Quadcopter Airfoil Analyses

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Abstract

This project focuses on the aerodynamic analysis of airfoils for quadcopter applications, aiming to optimize the performance of quadcopters through the selection and analysis of various airfoil profiles. Quadcopters are unmanned aerial vehicles with four rotors arranged in a symmetric configuration. Each diagonal pair rotates in the same direction, allowing the offset to ensure the quadcopter remains level. The airfoil selection is crucial as it impacts aerodynamic performance, stability, and efficiency.

The parameter of interest in these airfoils is maximum thrust and settling thrust produced, along with material wear of the propellers themselves. The testing of thrust production was done with the construction of a fish scale. This was built with wood, a bearing, rubber padding, a scale, and various 3D printed custom components. The details of this testing unit will be discussed further in a later section.

Furthermore, the findings of this research can be utilized in the design and optimization of quadcopter platforms for various applications outside of academic studies. However, with this semester ending, more research on other parameters could not be done. The continuation of optimizing other design parameters would enhance the overall understanding and performance capabilities of quadcopters.

Contents

1. Introduction

The concept of this project began with knowing how airfoil selection impacts airplane lift, and if this same knowledge is applicable to quadcopters. The comprehensive implementation of airfoil aerodynamics comes from both industry experience and class coursework. After taking the Intro to Aerodynamics course this past fall semester and the Fundamentals of Flight course this current spring semester, we have learned that an airfoil's profile is significantly important as it directly affects lift generation.

For several projects in Intro to Aerodynamics we were shown how to navigate the public airfoil database, Airfoiltools.com. Here is where we researched and selected our airfoils. The categories of airfoils chosen were symmetric, high camber, and rectangular. In addition to the three chosen to manufacture ourselves, we also chose to test an aftermarket set of propellers which was purchased online. Including the manufacturer propellers that came with the quadcopter, the resulted testing is with five sets of propellers.

Over the last several years quadcopters have gained significant attention from commercial consumers as it is now affordable for the public to purchase these, using them for applications such as videography, surveillance, and mapping. The performance and efficiency of quadcopters are directly influenced by their aerodynamic characteristics, the main contributor being the propeller's airfoil. The goal of this research paper is to discuss the differences in airfoil performance as it pertains to the focus of thrust generation. The reasoning and construction process of the testing apparatus will be explained in detail along with the corresponding results. Further ways in which this research project can be expanded are to include the optimization of other parameters, some of which will be stated in a later section.

2. Outline of Subject matter

2.1 Introduction

The overall design of this project is testing five different sets of propellers, consisting of the manufacturers' set, three sets imported from Airfoiltools.com and 3D printed, and an aftermarket third-party set purchased online. Each propeller set is installed using the same hardware included with the quadcopter. Once installed, the quadcopter is then attached and secured to the fish scale apparatus and tested in multiple set time intervals, allowing us to collect the maximum and settling thrust data for each run time.

2.2 Design

The initial design of this research topic was to have the quadcopter lift payload until failure for each set of propellers. After discussing this with multiple professors on the best approach, the suggestion that seemed the most logical and appropriate was to construct a fish scale thrust stand. This allows us to get a more exact reading since the scale has a higher resolution (1 gram) than adding payload in larger intervals (1 ounce). An additional benefit is by constraining the quadcopter to only go vertically, it limits its ability to roll or yaw which could lead to a lesser maximum thrust.

The decision to design three different propellers came from wanting to cover three diverse categories of airfoils: symmetric, high camber, and rectangular. Symmetric airfoils are typically incorporated in helicopter rotors or aerobatic airplanes because of the equally distributed pressure balance on each surface. High camber airfoils are preferred in scenarios where there is low takeoff speed or a short takeoff distance, and the combination thereof. The camber allows there to be a pressure difference between the top and bottom surfaces of the airfoil, resulting in greater lift generation. Rectangular airfoils are not used on any practical flight aircraft as they are not relatively aerodynamic, typically only used in tutorials or examples to understand general concepts. Unless a model plane has a wing or tail made of cardboard, this airfoil shape is presumed to be quite unstable in flight. This was chosen to decern if an airfoil is rotating at a high speed, does the shape impact the flight stability.

2.2.1 Design Procedure

The quadcopter that is used in this research opportunity is the Bwine F7MINI.

The construction of the fish scale thrust stand will be disclosed first, followed by each propeller's manufacturing process.

The materials used to build the thrust stand include the following:

- One wooden 2 ft long 2 in x 4 in
- One wooden base 12 in x 26 in x ½ in
- One wooden 1 ft rod ¾ in diameter
- One ball bearing with ¾ in inner diameter
- One piece of rubber padding
- One digital fish scale
- One counterweight
- One custom 3D printed drone securing bracket component
- Two custom 3D printed rod to base mounts
- Two rubber bands
- Various hardware

The wooden components, rubber padding, and various hardware were purchased from Home Depot, and the bearing was purchased from Tractor Supply Co.

All the 3D printed components were created in SolidWorks, sliced in Cura, then printed with polylactic acid (PLA) at varying infill. The two identical mounts were printed at 25% triangular patterned infill since they are essentially only holding the rod. The diameter of the mounts is 0.751" to allow for the printing tolerance, resulting in a press fit. The SolidWorks model can be seen below in Figure 1.

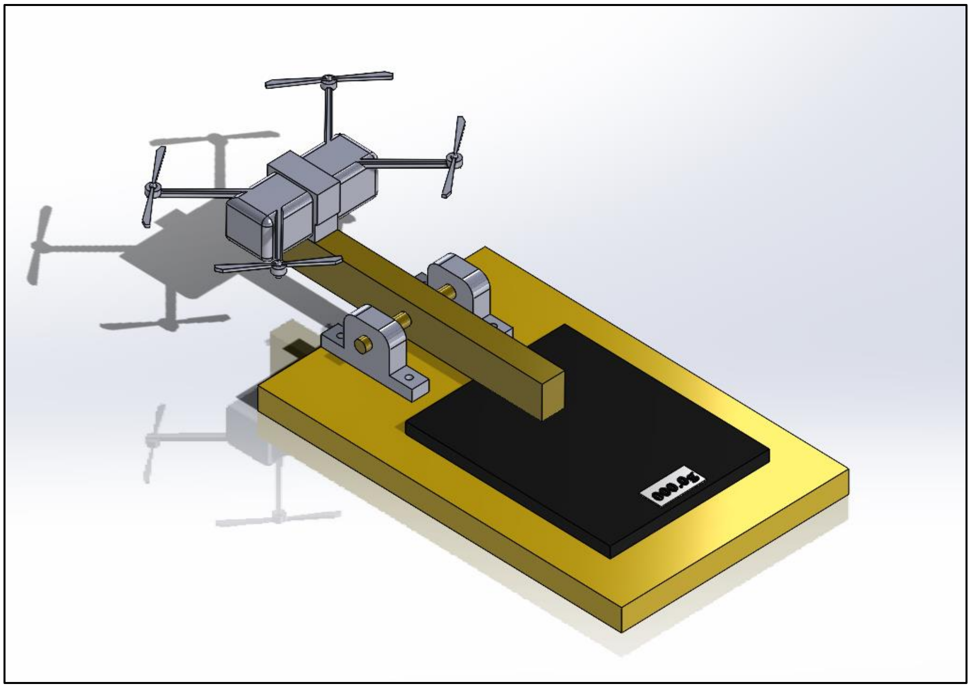


Figure 1

The quadcopter securing bracket is made of two pieces, a stationary bottom, and a removable top, both printed at 50% infill. The bracket is snug to the quadcopter to diminish any potential yaw or roll motions. The bottom section is secured into the lever arm with screws. There are two slots, one on each side of the quadcopter, where the top piece secures into as a clip. The SolidWorks model for each can be seen below. The bottom is Figure 2, and the top is Figure 3.

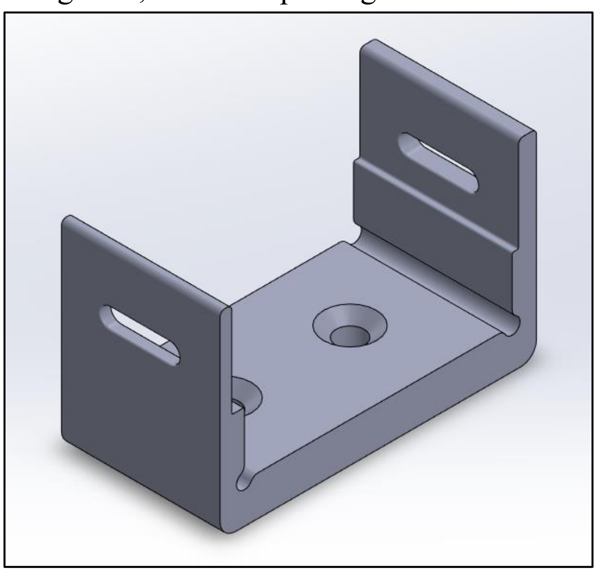


Figure 2

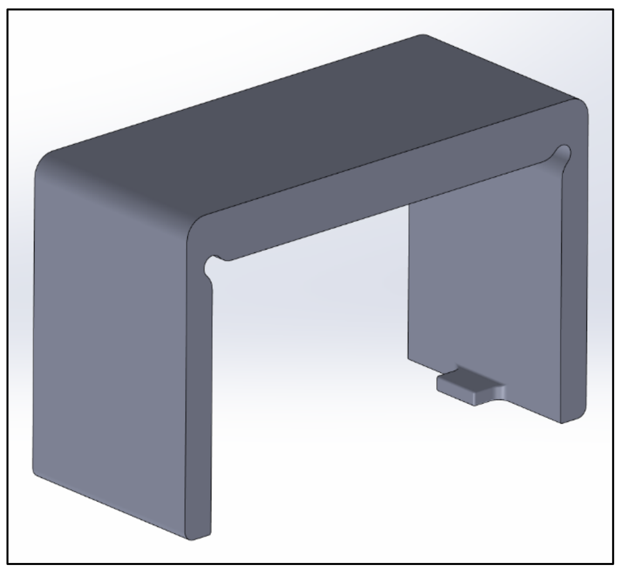


Figure 3

Once printed, these mounts are placed on the rod, at the appropriate, measured distance, and screwed into the base, this set up can be seen in Figure 4, which can be seen to the right. This concludes the design and construction of the static elements.

The lever arm is the dynamic element of this thrust stand, converting the upward thrust force to an equivalent downward force measured as pressure by the fish scale. In order to minimize any friction involved in the transferring of force, a ball bearing was selected to be the pivot point. The 2 in x 4 in was reduced to ¾ in x 2 in. The center of each direction was marked for the exact middle. The bearing was to be press fit into the lever arm and remain flush on one side. To accomplish this, a counterbore of the bearing diameter and thickness was drilled. A through hole of 1 in diameter, concentric to the counterbore, is drilled, allowing the bearing to move freely around the rod with no interferences. The bearing was press fit and secured into the lever arm with JB Weld adhesive. The stationary quadcopter securing bracket is screwed into the predrilled holes in the level arm. A section of rubber padding is cut and glued to the surface of the lever that interfaces with the scale. This assembly is shown in Figure 5 to the right.

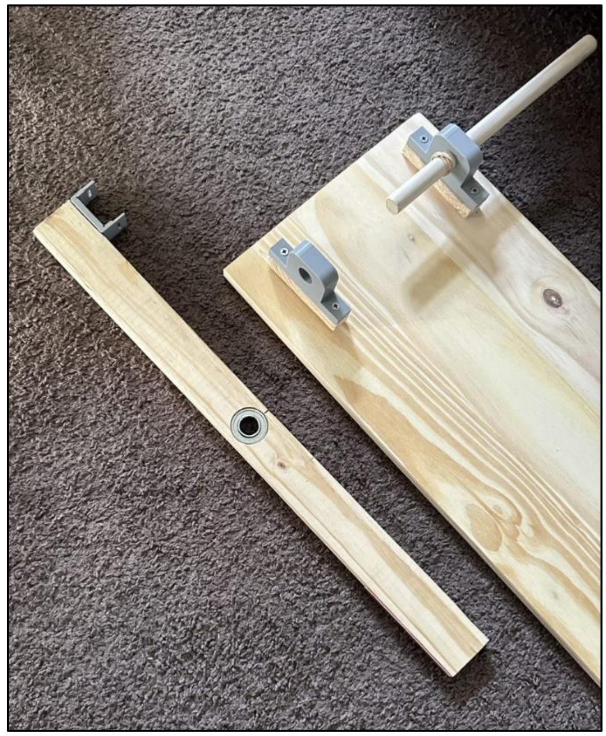


Figure 4

Figure 5

The lever arm slides onto the rod between the two mounts and is secured with a rubber band on each side to eradicate any unwanted lateral movement, as seen in Figure 6. The scale is then placed on the base and lined up under the rubber of the lever arm. The operational state of the thrust stand can be seen below in Figure 7.

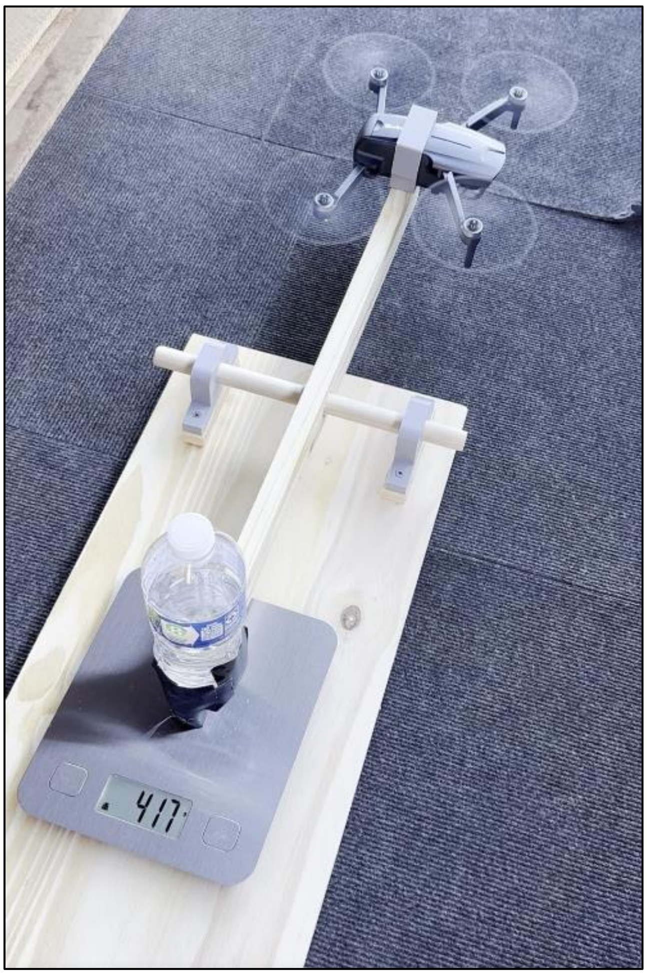


Figure 7

Figure 6

The three sets of propellers that were 3D printed all followed the same design and manufacturing process. The lengths of each propeller are 0.057 meters to remain consistent with the length of the manufacturer's propellers. The angle of attack of all 3D printed propellers varies, depending on the length from the interfacing diameter. Each motor rotates two individual propellers that are offset from the motor's axis of rotation. Each propeller is comprised of an interfacing diameter and the airfoil itself. The interfacing diameter does not sit on the axis of rotation of the motor shaft.

Propeller Set	Distance (m)	Chord (m)	Angle of Attack
3D-Printed Symmetric	0.004	0.011	30°
	0.025	0.016	40°
	0.054	0.009	15°
3D-Printed High Camber	0.004	0.011	30°
	0.025	0.016	40°
	0.054	0.009	15°
3D-Printed Rectangular	0.004	0.011	30°
	0.025	0.016	40°
	0.054	0.009	15°

Table 1

This closely resembles the manufacturer's airfoil; however, it is important to note that the manufacturer's airfoil is significantly more complex. A sweep of three different airfoils (at various chord lengths and angle of attack) was used to design the 3D printed propellers. The manufacturer airfoil's chord length and angle of attack change simultaneously as a function of distance to the interfacing diameter. The large difference between each propeller set is the cross-sectional geometry for each set. Two different airfoils were chosen for the first two 3D printed sets and a rectangular geometry was chosen for the third 3D printed set. These various cross-sectional geometries were chosen in hopes of clearly identifying the difference in aerodynamic efficiency between geometries. For example, we expect the high camber airfoil to produce the most thrust (or lift) and the rectangular geometry to produce the least amount of thrust.

The symmetric airfoil chosen is the NACA 0015, as seen below in Figure 8, which is from Airfoiltools.com.

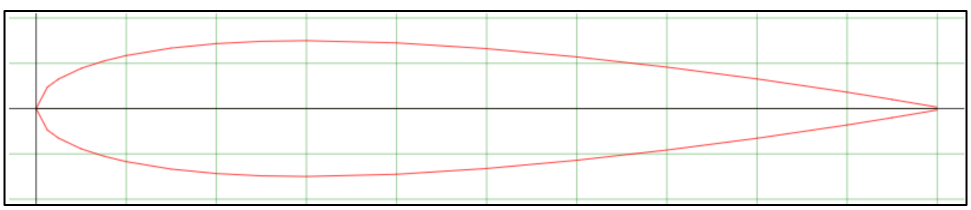


Figure 8

On that website, there is a Dat file provided that can be downloaded and imported into SolidWorks as a drawing file. From there, the airfoil is sized to appropriately fit the propeller pin interface. With the geometry finalized, this file is then exported as a stl which opens in the 3D printer slicing software Cura. The infill of all eight propellers is at 100%. Despite printing eight, not all eight are the same, as not all four rotors rotate the same direction, thus, the leading edge of four propellers must be mirrored. The propellers are printed with PLA.

The high camber airfoil chosen is the GOE 448, as seen in Figure 9, which is also from Airfoiltools.com. The camber line is the yellow, curved line in the airfoil.

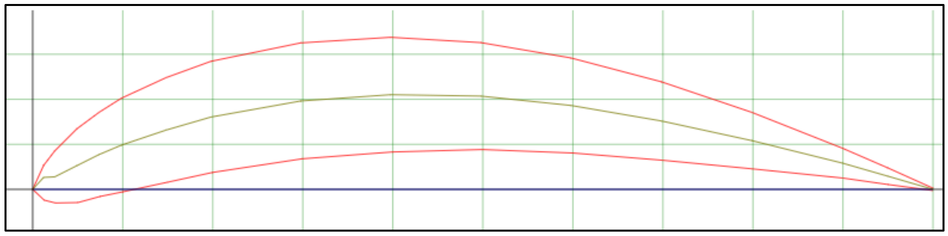


Figure 9

The rectangular airfoil is a rectangle with a thickness of 0.002 meters and width of 0.015 meters, remaining consistent with the manufacturer.

All 3D printed propellers were printed using FDM (Fused Deposition Modeling) as the 3D printing process. Figure 10 illustrates this process below where material is heated then deposited in layers along the z-axis until a final solid part is completed (Figure 10B). Each propeller was printed so that the upper surface of the airfoil would be as smooth as possible, and the lower surface would be in contact with the support material required for a successful print.

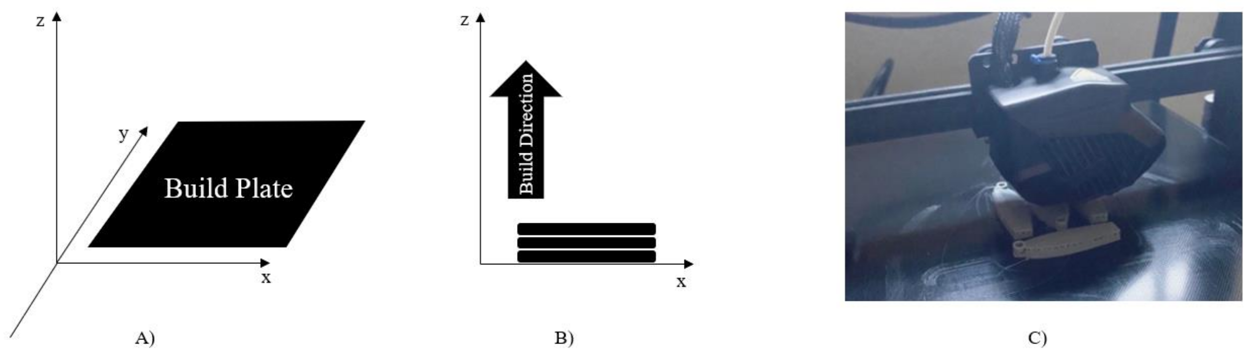


Figure 10

The aftermarket propellers are shown in Figure 11 on the left (orange stripe), which are next to the manufacturer's propeller on the right (white stripe). The overall shape of the propellers look very similar, however the aftermarket propeller has a more subtle sloping leading edge versus the manufacturer propeller, allowing more material to attach to the interfacing diameter.

Figure 11

The side profile in Figure 12 below displays a difference as well, with the aftermarket propeller having a larger angle of attack at the end.

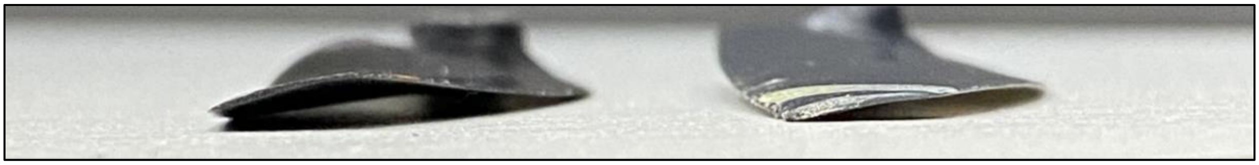


Figure 12

2.2.2 Design Details

A significant design detail is to include a counterweight opposite the quadcopter to balance the lever arm. The lever arm should lightly rest on the scale, which is then tared before flight. This allows the quadcopter to immediately interface with the scale, which avoids losing any potential thrust. Initially to find the minimum counterweight mass, a water bottle was fastened to the lever arm and filled with water until the critical point was reached. The water bottle and fasteners were removed and weighed, then replaced with a more permanent solution of equal weight.

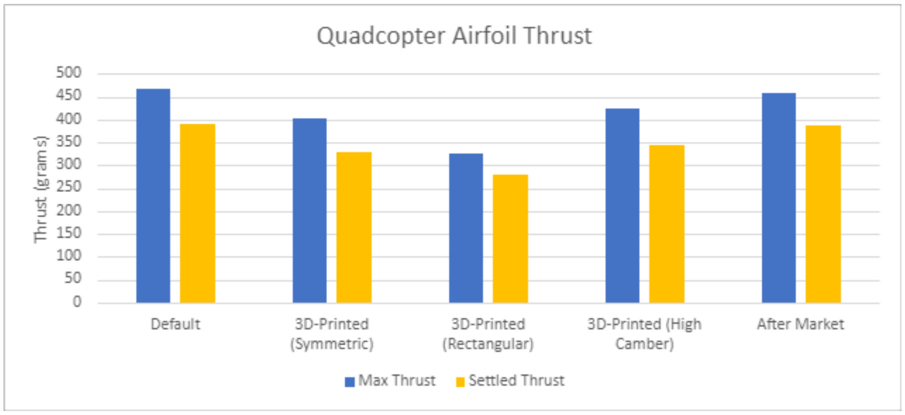
The thrust is measured at a fixed power governor. The quadcopter is given an immediate full throttle for each propeller set.

Originally, the idea of this project was to only record maximum thrust. However, after running multiple trials with the manufacturer's propellers, the quadcopter recognized that the altitude remained unchanged. As a result of thinking it was stuck, it would lower the revolutions per minute (RPM) to avoid draining the battery. The thrust force at which it settled during this interval is documented as the "Settling Thrust."

2.3 Verification

The testing process consisted of securing the propellers, clipping in the quadcopter, taring the scale, then running multiple trials to gather reliable data. Each propeller was run in 30 second intervals for 10 trials. At the start of each new propeller testing, the battery was replaced with one that was fully charged. Since there were two batteries, testing was able to remain constant. The changing of the battery was done to ensure that each propeller had the maximum available voltage.

The data collected is organized by the propeller type and includes the trial number, maximum thrust, and settling thrust. The entirety of the datasheet can be found in Appendix A, titled "Data Table 1: Total Thrust Dataset". With this data, the average of each maximum and settling thrust was calculated and displayed in Bar Graph 1.



Bar Graph 1

The results seem theoretically accurate, as the best performance came from the manufacturer and the worst came from the rectangular airfoil. The specific results are discussed in more detail in the following section.

2.4 Results

Thrust is a force that moves an aircraft in the direction of the desired motion. For a quadcopter, that motion is up. Drag is the force that acts opposite to the direction of thrust, slowing an object down. Drag is caused by friction and differences in air pressure. When these forces are balanced the quadcopter hovers in a stationary position. In our experiment we are inducing the stationary position, thus at both the maximum and settling thrust, the drag and thrust remain equal.

Referring to Bar Graph 1 above, the dataset that it is representing is in Appendix A, titled "Data Table 2: Average Thrust Dataset". For convenience it is also included below:

Propeller Set	Average Maximum Thrust (g)	Average Settling Thrust (g)
Default	467.3	389.6
3D-Printed Symmetric	402.5	330.2
3D-Printed High Camber	426.1	344.1
3D-Printed Rectangular	326.3	281.2
After Market	457.9	385.9

Table 2

These results generally aligned with what we hypothesized; the high camber airfoil would have the highest thrust production of the 3D printed propellers. The main reason as to why the 3D printed propellers produced less thrust than both purchased market propellers was the material. PLA is a fully biodegradable thermoplastic that has a tensile yield strength of approximately 4600 psi (32 MPa), as seen in Figure 13. Tensile yield strength is the strength of the material before it permanently stretches. The 3D printed propellers may produce a higher thrust when compared to the manufacturer's propellers, but this is highly dependent on the angle of attack and overall tensile strength. If the angle of attack of the

3D printed propellers is too high close to the interfacing diameter, then the material is expected to fail, as the area interfacing between the interfacing diameter and airfoil itself decreases.

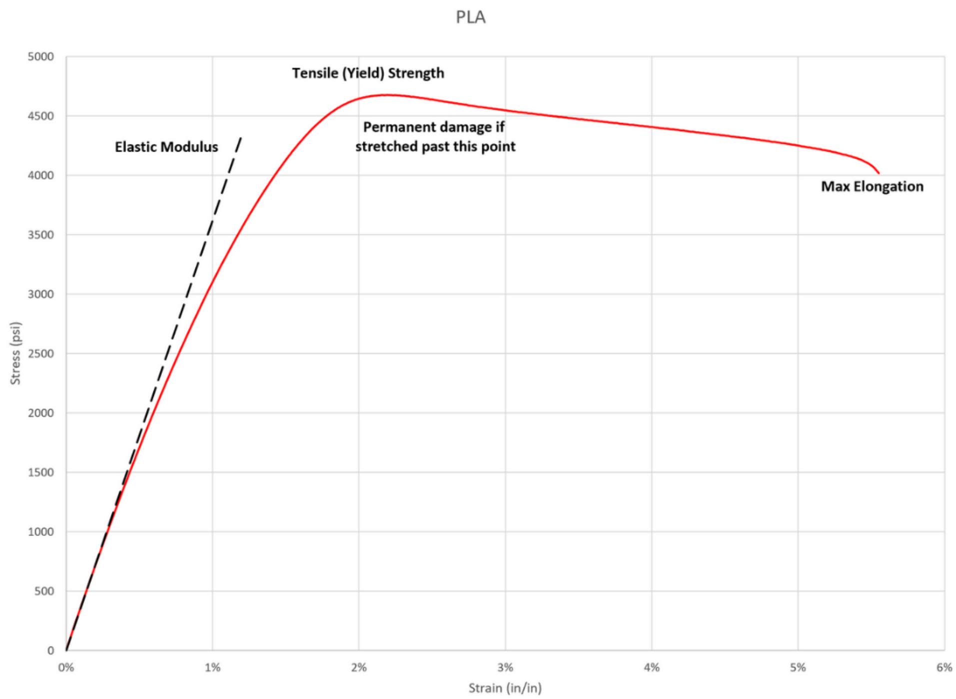


Figure 13

This is significantly less than the tensile strength of the purchased propellers, about 9500 psi (66 MPa). These propellers are made of a plastic called polycarbonate and manufactured via injection molding. The process of 3D printing is a linear layering process, thus allowing the possibility of air to travel through the print if there are any misalignments between layers. Considering these differences between materials, it is plausible that this contributes to the lower thrust production.

It is known that the different shape of the aftermarket blade is partially responsible for its better performance, this can be said because of the results of the 3D printed propellers and their baseline of chord/angle of attack. This means that the cross-sectional area significantly impacted total thrust calculated. However, the material of the aftermarket propeller also had a significant impact as smoothness was greatly increased. The weight of the aftermarket propellers is slightly less than that of the 3D printed propellers. It can then be inferred that the aftermarket propeller has less drag as a result of minimal manufacturing impurities.

2.5 Costs

The cost breakdown is listed in the following table, Table 3.

Part Name	Quantity	Price	Vendor
Circular Rod (¾")	1	$4.34	Home Depot
2 ft 2"x4" (Lever Arm)	1	$2.99	Home Depot
Wooden Base Plate	1	$10.00	Home Depot
PLA (Propellers/Mounts)	50 grams (7 pcs)	$1.25	Creality
Bearing	1	$12.99	Tractor Supply
Rubber Pad	1	$5.82	Home Depot
Screws	6	$3.50	Home Depot
5kg Fish Scale	1	$12.99	Amazon
Aftermarket Propellers	1	$11.99	Amazon
TOTALS:	20	$65.87	

Table 3

The entire experiment required 20 pieces of various hardware totaling $65.87. Each off-the-shelf component was sourced from either Home Depot, Amazon, or Tractor Supply. The group utilized a personal 3D printer to manufacture the mounts and propellers needed to conduct the experiment. The cost of the PLA was approximated at 50 grams worth of a 1-kilogram roll.

3. Conclusion

In conclusion, the group's custom thrust stand apparatus effectively measured the thrust of various sets of propellers. Examining the results of the experiment it is evident that thin, smooth, high camber airfoils seem to be more effective at generating lift for quadcopters, amongst the propellers manufactured with the PLA. Similar research has been conducted at the University of New Mexico's Mechanical Engineering Department [Ref. 6] where they concur "3D printing is a relatively new technology and although it facilitates the manufacturing process, it also affects the quality and shape of a design surface. These effects are not well understood but are of importance for aerodynamic performance of propellers. This may be of particular importance for small propellers. Because studies are scarce (if any) in this area, one of our research objectives is to investigate how 3D printing affects propeller's thrust and energy consumption.". The results taken from this referenced case study may not apply to our project, as the basic design of propellers significantly varies. There are two separate propellers assembled to each motor on our quadcopter (each propeller consisting of one airfoil), but the University of New Mexico's Mechanical Engineering Department had one propeller comprised of two airfoils rotating about the same axis as their motor.

4. Future Work

Future work may include exploring more advanced printing capabilities such as epoxy resin 3D printing, using a smaller nozzle to refine layer lines, or utilizing high strength materials (PETG or carbon fiber nylon). Optimizing these manufacturing technologies would enable higher profile surface precision of the propellers and increase the tensile strength, in turn rivaling the injection molded polycarbonate.

References

[1] “NACA 0015”, Airfoil Tools, 2023

[2] “GOE 448”, Airfoil Tools, 2023

[3] Home Depot, 2023

[4] Tractor Supply Co., 2023

[5] “Strength Testing 3D Printing Plastics”, Shadow Regime Design, 2019

[6] Hintz, C., Khanbolouki, P., Perez, A., Tehrani, M., Poroseva, S., “Experimental study of the effects of bio-inspired blades and 3D printing on the performance of a small propeller.”, 2018 Applied Aerodynamics Conference, 2018

Appendix A – Datasets

Data Table 1: Total Thrust Dataset

Propeller Set	Trial Number	Maximum Thrust (g)	Settling Thrust (g)
Default	1	470	391
	2	468	393
	3	469	390
	4	467	391
	5	469	387
	6	467	390
	7	468	391
	8	465	389
	9	464	386
	10	466	388
3D-Printed Symmetric	1	404	332
	2	405	333
	3	403	331
	4	404	329
	5	402	331
	6	403	330
	7	401	329
	8	402	328
	9	400	330
	10	401	329
3D-Printed High Camber	1	429	346
	2	427	345
	3	428	346
	4	426	344
	5	425	343
	6	427	345
	7	424	344
	8	425	343
	9	426	343
	10	424	342
3D-Printed Rectangular	1	328	283
	2	327	281
	3	328	283
	4	326	282
	5	327	281
	6	325	280
	7	326	282
	8	327	281
	9	324	279
	10	325	280
After Market	1	461	388
	2	459	386
	3	458	387
	4	459	387
	5	457	385
	6	458	386
	7	456	385
	8	457	384
	9	458	386
	10	456	385

Data Table 2: Average Thrust Dataset

Propeller Set	Average Maximum Thrust (g)	Average Settling Thrust (g)
Default	467.3	389.6
3D-Printed Symmetric	402.5	330.2
3D-Printed High Camber	426.1	344.1
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