# Design and Development of Slotted Blades to Increase Efficiency of Wind Turbines

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## Introduction

The project aims to develop horizontal axis wind turbine (HAWT) blades with slits that would slow down the turbine in order to simulate a new approach to the existing braking system that activates upon the system reaching cut-out speed. According to the International Renewable Energy Agency, the conventional braking systems can make up approximately 1.32% of the total HAWT costs (IRENA June 2012). Additionally, the research shows that overheating of the emergency brake behind the gearbox often causes conflagration (Mein S. 2019). Thus developing a new braking system that does not require additional mechanical or electromagnetic parts near the gearbox would lower the cost of production, installation, operation and maintenance while increasing the safety level of the operation. This is an important issue because wind energy is often perceived negatively in society. It is viewed as an unreliable and costly source of energy, compared to electricity and solar power ("Advantages and Challenges of Wind Energy"). This project serves to explore common issues found in wind turbines and find possible solutions to improve their efficiency.

## Background

When conventional HAWTs are exposed to high wind speed of around 60 miles per hour or higher, the system reaches cut-out speed. Once the apparatus reaches the cut-out speed, mechanical or electronic braking systems are used in order to slow its shaft speed down to safe levels. This process prevents overheating the gearbox and unnecessary strain on the rotor. In order to solve this problem, the current braking system typically has either additional mechanical or electromagnetic or combination of parts to slow down the shaft speed.

Some small HAWTs use the generator as a brake on an induction machine. For this electrodynamic braking, the generator is disconnected from the grid and then connected to a series-parallel of resistors and capacitors, slowing down the generator to lower the revolutions per minute (RPM) for a small disc brake to be engaged (Tong W. 2010). Larger HAWTS commonly use a disc brake on the high speed shaft. However this arrangement has a drawback in that the brake has to be sized for the maximum anticipated rotor torque and everytime the rotor is halted, the drivetrain and the gearbox always experience maximum torque (Tong W. 2010). This excessive stress on the drivetrain and the gearbox could accumulate to break down the braking system in the long run.

This project aims to provide an alternative way of reducing the RPM of the rotor when the system is exposed to high wind speed by designing slits in the HAWT blades. Hypothetically the slits would slow down the rotational speed of the rotor relative to the controlled blades which are without the slits. This design would simulate the external braking system which only activates upon the system reaching cut-out speed to reduce the total amount of kinetic energy that the rotor blades receive from the wind.

## Specifications

The wind turbine design is based on the constraints of the subsonic wind tunnel. The height and width of the throat was 11.75 inches. The length of the throat was 22 inches, with 11 inches free in front of the sting. The sting had a diameter of 0.375 inches and a length of 1 inch. The stop collar of the sting was 7/16 of an inch. The back exit had a diameter of 24 inches and the front panel had a length of 37 inches for each edge. As a result, the blade diameter was determined to be $(\frac{1}{2} - \frac{3}{4})$ multiplied by the wind tunnel diameter. The blades were designed to be three different types: one set of control blades with no slit, one set with one slit, and another set with a slit double the unit width of the first.

For measurement specifications, the target tip-speed ratio for the wind turbine was 5 with a minimum of 4.19 and an optimal range (exceeded target expectations) of 5.24-5.45. The target angle of attack was around 5°, which is ideal for small scale wind turbines. Based on Betz's law, the theoretical maximum efficiency is approximately 59%. However, the target for this specific wind turbine was 50% because most wind turbines usually have a maximum efficiency in this range. The cut-in wind speed was about 7 mph, while the cut-out wind speed was about 55 mph. The maximum shear for the core material was about ±1.1 MPa. Typical operating temperatures for wind turbines is about 4 to 104°F, so this range was applied for this experiment.

To create a scale model of the turbine, a set of blades with a central hub were first created in SolidWorks. When using Stratasys F170 3D printers at the University of Virginia Rapid Prototyping Lab, the depositions of ABS plastic were too thick to allow for the proper resolution of the slits within the blades at 0.01 inches (Figure 1).

**Figure 1.** Version 1 of turbine in wind tunnel with larger hub and and clear deposition lines on blades

This gave the opportunity to revisit the design and a new hub was much smaller, allowing for less interference with the blades. Moving on to the second version of the turbine, low force stereolithography printers were used which allowed for the print to resolve down to 25 microns. Specifically, the FormLabs Form 2 printers were used at the School of Architecture’s FabLab. Using the “tough” resin, this print was much more precise, but more difficult to clean up. In the curing process there were a handful of inconsistencies across blades of the same type, but they each largely followed the same geometry (Figures 2 & 3).

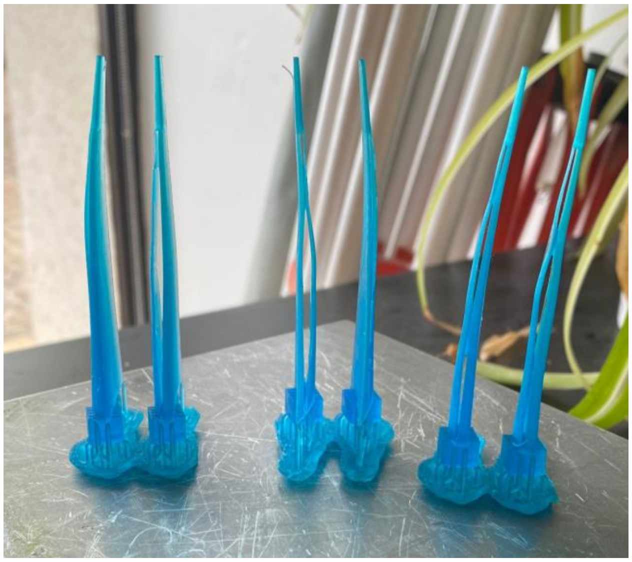


**Figure 2.** Resin blades after curing, seen with inconsistent forms across each blade type

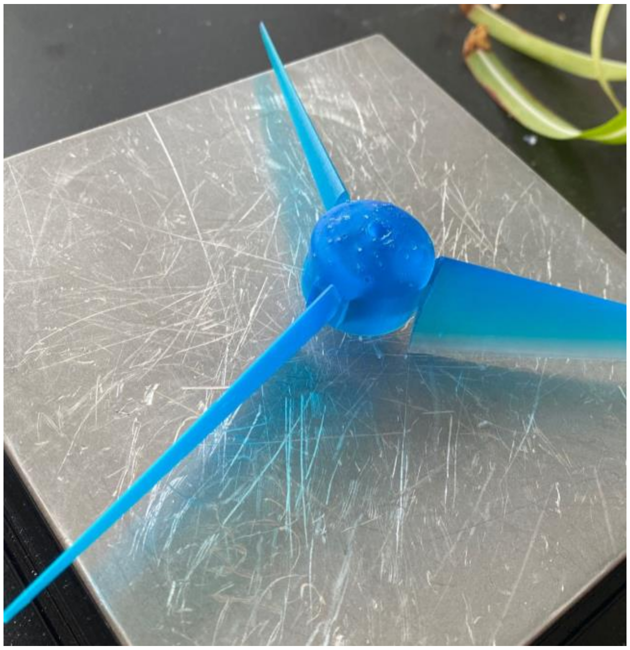


**Figure 3.** Assembled resin turbine with solid blades (no slit) and a smaller hub

In order to properly test the prior specifications, this scaled version of the turbine was placed inside the wind tunnel and tested at varying wind speeds and orientations (Figures 4 & 5).

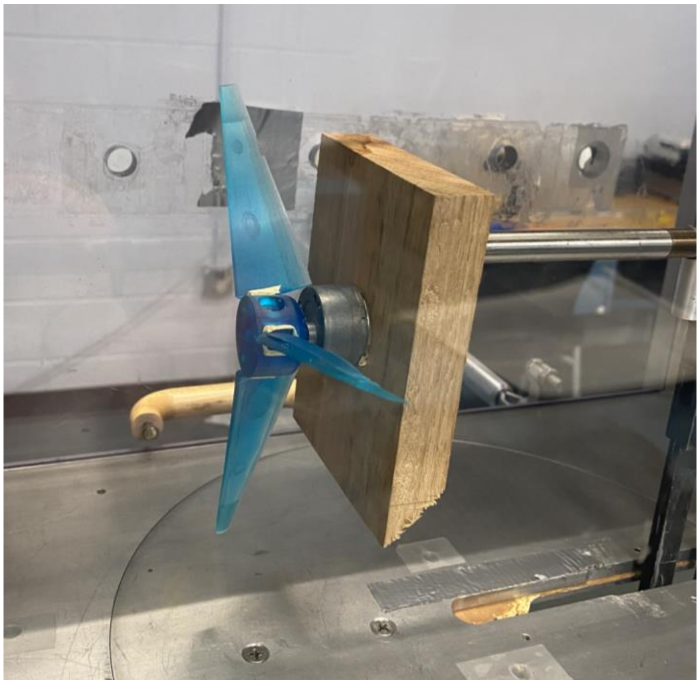


**Figure 4.** Assembled testing apparatus of turbine in one orientation

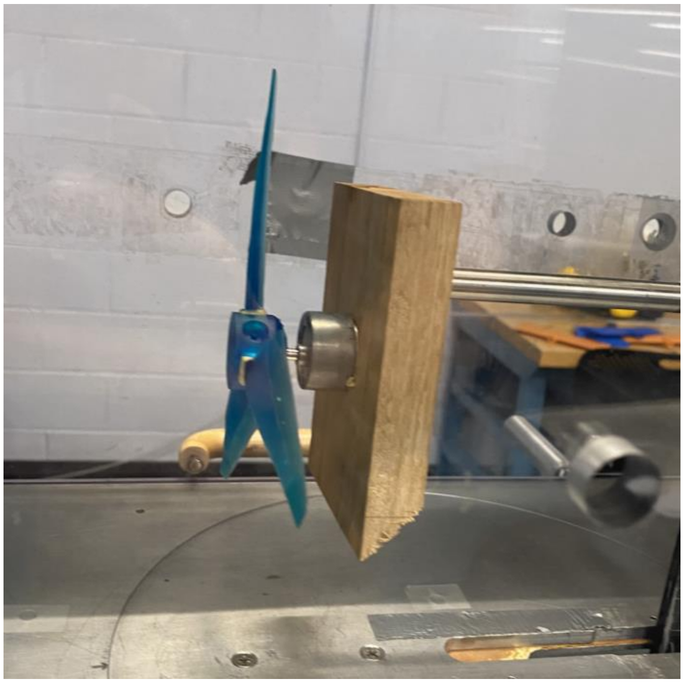


**Figure 5.** Assembled testing apparatus in other orientation

Early tests used masking tape to secure the blades into the central hub which led to blades breaking away or snapping. Both versions of the print suffered at least a single incident wherein the blades snapped at either 40 mph or 60 mph wind speeds (Figure 6).

**Figure 6.** Broken blade resulting from high wind speeds and ineffective interfacing between the blade and the hub

Later trials shifted to use set screws which allowed the blades to adequately sit inside the hub even at higher wind speeds (Figure 7).

**Figure 7.** Testing apparatus with resin turbine secured with set screws

Additionally, due to the gear ratio of the motor, the force of the turbine could not rotate the motor shaft even at exceedingly high wind speeds. Instead, the turbine was left unsecured on the motor shaft allowing it to spin without needing to drive the motor.

Accompanying this work was a simulation of blade performance using SolidWorks Computational Fluid Dynamics (CFD) models. This allowed for a greater understanding of the behavior of the turbine blades alone without needing to make assumptions about the effect of other erroneous or questionable factors which came into play in the real model.

The wind tunnel testing only provided the resources to measure the rotations per minute of the wind turbines within a degree of error. Recordings were taken of the spinning blades, then placed into Avidemux 2.7.6, allowing for a frame-by-frame count of the passing blades. The time required for a single blade to do one full rotation was measured allowing for extrapolation over the course of an entire minute. Here, it should be noted that due to the high rate of rotation at many of the wind speeds, a great amount of aliasing occurred. In these instances the errors are significant (over 700 RPM). Due to this and the blade fractures which occurred throughout the testing process, there were not enough data points to point towards an effective conclusion. From what is available, there seems not to be any relation between the size or presence of blade slits and the rotational speed of the turbine.

The SolidWorks CFD models provided a simulated measure of the torque experienced by the DC motor shaft in response to differing wind speeds. At a simulated wind speed of 20 mph the torque experienced by the shaft was 0.001129 N*m. At 60 mph the calculated torque was 0.009491 N*m. This data was used to evaluate the effectiveness of the original DC motor after an unsuccessful first trial run in the wind tunnel. See Appendix C for CFD output data.

The operating temperature was not explicitly tested. Instead, the general form of the turbine blades were the focus of study in this work.

## Cost Analysis

Costs were a large constraint for this project. The budget for this project was $1000. To make the wind turbine hub and blades, it cost $2.50 per cubic inch of ABS plastic. The final design required a total volume of 1.84 cubic inches of ABS plastic/resin.

The motor selected for this experiment was a 12 V, 156 mA reversible gear head DC motor. The cost for this motor was $17.95. This motor provided too much resistance in the first round of trials but was somewhat more successful in later iterations.

Overall, this was a relatively cost-effective experimental model. However, when scaled up or including more wind turbine parts in the body, it is inconclusive as to whether this would be cost effective.

## Conclusion

Overall, the wind turbine blades with slits did not meet some of the specifications set for this experiment. As shown in the data in Appendix A, there were not enough data points to form a conclusive relationship. It appeared that the trends for the control blades, the single slit blades, and the double slit blades data were similar. Based on the results of this experiment, there should be improvements towards the experimental design of this project. For example, it would be more beneficial to collect more data points by increasing the time to record the video or by conducting more experimental trials. This would increase the accuracy and precision of the data. Furthermore, it might be useful to collect data by using another method of data collection that could more accurately capture the data points and reduce the aliasing caused by high rotation rates. This would further reduce measurement uncertainty.

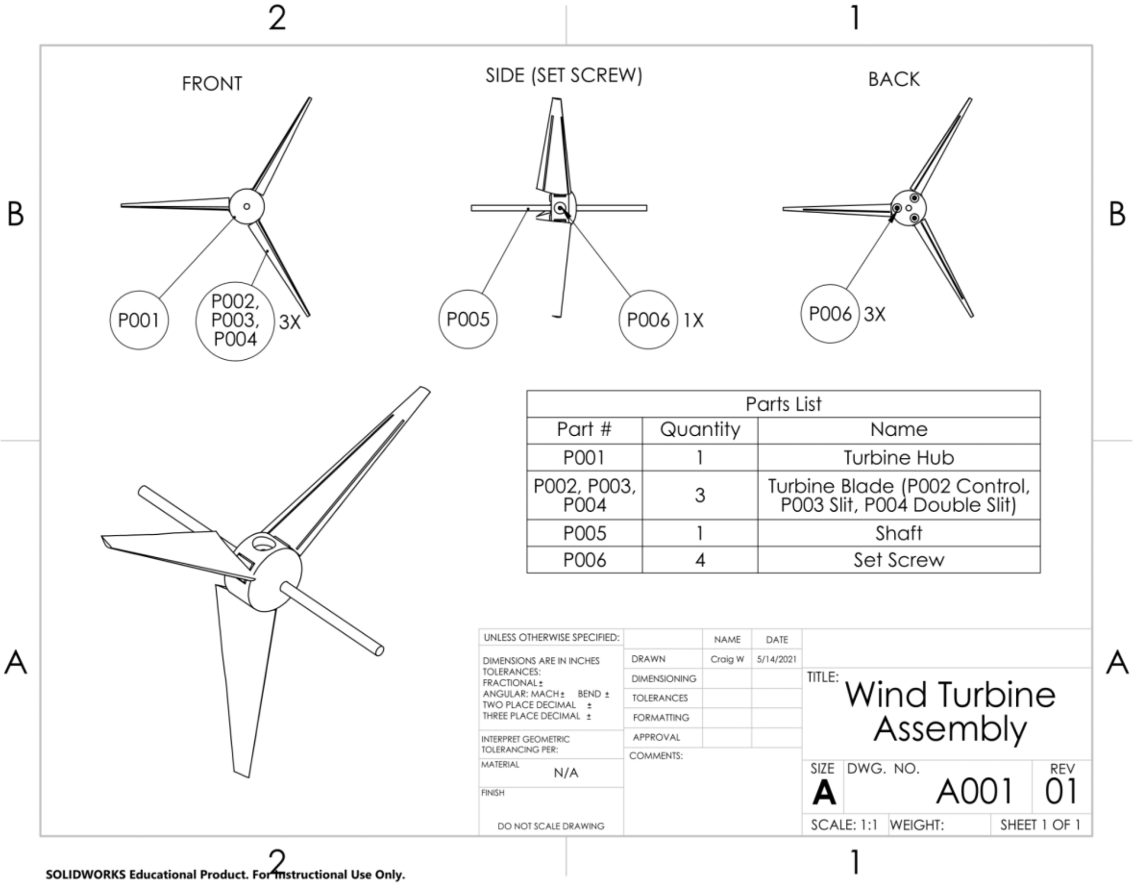
Future similar experiments could involve different design configurations for the wind turbine. For instance, using different materials to minimize the weight of the turbine blades without compromising the strength and durability of the blades could be used to increase the efficiency of the wind turbine. Additionally, different blade shapes such as flat and curved blades could be a possible experiment to test the efficiency. Other design factors such as dimpled or reversible blades could be implemented in future experiments. Another possible future experiment could be testing the wind turbine in different environments, such as a floating wind turbine in water. Other variables could also be measured, such as turbulence to test the durability of a wind turbine.

## Appendix

Appendix A: Table of Results for Control, Single Slit, and Double Slit Blades

| Blade | Turbine RPM | Wind Speed [mph] | Blade Version | Angle of Attack [Deg] |
|---|---|---|---|---|
| No Slit | 328 | 60 | 0 | 5 |
| Single Slit | 359 | 60 | 0 | 5 |
| No Slit | 212 | 20 | 1 | 5 |
| No Slit | 448 | 40 | 1 | 5 |
| No Slit | 1224 | 20 | 1 | -85 |
| No Slit | 3750 | 40 | 1 | -85 |
| Single Slit | 1818 | 20 | 1 | -85 |
| Single Slit | 276 | 20 | 1 | 5 |
| No Slit | 1200 | 30 | 2 | -85 |
| No Slit | 1200 | 40 | 2 | -85 |
| No Slit | 1818 | 30 | 2 | -85 |
| No Slit | 1765 | 30 | 2 | -85 |
| Single Slit | 1765 | 30 | 2 | -85 |
| Single Slit | 1818 | 30 | 2 | -85 |
| Double Slit | 1765 | 30 | 2 | -85 |
| Double Slit | 1765 | 30 | 2 | -85 |

# Appendix B: Detailed Drawings



| Parts List | | |
|---|---|---|
| Part # | Quantity | Name |
| P001 | 1 | Turbine Hub |
| P002, P003, P004 | 3 | Turbine Blade (P002 Control, P003 Slit, P004 Double Slit) |
| P005 | 1 | Shaft |
| P006 | 4 | Set Screw |

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL N/A
FINISH
DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
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| DIMENSIONING | | |
| TOLERANCES | | |
| FORMATTING | | |
| APPROVAL | | |

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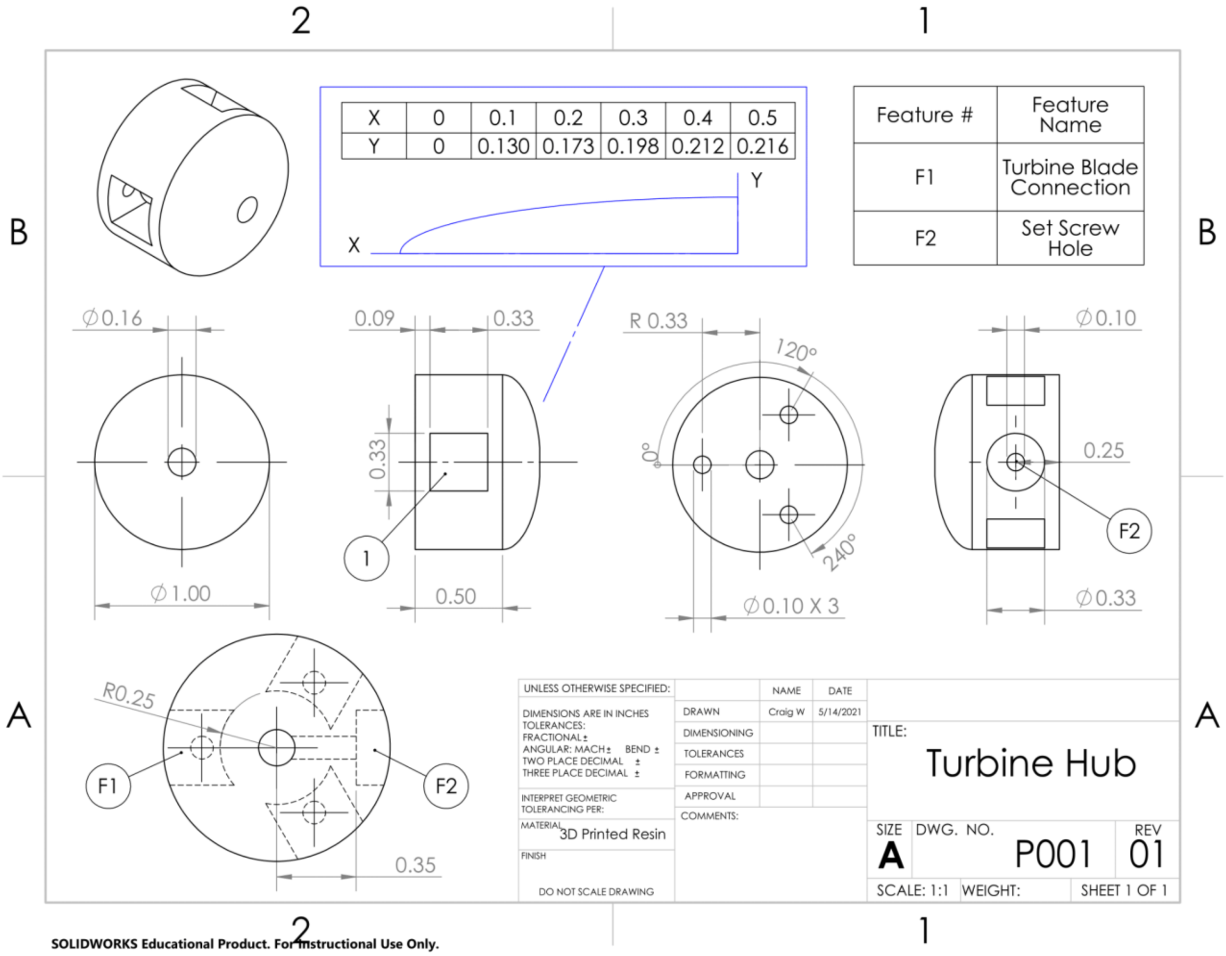

| X | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|---|---|---|---|---|---|---|
| Y | 0 | 0.130 | 0.173 | 0.198 | 0.212 | 0.216 |

| Feature # | Feature Name |
|---|---|
| F1 | Turbine Blade Connection |
| F2 | Set Screw Hole |

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| INTERPRET GEOMETRIC TOLERANCING PER: | APPROVAL | | |
| MATERIAL 3D Printed Resin | COMMENTS: | | |
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TITLE:

Turbine Hub

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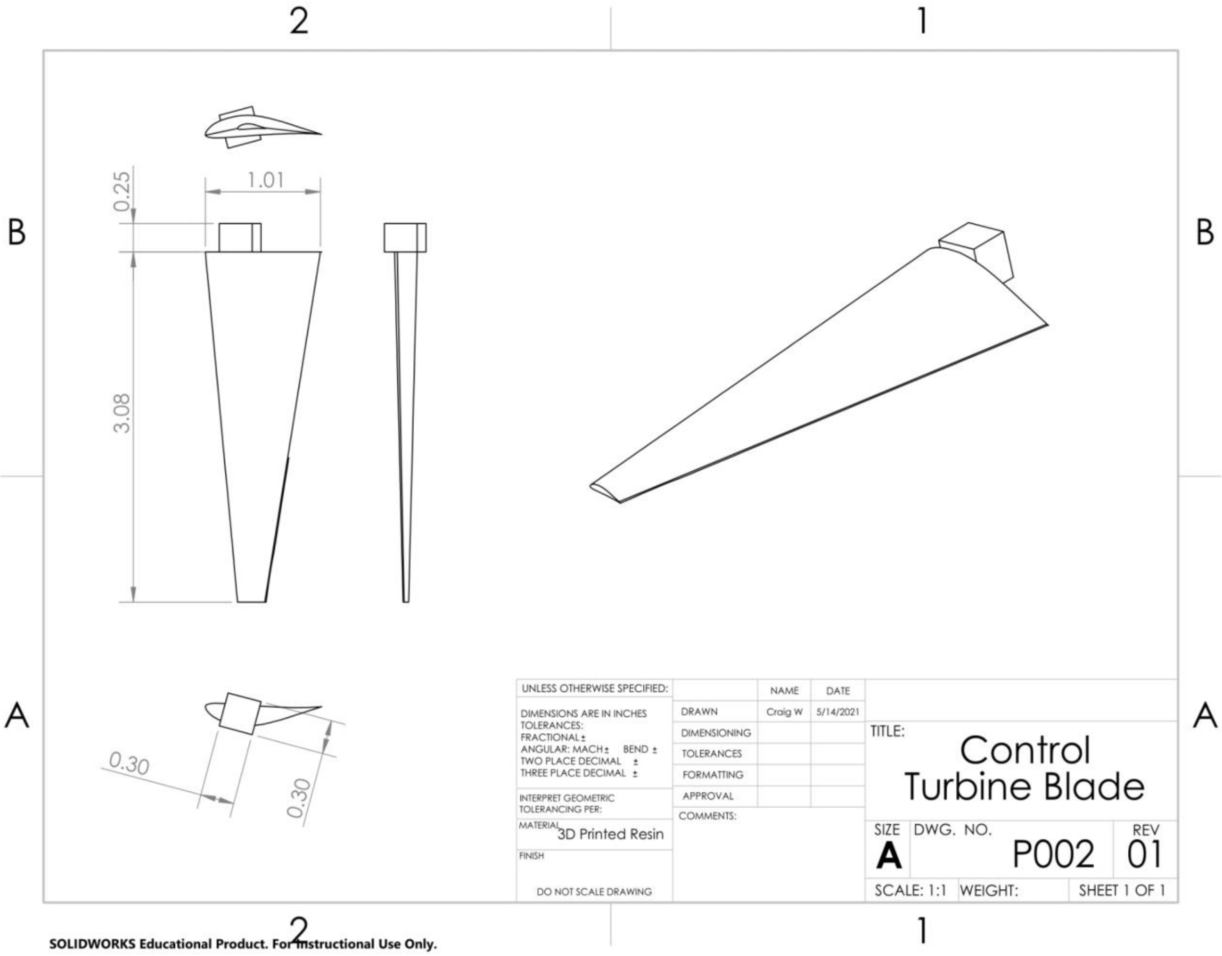
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ANGULAR: MACH ± BEND ±
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MATERIAL 3D Printed Resin
FINISH
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NAME
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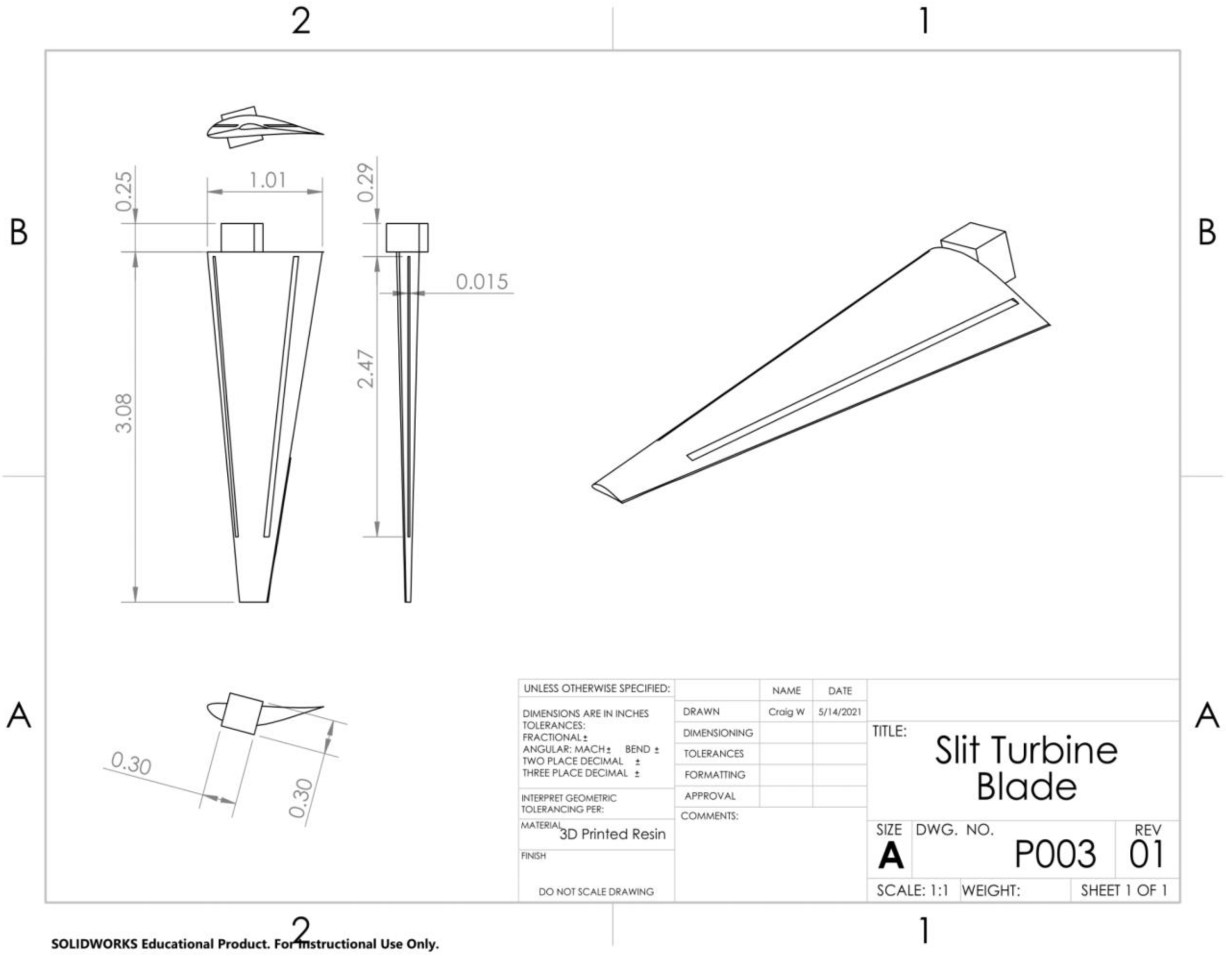
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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL 3D Printed Resin
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5/14/2021
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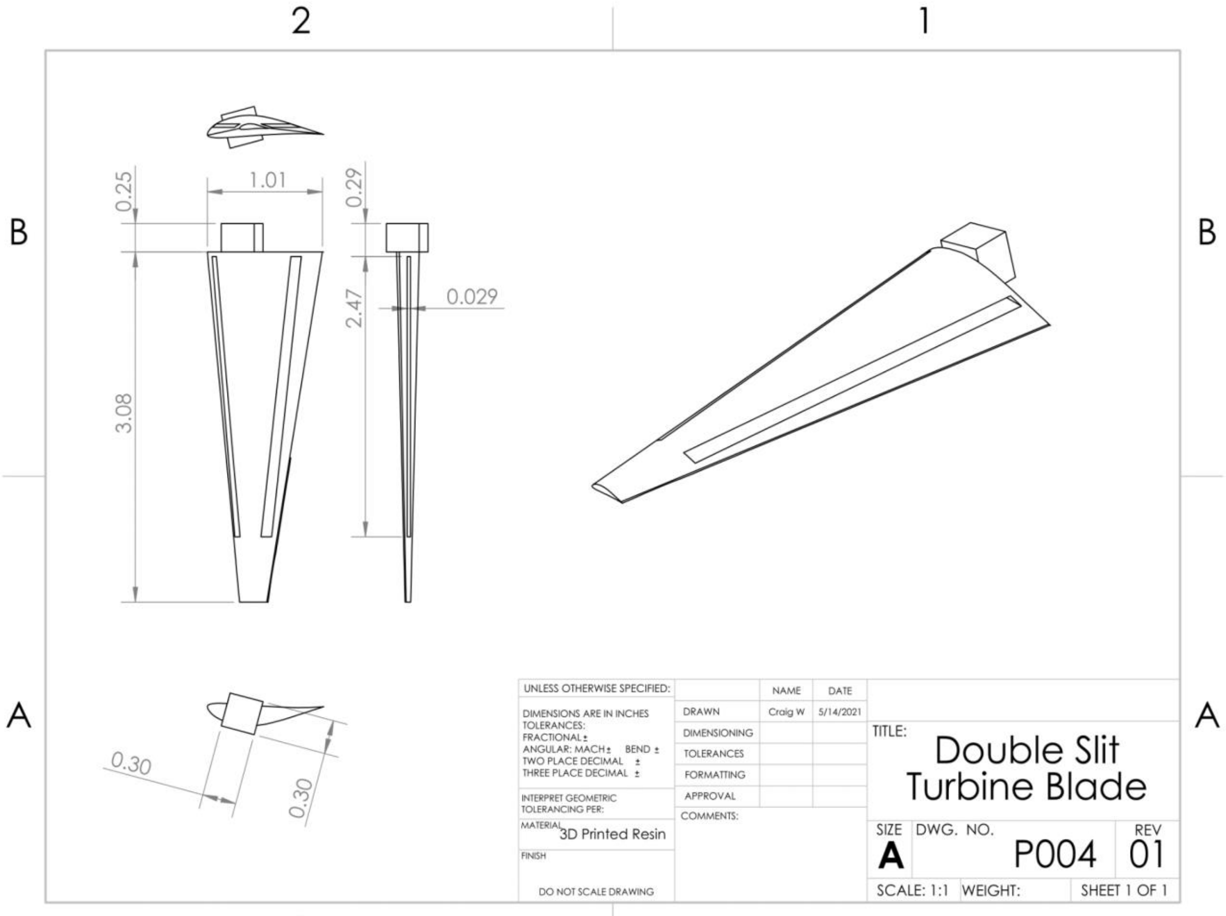

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FINISH

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| TOLERANCES | | |
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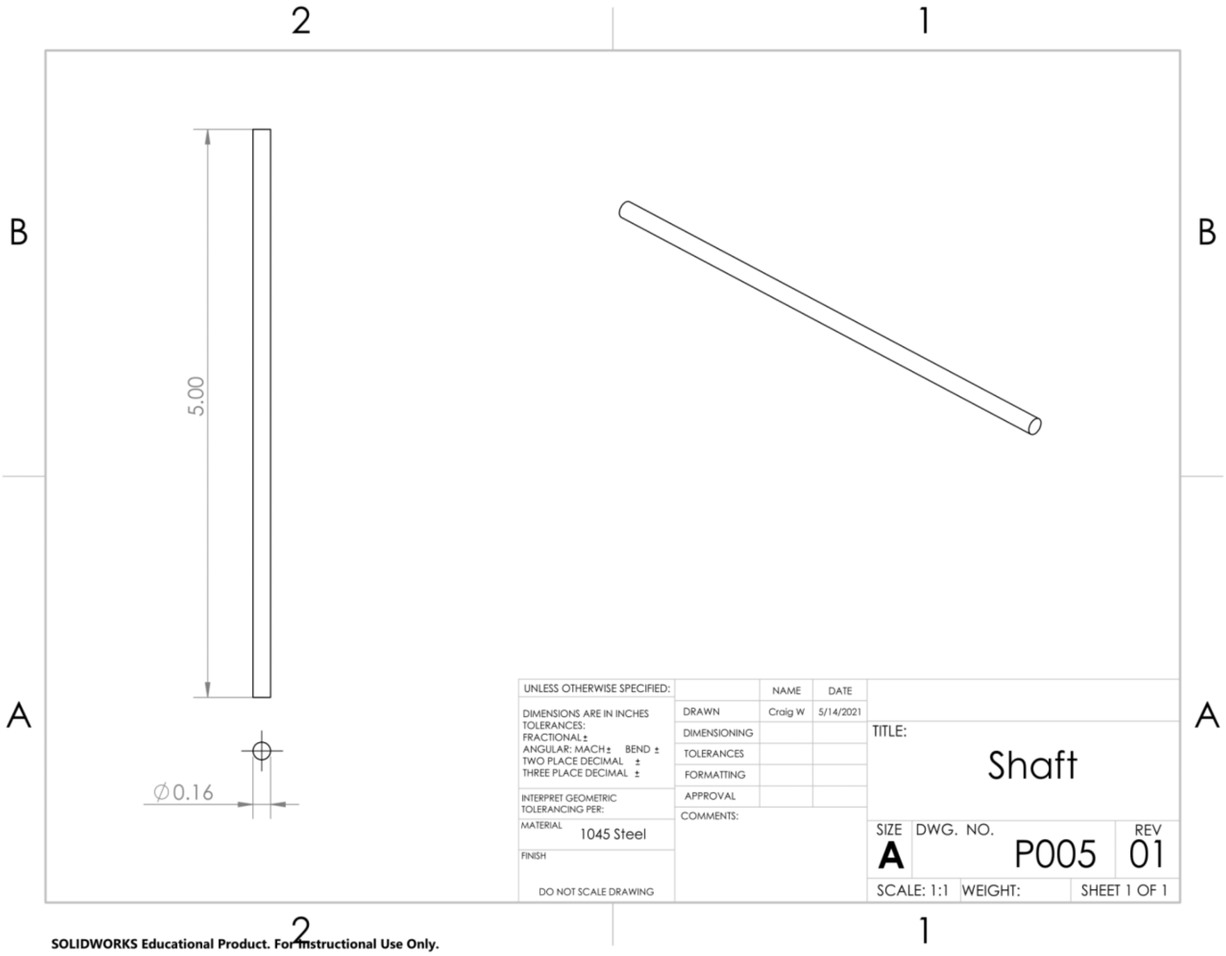

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| TOLERANCES | | |
| FORMATTING | | |
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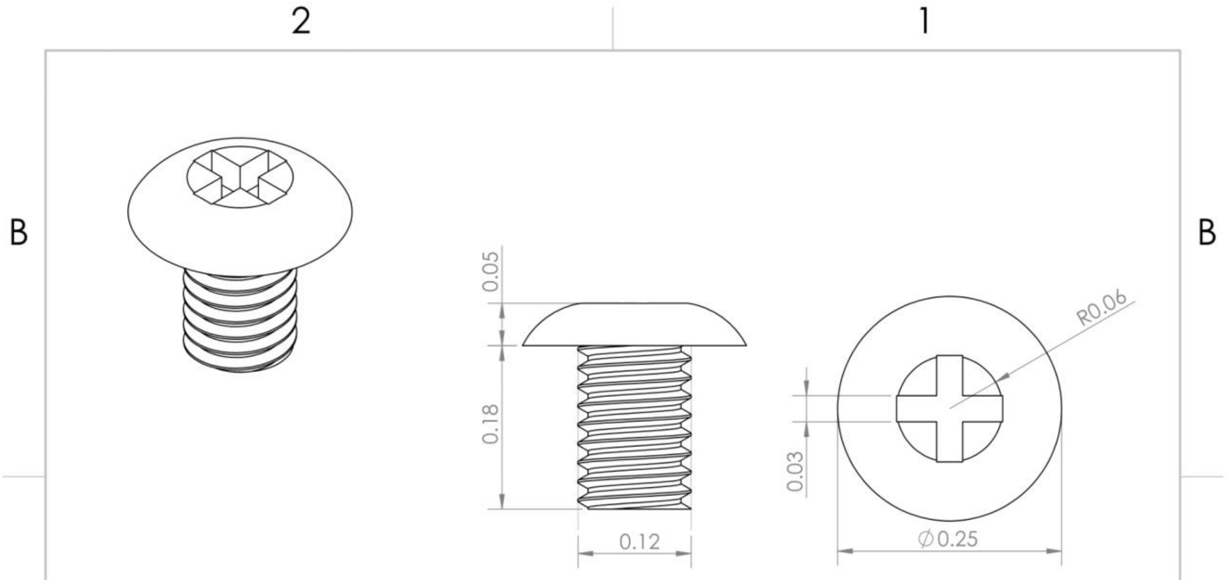

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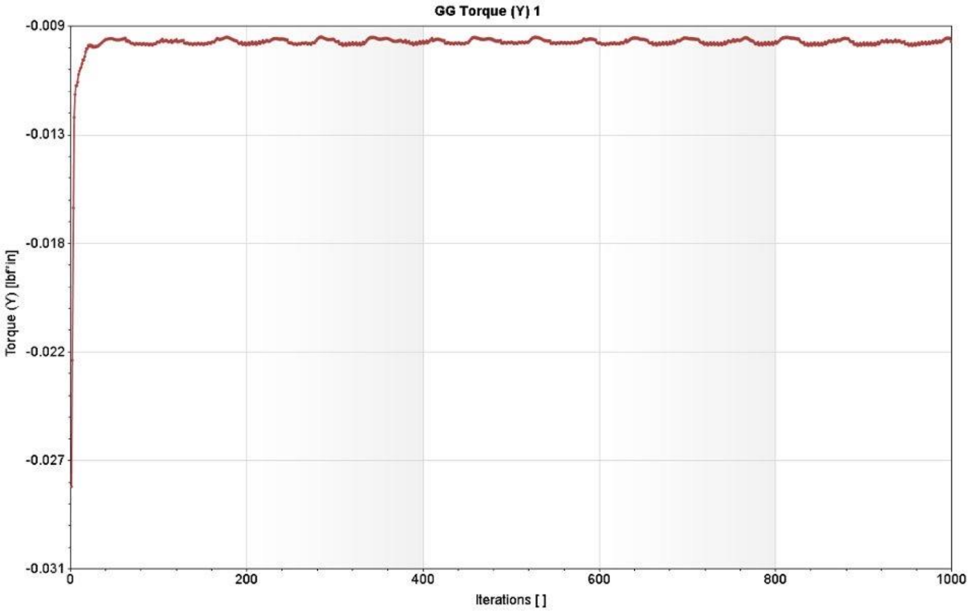
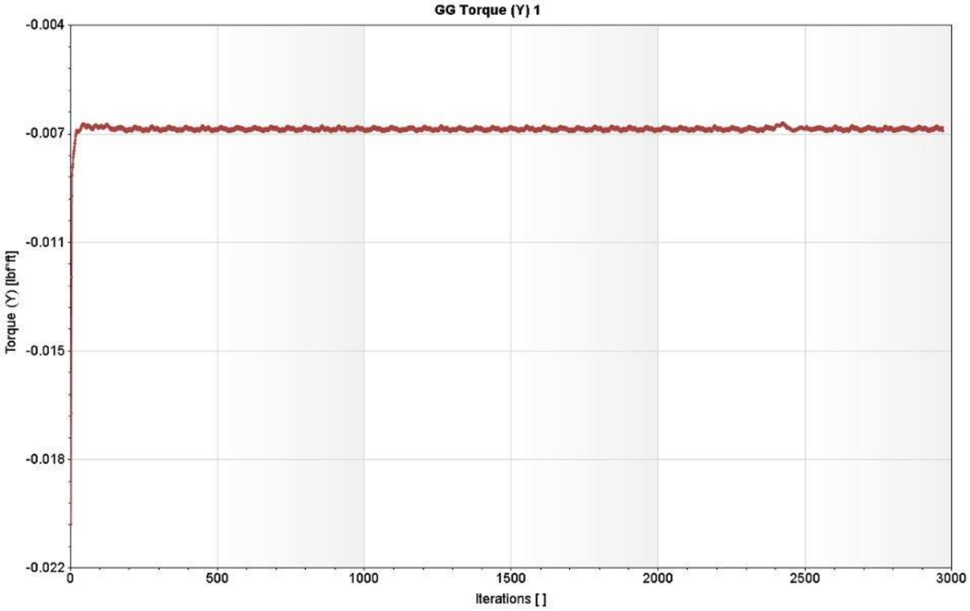
# Appendix C: Solidworks CFD Output Data



Dataset 1: Shaft Torque at 20 mph (lbf*in)



Dataset 2: Shaft Torque at 60 mph (lbf*ft)

## References

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