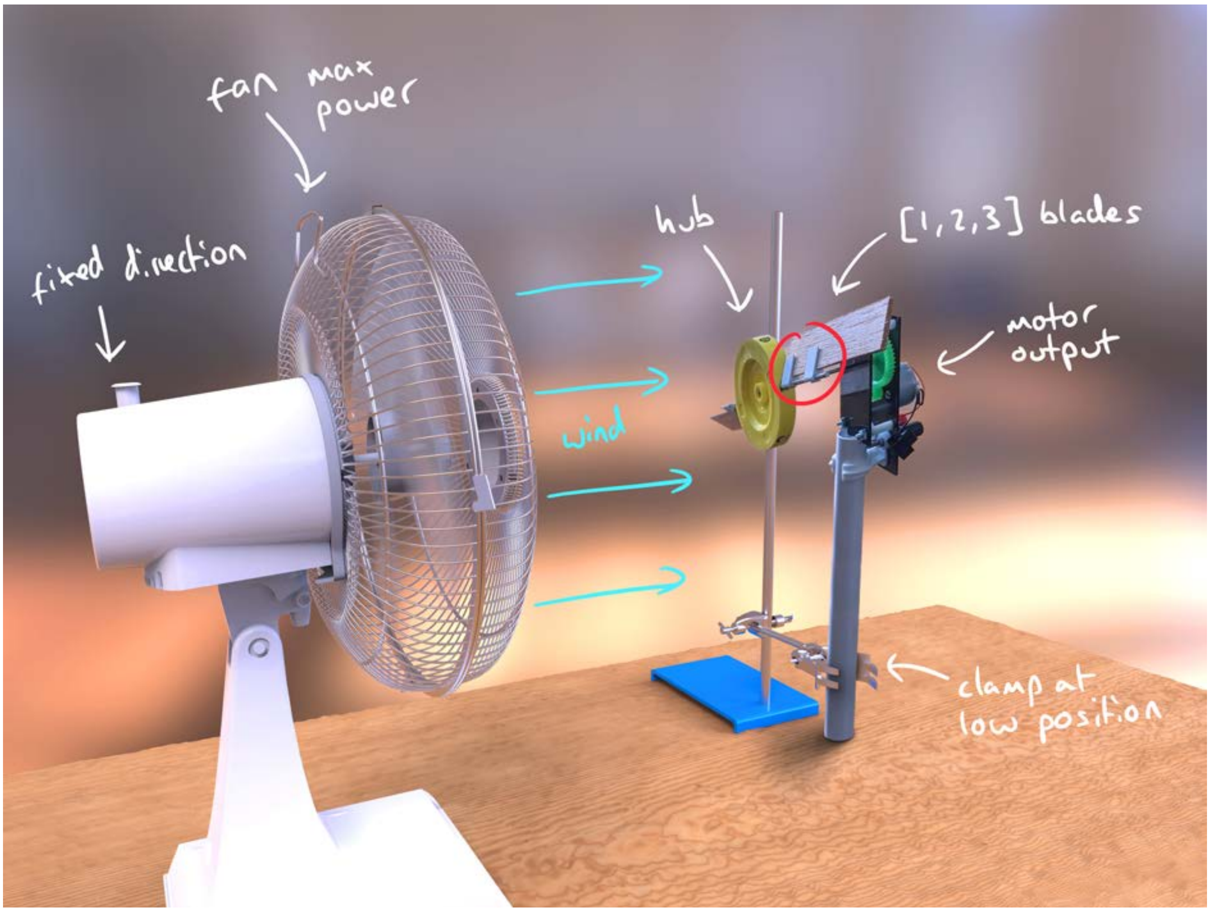
Assignment 1b

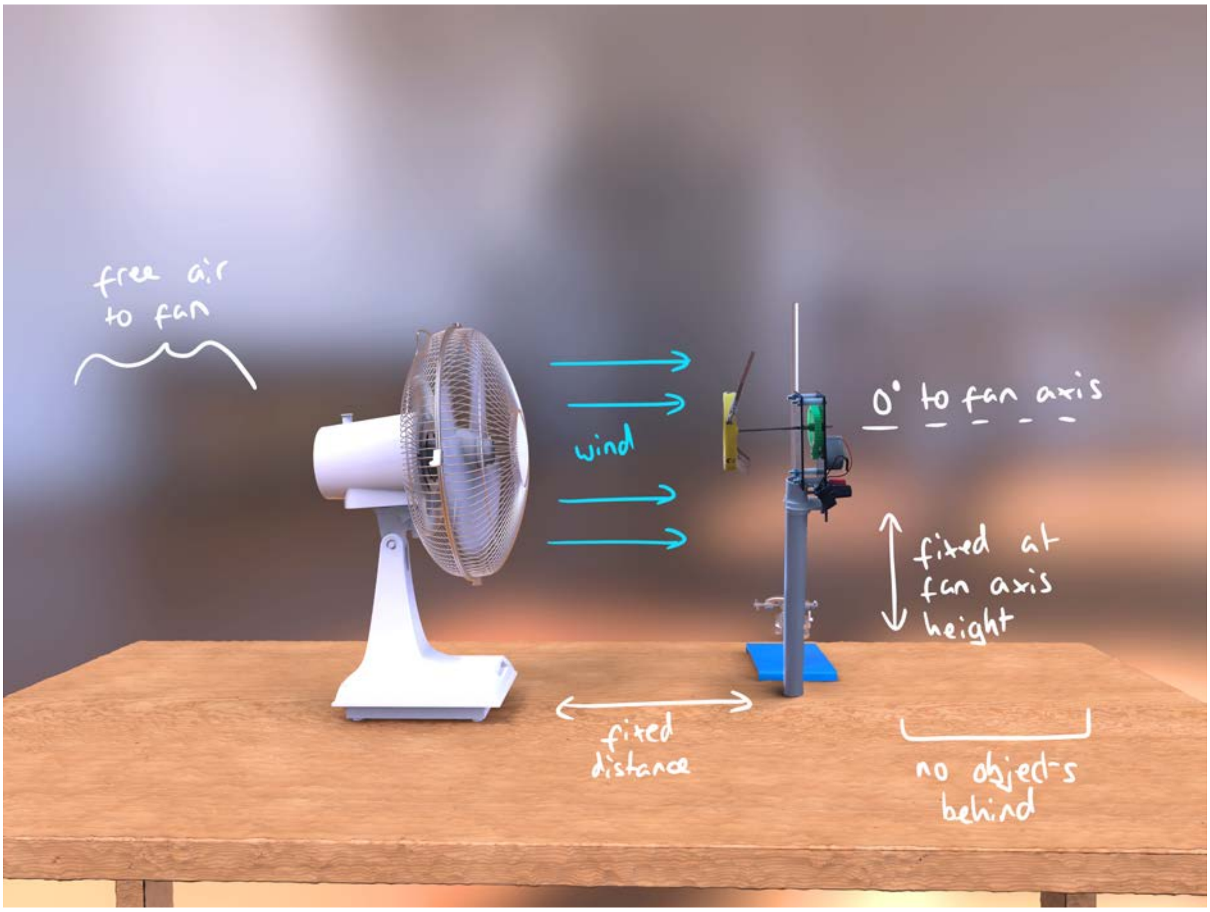
i - Aim & Objectives

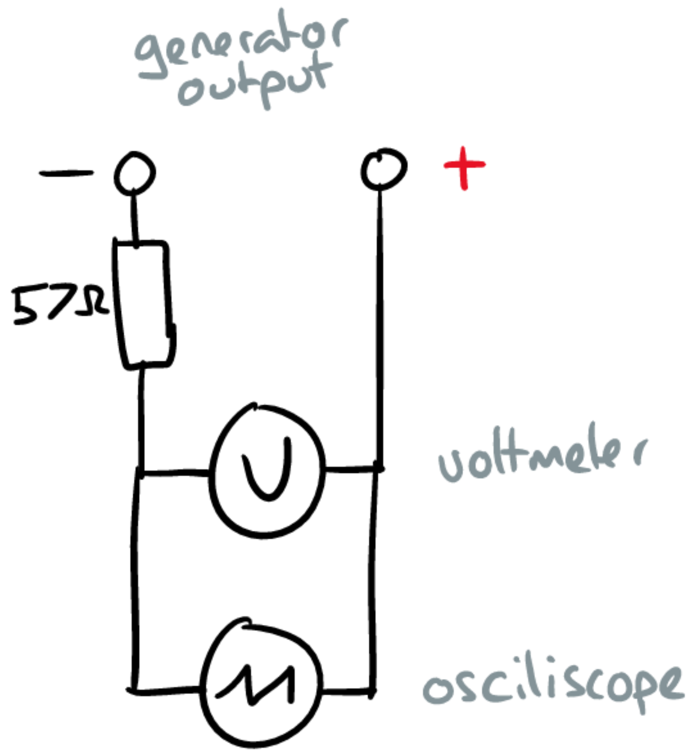
- Confidently determine the interaction between three selected input factors, and an output factor of the small scale wind turbine.
- Select three input factors which can provide useful information when designing and building a wind turbine.
- Conduct practical experiments according to best practices; minimising errors and ensuring valid data.
- Sufficiently minimise the resource (time / material) requirements, without compromising the output data.
- Conduct an analysis of variance, and understand the importance behind statistical significance, and the resultant terms including F-ratio.

ii - Experimental Setup

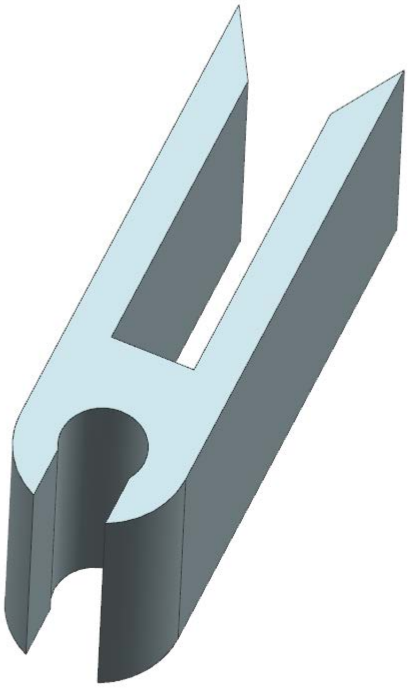
Below are two annotated renders of the experimental setup, and the circuit diagram of the generator output and measurement tools.

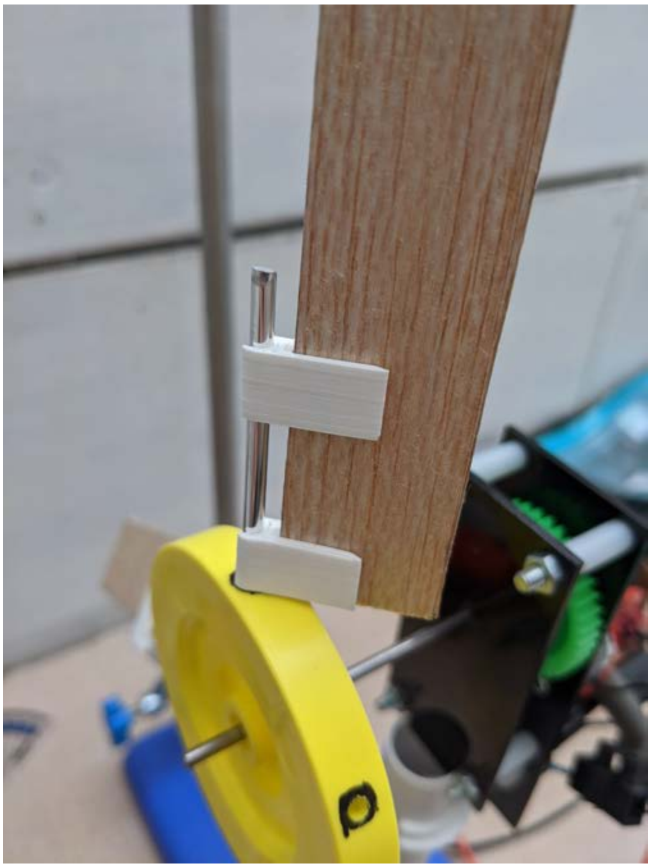

fan max power
fixed direction
hub
[1,2,3] blades
motor output
wind
clamp at low position


free air to fan
wind
0° to fan axis
fixed at fan axis height
fixed distance
no objects behind



To help repeatability, and to minimise rotor movement during the experiment, clips were 3D printed to hold the rotors to the rotor shafts. This removed random errors from tape or glue which could influence the aerodynamic or structural properties of the turbine. Two iterations minimised the size of each clip, and they were a tight interference fit ensuring that no movement (e.g. changing pitch angle) could occur during the test.





Throughout the experiment there were uncontrolled factors which could influence the results. This includes rapidly changing temperatures and external wind / drafts, as the experiments were conducted in an enclosed lean-to.

Further Notes

- To help reduce friction as an uncontrolled factor (e.g. friction changes as the gears heat and cool), the gear train was oiled using 3 in 1 general purpose oil.
- The turbine was allowed to reach equilibrium speed by allowing it to run for ~30s before measurements were taken.
- To ensure the most accurate readings, the oscilloscope was used to log DC average voltage, and frequency of the voltage signal (which is proportional to the rpm). These averages were over a time range of 30s.
- To back-up the oscilloscope data, a multimeter on voltage would also measure the DC average voltage, and a visual check to ensure the values were similar was performed, however only oscilloscope values were recorded to ensure no equipment error was introduced.

iii - Factors & Levels

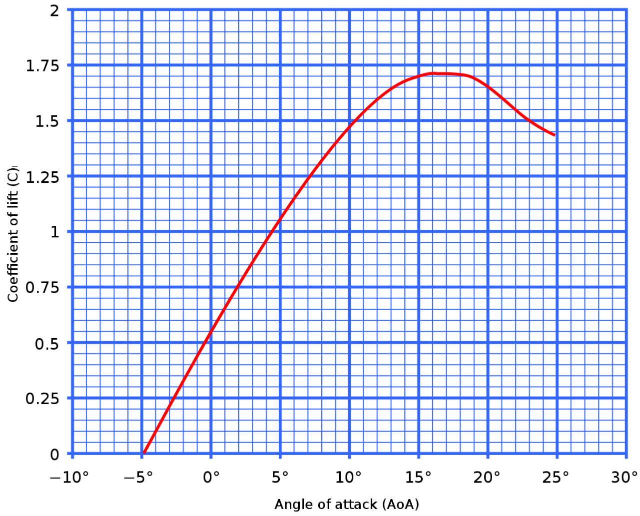
As assignment 1c was conducted before this, the research in that assignment will influence this one.

- Pitch Angle: easy to implement in the practical experiment, and it's relatively clear influence over output power (which should react similarly to rotor rpm) in the tests conducted for 1c.

  Due to the complexity of accurately measuring the wind speed from the fan, it is difficult to equate pitch angle to angle of attack in this small scale experiment. As the wind speed will be approximately constant during the experiment, it can be assumed that $AoA \propto Pitch$. Therefore, data from angle of attack can be used in place of pitch angle in this case.

  For small angles, the coefficient of lift, and resultantly force, and rpm are approximately linear, therefore allowing only two measurements to be taken.

  To attempt to ensure the angle of attack stays small, the pitch angles were selected to be as small as possible while still overcoming friction in the worst case scenario, and ensuring the range between chosen angles was large enough to minimise random errors (for example visual angle measurement errors)



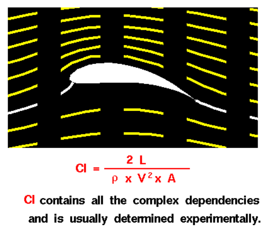
  Approximations are made by assuming the cuboid rotors act in a similar manner to an aerofoil profile.

- Chord length of each blade: also easy to implement. The lift is proportional to the wing area, which will be varied linearly with chord length if span is kept constant. Therefore, only two measurements are needed. To help reduce influence of errors, a large jump in chord length will ensure the largest change in output data. The two chord length values used are 25mm +- 0.25mm, and 75mm +- 0.25mm.

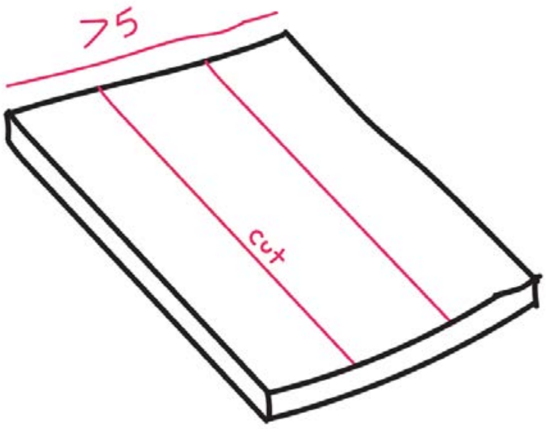
The Lift Coefficient

The lift coefficient is a number that aerodynamicists use to model all of the complex dependencies of shape, inclination, and some flow conditions on lift. This

https://www.grc.nasa.gov/WWW/K-12/airplane/liftco.html



These values were chosen specifically to help minimise material usage. One sheet could be cut into three for chord length C0, and three whole sheets could be used for chord length C1. These whole sheets were therefore undamaged to allow reuse or adaptation in the future.



- Number of blades: More blades will decrease aerodynamic efficiency by increasing the drag (e.g. each blade has a fixed drag force, doubling the blades will ~2x the total drag force).

This is shown by the drag equation:

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

Doubling the number of blades effectively doubles the area, A. Drag is proportional to the square of wind speed, so it can be assumed that wind speed to drag is not linear. Therefore, three measurements will be taken. 1, 2, and 3 blades will be used as this is possible without modification of the central hub, and ensures constant spacing between levels.

The number of blades will affect the torque produced, which may help overcome mechanical resistance, and generated magnetic fields when current is flowing in the generator. The number of blades also affects the mechanical response of the turbine; two blades can produce oscillatory vibrations as the 'blade plane' goes in and out of alignment with the direction of the wind, resultantly varying the force produced.

When testing with one blade, a second will be positioned on the opposite side, but with a 0° pitch angle to contribute minimally to the generated force. This is less preferred over setting the angle of attack to 0°, but as previously discussed the AoA is difficult to accurately determine given the experimental setup.

This allows the blade to be balanced, and ensures gravity does not influence the speed of the turbine more than it would with two or three blades. This does have an effect on the drag of the turbine, which may influence the results, however the unbalanced alternative would likely produce less favourable results.

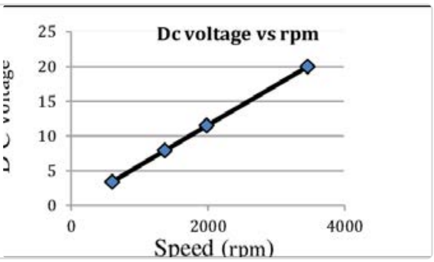
Other factors

- Wind speed would have been ideal to test, however:
  - *Voltage output is proportional to rpm, and voltage is proportional to power ($P = VI$).*

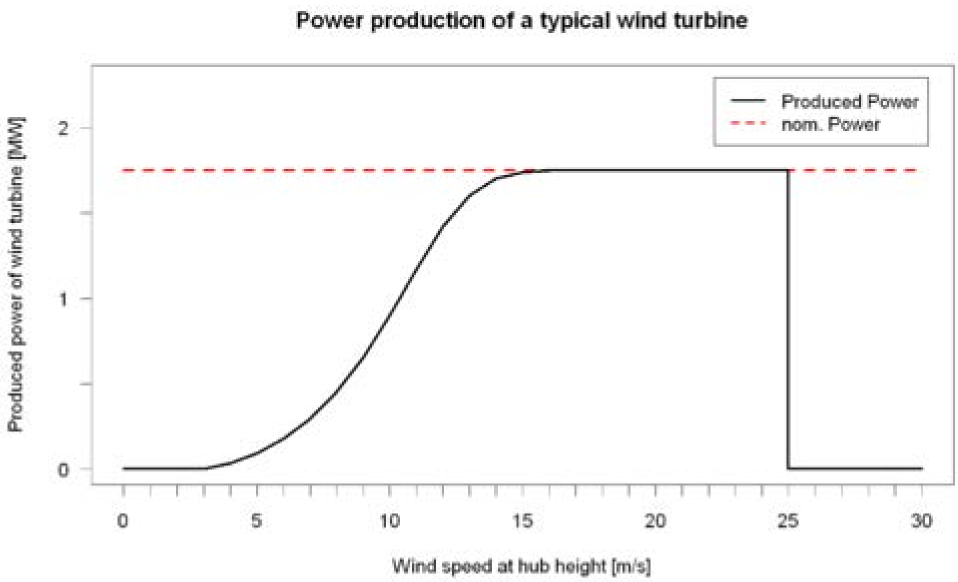
Fig 11: Graph of DC Voltage v/s Speed in RPM

Download scientific diagram | Graph of DC Voltage v/s Speed in RPM from publication: Design and Development of Solar Hybrid Bicycle | Since the fuel

https://www.researchgate.net/figure/Graph-of-DC-Voltage-v-s-Speed-in-RPM_fig7_305683710



  - *The power output (and resultantly RPM) of a turbine is **not** proportional to wind speed.*



    - *Therefore, more than two measurements would need to be taken. With the supplied fan, this is not possible.*

- Control factors such as yaw angle (angle between wind direction and wind turbine direction) would be interesting to test, however real-world turbines are designed to minimise this and therefore data obtained may not be extensively useful.

iv - Experimental Dataset

Refer to `data_cleaned.csv`.

Experiments are coded according to below table.

```
ID Key
#    - Repeat number     ( 0:One  |  1:Two  |  2:Three  |  3:Four )
 #   - Number of blades  ( 0:One  |  1:Two  |  2:Three )
  #  - Pitch angle       ( 0:20d  |  1:30d )
   # - Chord length      ( 0:25mm |  1:75mm )
```

v - Results

Source of Variance

Source	SSQ	DoF	Mean SQ	F Ratio	P Values	Significant at 0.05

Aa Source	# SSQ	# DoF	# Mean SQ	# F Ratio	P Values	Significant at 0.05
P	4.549161	1	4.549161	29.56602	<0.00001	☑
B	28.04891	2	14.02445	91.14809	<0.00001	☑
C	55.51516	1	55.51516	360.8055	<0.00001	☑
PB	0.307032	2	0.153516	0.997736	0.375421	☐
PC	0.796448	1	0.796448	5.176293	0.026892	☑
BC	11.15876	2	5.579382	36.26166	<0.00001	☑
PBC	1.438866	2	0.719433	4.675758	0.013403	☑
Within, Y	5.539122	36	0.153864			☐
Total, T	107.3535	47	2.284116			☐

vi - Significance

All of the results show statistical significance at a significance level of 0.05, except for the source from interaction between P (pitch angle) and B (the number of blades). Therefore, for the significant sources, we can reject H_0 (the null hypothesis that the input variance of the sources has no effect on the output variance of the turbine voltage), in favour of H_1, suggesting that the input variance of the sources does have an effect on the output variance of the turbine voltage.

vii - Discussion

The F ratio is an indication of how impactful the input factor is on the output factor. It can be described as a ratio of the F value which describes the variance obtained through the experimental data, and an F ratio which describes the variance of the data if H_0 is true, i.e. there is no relationship between the input and output factors, and any variance comes from randomness in the experiment and measurements.

If in reality, H_0 is true, then the numerator and denominator are approximately equal, and so the F ratio is approximately 1. However, if the numerator is much greater than the denominator, it indicates that the amount of variance is much greater than can be explained by randomness in the experiment - and must be explained by something else; that there is a relationship between the input and output factors.

Based on this, we can see that the source of chord length variation has the highest F ratio, and therefore causes the highest amount of variance in the output data which cannot be explained by randomness.

Degrees of freedom does factor into the significance of this result, however this specific source has a DoF of 1, and therefore can be said to have the highest F-ratio regardless of the other sources DoF.

This result is not surprising as the chord length is a defining factor in the coefficient of lift equation (and resultantly a defining factor in influencing the lift of the aerofoil), in the form $S = cs$ (area = chord length * span)

$$C_L = \frac{L}{\frac{1}{2}\rho u^2 S}$$

This makes sense when considering the practical effect of chord length. If lift is created by a difference in pressure above and below the wing, and force is pressure multiplied by the area on which it is acting, having a longer chord allows the pressure to act on a greater area, increasing force.

The same argument can be made when considering the effect of number of blades B on the output voltage, when looking at the blade element expression for change in force (for a rotor element).

$$dF_x = \frac{B\rho c {v_1}^2 (1-a)^2}{2sin^2\theta} \times C_x \ dr$$

However, existing research revealed that increasing the number of blades indefinitely is not the optimal solution. Possible reasons for this is that adding more blades will result in turbulent flow onto the blades, as caused by other blades on the turbine, which allows for less energy extraction than ideal laminar flow.

In reality, increased number of blades will increase the maximum possible torque on the rotors, which is used to overcome friction within the system. The small scale apparatus likely has much more friction proportionally than a real wind turbine (even though the gear train was lubricated before testing), and therefore the increased torque availability had a much higher impact than in a full-scale turbine.

Although the above discussion refers to force and not the output voltage, the two are related through output rpm. In an ideal generator, output voltage is a linear function of rpm. The rpm during the experiment is at equilibrium; the point at which all system forces are balanced. This means the lift force from the rotors will balance the friction forces, which is also a function of rpm. Therefore, it is suitable to refer to force on the rotor when discussing output generator voltage.

The only insignificant factor was the product of number of blades and pitch angle. Therefore, there is no interaction between these two factors which results in a significant effect on the output voltage variance.

Although the two sources had significant effect on the output variance when taken in isolation, a lack of significance of their product suggests that varying the number of blades had a similar effect on output variance, regardless of which pitch angle it was at. Similarly, varying the pitch angle had a similar effect on output variance, regardless of the number of blades.

An overview of experimental limitations which could have impacted the results are shown in the table below.

Experimental Limitation

Name	Description
Friction in small scale turbine	Likely much more impactful proportionally than a full scale turbine. May vary over the course of the experiment as lubricant disperses.
Environmental temperature variation	Tests were conducted in the middle of the day when temperature should be approximately constant, and randomisation of experiments should help reduce impact. Lower temperature may result in denser air and higher force for given controlled factors.
Environmental wind variation	Tests were conducted in an enclosed lean-to with noticeable drafts, which could randomly effect the output voltage.
Accuracy of rotor blades	Hand cut from fairly uncontrolled balsa wood. Variations in dimensions could unintentionally vary chord length or span, or blade profile. Density variations could vary dynamic response of the system.
Turbine vibrations	At high rpm, the turbine would vibrate and flex much more than at lower rpm. Therefore, energy extracted by the blades could be converted into vibration instead of generated power, which could reduce the voltage by a greater amount for higher rpm tests.
Visual pitch angle measurements	The pitch angle was measured with a protractor by eye. This results in a maximum precision of ~0.5° however difficulties with visual measurements result in an accuracy of likely much less.

Name	Description
Manual experiment setup	As blades were frequently removed and attached to the experiment, their positions (such as distance from the hub) may vary slightly between tests. Although measures were taken to minimise this, such as printed clips, this could still influence the results.