Scooturbine: A Recycled Wind Generator Integration Report

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I. Introduction

Previous design work has focused on theoretical blade optimisation and environmental analysis for the *Scooterbine* micro wind turbine. This report focuses on the integration of those blade designs with a functional turbine design. This includes discussion of mounting the developed blades to a functional rotor hub, development of a nacelle that can be mounted to a rigid tower, and the design and implementation of a gearing system for transmitting power from the rotor to the scooter motor being used as a generator.

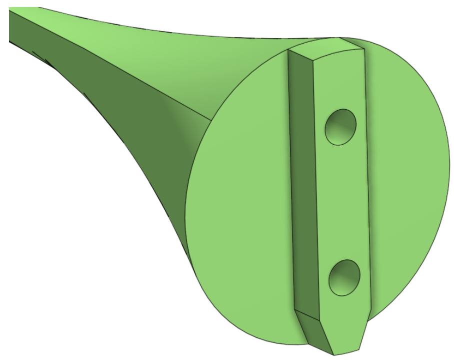


Fig. 1: View of the root section of an A18 blade.

II. Rotor

A. Hub Design

In a previous report blade design has been thoroughly discussed. However, that report does not cover the practicalities of safely securing blades to a drive shaft. This is further complicated by the need to swap out blades to evaluate a range of airfoils. Based on this, a decision was made to design a hub with interchangeable blades, rather than printing a separate hub for each blade design.

Given that interchangeable blades rules out gluing the blades to the hub, it was decided that bolts attaching to the blades along their primary axis would be an effective alternative. Figure 1 shows these bolt holes on the root of a blade, designed for an M5 bolt to self-tap into the plastic. A raised block has been added to allow for longer bolts, and to assist with orientation of the blade into a hub.

With blades designed for bolts to attach along their main axis, the hub design needed to allow bolts to be attached from inside the hub. To achieve this, the hub has been designed to be fabricated as three separate components that can be assembled into a full hub once the blades are firmly secured. This hub design is shown in figures 2 through 5. Figure 2 highlights the blade socket, showing the slot for the raised section of the blade, along with two securing bolt holes. It is worth raising the point that the blade will only fit in this socket in one direction, and therefore the segments are directional. Blades have been designed such that the arrow in the slot shape points out from the rotor, into the oncoming wind.

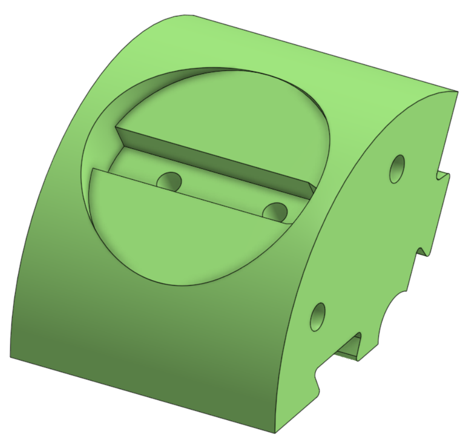


Fig. 2: Front view of hub segment

Figure 3 shows an inside view of a single hub segment. This is intended to highlight the internal bolt slots. Bolts are attached to the blade through the two holes shown, and the bolt heads sit inside the cutouts, ensuring they do not block the drive shaft.

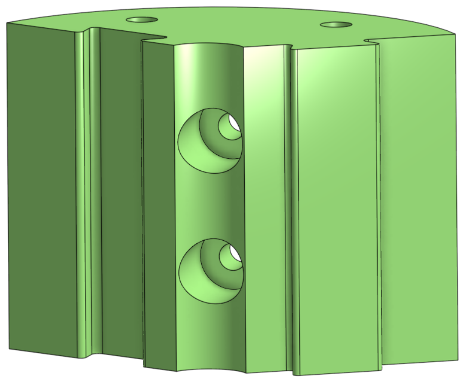


Fig. 3: Inside view of hub segment

Figure 4 shows this same hub segment in an isometric view. This highlights the jigsaw like mechanism for slotting identical units together. Three of these hub segments are printed, and slotted together to form a full hub, as shown in Figure 5.

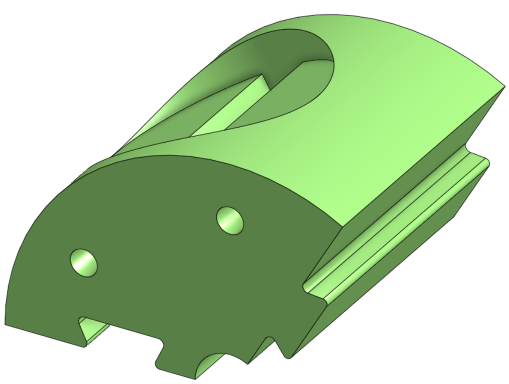


Fig. 4: Isometric view of hub segment

In order to fix the hub to the front of the drive shaft and ensure it reliably transfers rotational energy, caps were designed to mount the hub segments to. Each hub segment has two bolt holes in the front, and two in the back to facilitate this design.

In order to secure the hub to the drive shaft the back cap was designed to bolt to each hub segment, and clamp to the shaft. This is shown in Figure 6. There are holes for mounting to each hub segment, along with a clamping mechanism to go around the drive shaft. If this friction fit is not tight enough, an extra bolt hole exists on each side of the flange to drive a bolt all the way through the shaft.

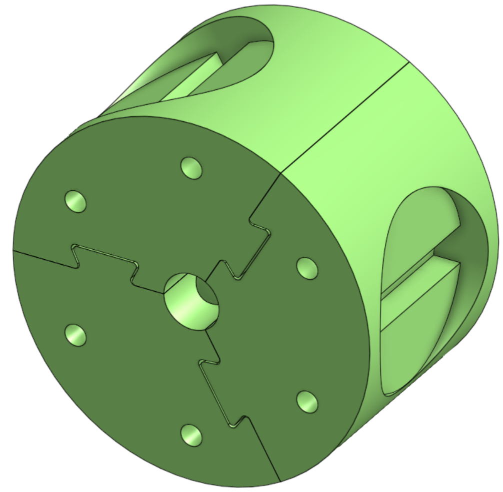


Fig. 5: Isometric view of assembled hub

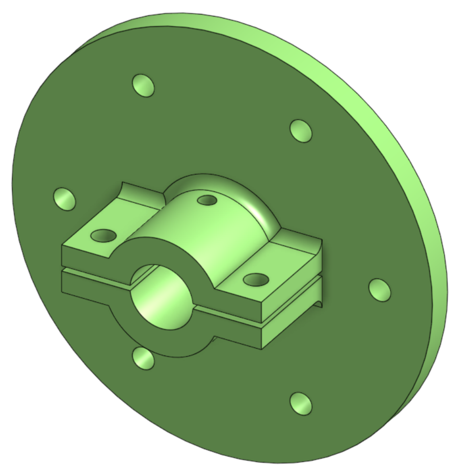


Fig. 6: Isometric view of rear hub cap.

Finally, Figure 7 shows the side profile of a fully assembled hub unit. This shows all the parts discussed previously, along with a rounded front cap designed to reduce any turbulence effects at the front of the hub.

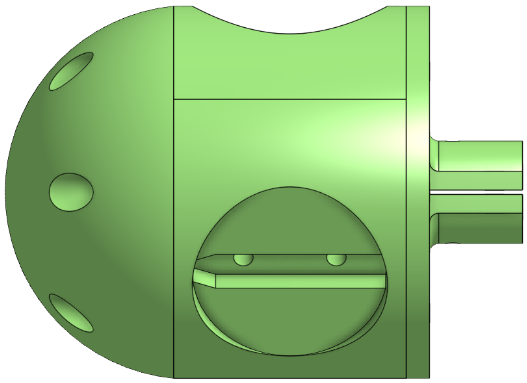


Fig. 7: Side view of hub

B. Blade Fabrication

Blade designs presented previously did not account for fabrication techniques, and rather existed as a base model based on theoretical analysis. In order to print the 600mm blades it was necessary to devise a method of splitting the blades into two or more segments in order to fit components into the build volume of the 3D printer being utilised.

In order to minimise forces on the join between segments, blades were segmented as close to the tip as the build volume of the printer would allow. Figure 8 shows how this segmenting was done, with the pin component being a short tip piece that glues onto the main blade.

A half lap join has been used between segments, with approximately 15mm of overlap between the tip and root. An epoxy glue was coated around the join, and sanded smooth when set, ensuring a strong join with minimal impact on aerodynamics. In order to smooth the part and ensure maximum strength, an epoxy resin was painted onto each blade after assembly. This resin flows into the layer lines of the print, adding extra strength and minimising any adverse effects at high speeds.

III. Electrical Components

A. Generator

This project is based around the idea of recycling unused electric motors as generator units, with this specific turbine utilising a recycled electric scooter motor. Figure 9 shows the motor utilised in this project. The internal structure of this motor is shown in Figure 9b. There is a central axle designed to be fixed to the forks of a scooter, with the stator coils fixed to this shaft. Three phase power is passed through the centre of the axle in order to drive the stator. The wheel is then placed onto this axle, sitting on a pair of bearings. Inside the wheel is a ring of permanent magnets, making the wheel is the rotor.

This motor configuration is incredibly effective for driving a scooter, however it is an awkward configuration for mounting inside a turbine as a generator. Figure 9a shows the exterior of the generator rotor with five bolts visible. These are the only accessible mount points, and will be utilised later in the project for attaching gearing hardware to the generator.

Finally, little is known about the exact behaviour of this motor. A datasheet is not available, so any information on characteristics must be obtained experimentally.

B. Three Phase Rectifier

Output from the selected generator is three-phase power. In order to provide an output usable for battery storage systems this three-phase AC power must be converted to DC. For this stage of the process this is done with a simple three phase rectifier [1]. A basic PCB was designed and fabricated to perform this functionality, shown in Figure 10.

C. Load Considerations

In order to measure power output of the generator, there must be a load placed on the output. Eventually this will be a variable load, with some form of buck/boost converter topology outputting energy to a storage system.

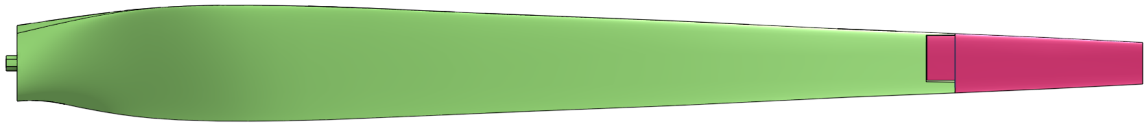
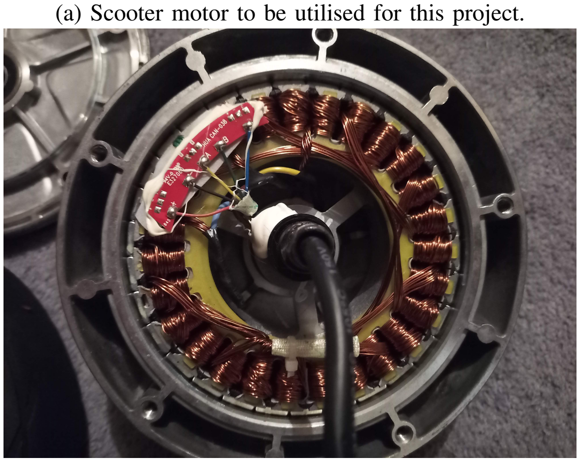


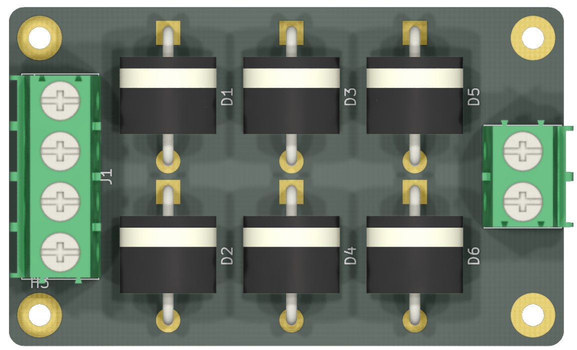
Fig. 8: Full span of blade, showing position of the segment join (Interface between green and pink segments).

(a) Scooter motor to be utilised for this project.

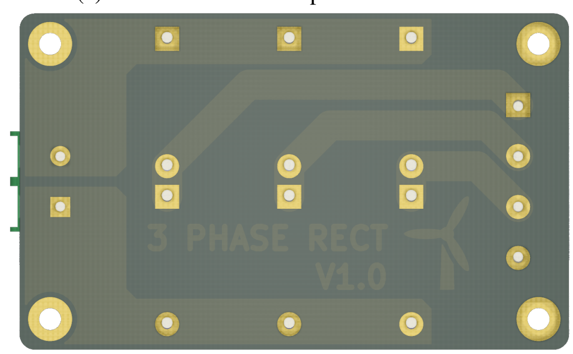


(b) Internals of scooter motor.

Fig. 9: Exterior and interior views of the generator being utilised.



(a) Front view of three phase rectifier PCB



(b) Back view of three phase rectifier PCB

Fig. 10: Three phase rectifier board developed to provide an unfiltered DC output from the generator.

However, development of a highly complex charge controller is out of scope for this project. Therefore in order to collect data on turbine output relative to wind speed and blade shape, a known load will be connected to the generator output to dissipate generated energy. A range of 100W dump loads have been obtained, and testing with the physical system in place will give insights into what loads to ensure the rotor spins up in the desired windspeeds.

IV. Nacelle & Tower

In order to extract energy with the developed rotor, a system was required to raise the rotor above the ground, mount the generator, and orient the rotor towards the oncoming wind.

Figure 11 shows a diagram of turbine hardware supporting the rotor. This diagram can be described by

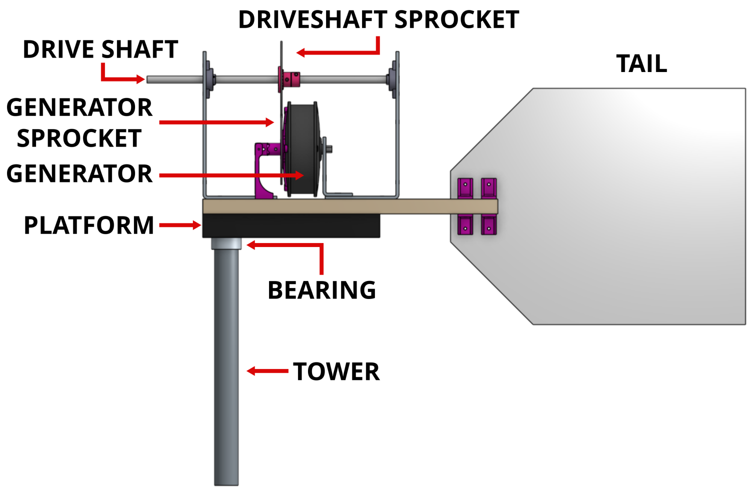


Fig. 11: Side view of nacelle mounted on turbine tower.

two main components, the "tower" and the "nacelle". The tower is simply the rigid metal pole fixing the turbine to the fence line. There is a bearing in the top of the tower, attached to all the turbine elements that are required to rotate to face into the wind. This unit sitting on the bearing is referred to as the nacelle.

Brackets are mounted to the platform sitting on the tower bearing. These brackets hold the drive shaft bearings in place, and align the drive shaft with the generator. Rotor components are fixed to the excess drive shaft length sticking out beyond the front bracket of the nacelle. At the back of the platform are mount points for a large sheet of corflute that acts as a rudder to steer the nacelle and point the rotor into the wind.

Inside the nacelle are brackets mounting the stator of the generator. This must be securely fixed and not rotate along with the rotor. In order to achieve this a mounting system has been designed to tension the stator axle against brackets on each side of the generator. This mounting mechanism acts to hold the stator stationary while also effectively extending the axle to allow enough space for sprocket systems to drive the generator.

V. Gear Train

In order to transfer power from the drive shaft to the generator, a pair of sprockets has been utilised. These sprockets are recovered from bicycles, and are to be linked together with a length of bicycle chain.

It is important to implement a gearing system as the drive shaft will not necessarily rotate at the optimal speed for the generator. Designs presented in the following sections ensure that sprockets are interchangeable, to allow analysis of how gear ratio impacts turbine behaviour. Ideally this will lead to a gear ratio that operates the generator at the optimal speed in normal conditions.

A. Theory

Given that a gear train is implemented to match rotor speed to optimal generator speed, it is important to initially determine the average rotor speed. Following this, an optimal generator speed needs to be determined. With both of these values, a desired gear ratio can be calculated.

Blade design work has specified a TSR of 7, meaning that the blade tips will be travelling at seven times the speed of the oncoming airflow. Pairing this with the average windspeed of 7.08m/s determined previously, the average rotations per minute (RPM) of the rotor can be determined as follows:

$$v_{air} = 7.08m/s$$
$$v_{tip} = 7v_{air} = 49.56m/s$$
$$r_{rotor} = 0.65m$$
$$C_{rotor} = 2\pi r_{rotor} = 4.084m$$
$$T_{rotation} = \frac{C_{rotor}}{v_{tip}} = 0.0824s$$
$$f_{rotor} = \frac{1}{T_{rotation}} = 12.13Hz$$
$$RPM = 60f_{rotor} = 728RPM$$

This indicates the rotor will rotate at $\approx 700RPM$ in average wind conditions.

In terms of determining optimal generator speed, this is more difficult. As discussed, little is known about these motors. In general wind turbine generators will exhibit a maximum power point, where the power reaches the highest point on a power vs RPM plot [2]. This point varies with windspeed, which is part of the reason that large scale turbines have a gearbox allowing for ratio switching. In a smaller project, it is not feasible to switch gears automatically. Therefore the goal is to select a gear ratio for which the generator will be at the maximum power point in an average windspeed.

Given that a power vs RPM curve does not exist for these motors, this data must be obtained experimentally. Due to lockdown this testing could not be performed, and instead an attempt will be made to collect this data while testing the turbine in situ. An initial gear ratio is to be selected based on a previous University project that worked with recycled scooter motors. This study looked at power output as RPM increased, however RPM was not increased above 500RPM. Data showed that power output increased with an RPM increase for all speeds below 500RPM [3].

Therefore, an initial gear ratio is to be implemented to drop the 700RPM of the drive shaft to 500RPM at the generator.

B. Sprocket Selection

An eight speed cassette from a bike has been repurposed for this project, and a pair of sprockets needed to be selected form this cassette that will implement the desired gear ratio. In order to do this, the following variables and equations were defined:

$$R_d = \text{Driveshaft sprocket RPM}$$
$$R_g = \text{Generator sprocket RPM}$$
$$n_d = \text{Number of teeth on driveshaft sprocket}$$
$$n_g = \text{Number of teeth on generator sprocket}$$

$$\frac{n_d}{n_g} = \frac{R_g}{R_d} \tag{1}$$

Equation 1 is a common ratio, relating RPM to tooth count. Figure 12 uses this equation to calculate all the possible gear ratios with the eight available sprockets. This grid allows for easy selection of a gear train, making testing various generator RPM targets relatively easy.

Drive Gear Teeth [n_d]	Driven Gear Teeth [n_g]							
	15	17	19	21	23	25	30	34
15		0.88	0.79	0.71	0.65	0.60	0.50	0.44
17	1.13		0.89	0.81	0.74	0.68	0.57	0.50
19	1.27	1.12		0.90	0.83	0.76	0.63	0.56
21	1.40	1.24	1.11		0.91	0.84	0.70	0.62
23	1.53	1.35	1.21	1.10		0.92	0.77	0.68
25	1.67	1.47	1.32	1.19	1.09		0.83	0.74
30	2.00	1.76	1.58	1.43	1.30	1.20		0.88
34	2.27	2.00	1.79	1.62	1.48	1.36	1.13	

Fig. 12: Gear combination grid. Shows the gear ratio $\frac{n_d}{n_g}$ of each possible sprocket combination.

For the initial setup, a ratio of $\frac{500}{700} \approx 0.71$ was required. To achieve this the 15 tooth sprocket was used as the drive sprocket, and the 21 tooth sprocket was used as the generator sprocket.

C. Driveshaft Sprocket Mounting

In order to fix a cassette to the hub of a bicycle, each sprocket has a cutout for locking to an internal spine. Along with this, there are three mounting holes spaced evenly on each sprocket. These two facts were utilised to create a mechanism for mounting the drive

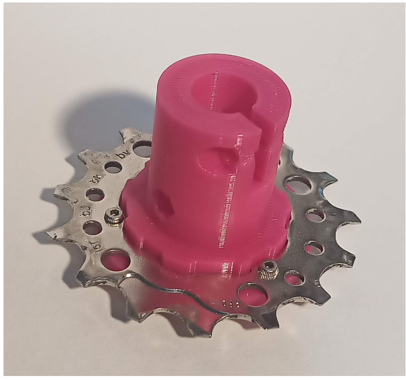


Fig. 13: Driven sprocket mounting mechanism.

Fig. 14: Generator sprocket mounting mechanism.

sprocket to the driveshaft. Figure 13 shows this design with the 15 tooth sprocket mounted.

There is a large hole in the centre of this mount for the driveshaft to pass through, and there is a clamping mechanism at the top to clamp the mount to the shaft. There is also a hole going all the way through the unit perpendicular to the axis of rotation, allowing for a bolt to be passed right through the shaft. The sprocket is held in the axis of rotation primarily by the locking shape, and is held in the axis of the drive shaft by three small screws, two of which can be seen in Figure 13.

D. Generator Sprocket Mounting

There are five bolts on one face of the motor, used to hold the two wheel halves together. These five mount points have been utilised as anchor points for the generator sprocket. Figure 14 shows the generator sprocket mounted to the generator. This mounting system utilises the same technique as the driveshaft mounting system, allowing ease of access to change sprockets.

E. Sprocket Train Assembly

With both mounts designed and printed, the sprocket train was installed in the nacelle. Figure 15 shows this assembly, giving further context for each of the previously discussed mounts.

Integration of this system highlighted the necessity for accurate alignment of sprockets to minimise sys-

Fig. 15: Fully assembled gear train. Shaft running along the top is the driveshaft.

tem losses and breakdowns. If the driveshaft is not aligned properly with the generator shaft, then the chain tends to slip off the sprockets as the rotor spins up. Additionally, there appears to be stiffness in a number of the chain links.

These components were discarded by a bike mechanic, and therefore likely have a significant amount of wear that may lead to losses in the system. However, further adjustment of this system before formal testing will likely minimise these losses. This adjustment may involve measures such as cleaning and re-lubricating chain links, precisely aligning the driveshaft to the generator shaft, and readjustment of chain links to ensure minimal friction in the split link.

VI. Fully Integrated System

Figure 16 shows the turbine in it's final location, with all of the discussed components integrated.

Fig. 16: Fully integrated Scooterbine prototype.

Integration of system components was generally very smooth. Most of the components fit together and behave as expected, with the only issue being the nacelle platform. It can be seen that the platform bows under the weight of the generator, due to the fact that weak plywood was utilised. Re-enforcing beams have been identified, and will be attached prior to final testing.

In order to verify successful integration, a small amount of initial testing has been performed, with the turbine installed on an averagely windy day. An averagely windy day is defined by sustained periods of windspeeds around 7m/s, which are approximately the conditions designed for. This testing primarily looks at the tower and nacelle stability, and the behaviour of the developed rotor.

In order to determine how the rotor behaves the generator was disconnected, allowing the rotor to rotate freely. Once the rotor was spun up, frequency analysis of the sound produced by the rotor was utilised to obtain an approximation of rotor velocity.

Figure 17 shows the result of this analysis. Spectroid, the app utilised to obtain this data, does not plot time on the spectrogram. In this plot the vertical axis represents time, with brightness representing magnitude and the horizontal axis representing frequency. There is a block of sound shown in the spectrogram, abruptly stopping close to the end of the plot. This abrupt stop aligned with braking of the rotor.

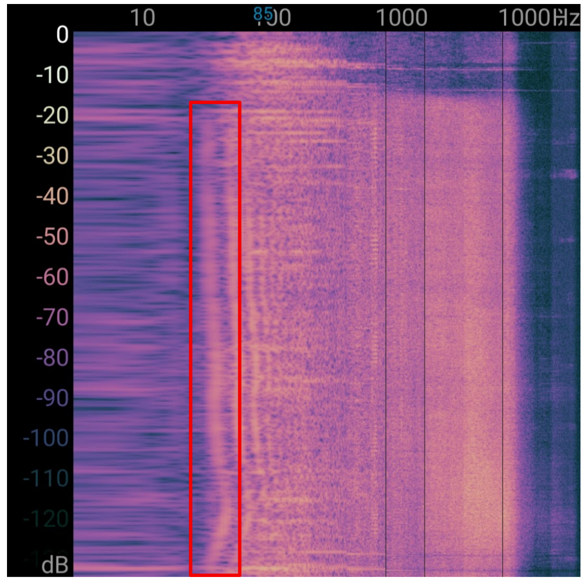


Fig. 17: Frequency analysis of rotor in operation. Vertical axis represents time. Fundamental frequency highlighted in red. Image captured with Spectroid.

Of particular interest is a very clear band of sound at approximately 35Hz, highlighted in red. This band also ends when the turbine is stopped. Given that it is the lowest frequency band visible in the plot, it is proposed that this is the fundamental frequency produced by the rotor.

Given that there are three blades generating sound it is proposed that this frequency is three times the rotational frequency of the rotor. Therefore, this frequency can be converted to rotor RPM as follows:

$$
\begin{aligned}
f_{fund} &= 35Hz \\
f_{rot} &= 11.67Hz \\
RPM_{rot} &= 11.67Hz \times 60s \\
RPM_{rot} &= 700RPM
\end{aligned}
$$

These calculations suggest the rotor had an RPM of approximately 700RPM. There were fluctuations in the fundamental frequency, with it reaching up to approximately 45Hz early on in the recording. Design calculations for this turbine have suggested that RPM in an average 7m/s windspeed should sit around 730RPM. This initial testing indicates that the rotor is meeting this expectation.

Finally, a small amount of initial testing has been done with the generator linked to the drive shaft. Windspeeds could not be determined during this testing as an anemometer was not available. However, it was very apparent that the system had a high cut in speed with the gear ratio utilised.

In order to generate energy the rotor needed an initial kick before it began rotating in the wind, suggesting that a higher (or easier) gear ratio may be required. Gearing installations have been designed to easily allow for different sprocket combinations, and analysing different ratios will be a significant portion of the formal testing procedures. An anemometer will be obtained for this analysis, allowing for analysis of cut in windspeed of different gear ratios.

With the rotor spinning, line current and line voltage were measured across two phases of the generator. With the generator spun up at full speed, line voltage was measured to be $20V_{RMS}$, and line current was measured at $0.2A_{RMS}$. Power factor was not measured during this testing, and the system was not connected to the three phase rectifier, therefore power output could not be easily determined. However this testing has shown that this setup is capable of generating power, and formal testing can obtain quantitative results from the three phase rectifier.

VII. Next Steps

A. Formal Testing

1) Testing Objectives: With integration completed, it is now possible to test the generation capacity of the turbine. Formal testing will address the following things:

- Analysis of the effect gear ratio has on turbine cut in speed will be performed. Ideally the system should cut in somewhere below the average windspeed of 7m/s. This will assist with selecting a final gear ratio for use in the remaining testing.
- Power curves will be generated for two different blade profiles (A18 and SD7032), determining the behaviour of each blade and drawing conclusions on whether a wider drag bucket is optimal in the target location. Power data will be collected from the DC output of the three phase rectifier, bypassing the need to measure a wide range of AC parameters.
- Analysis will be performed on how load impacts the behaviour of the turbine. A range of dump loads have been obtained, and will be connected to the DC output of the three phase rectifier. Power curves will be developed for these loads.

2) Testing Risks & Mitigation: There following risks and mitigation strategies will be taken into account when performing formal testing of the *Scooterbine*:

Unpredictable Weather Patterns: Ideally testing would be performed in a wind tunnel, allowing for constant and precise control over wind speeds. However, this type of equipment is not available to the project. Therefore testing will be performed utilising on site wind. This poses a risk to the project as there may be a stretch of time with little to no wind.

Mitigation of this is difficult, as testing is fully at the mercy of the weather. In order to maximise the winds that are available a full testing plan will be drawn up, and will detail all the data that needs to be gathered. Along with this, all necessary hardware such as dump loads and windspeed measuring equipment will be accounted for in advance. This will mean that when suitable weather does occur, testing can be performed efficiently. These plans and hardware acquisitions will be done in the week following submission of this report, allowing just under two weeks for testing.

Damage to Hardware: Testing of the turbine for extended periods has not been performed. There is potential for prolonged use straining components such as the blades, driveshaft, or chain on the drive train. This risk has been mitigated by ensuring that backups exist of the all components, and extra filament is available to print and replace any damaged blades.

VIII. Conclusion

This report has outlined the process of designing a turbine platform for blades designed in the previous report. Designs have been completed for a rotor hub with interchangeable blades, and gearing systems to transfer power to the scooter motor being used as a generator. A tower and nacelle system has been developed to mount all of this hardware, and a three phase rectifier has been designed to provide a DC output that can be integrated with systems in the greenhouse.

Initial testing has indicated that the currently installed gearing system results in a high cut in speed, meaning that the turbine needs relatively high wind speeds to generate effectively. However, once the rotor is operational there is significant line voltage and current, showing good power generation potential.

With this integration work done, formal testing can be performed. A short plan has been presented, highlighting the key behaviour that testing aims to quantify. More detailed testing plans will be presented along with results in the final report.

References

[1] Electronics Tutorials. *Three Phase Rectification*. Accessed: 07/10/2021. URL: https://www.electronics-tutorials.ws/power/three-phase-rectification.html.

[2] Oliver Probst et al. "Small Wind Turbine Technology". In: *Wind Turbines*. Ed. by Ibrahim Al-Bahadly. Rijeka: IntechOpen, 2011. Chap. 5. DOI: 10.5772/15861. URL: https://doi.org/10.5772/15861.

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