Propeller Analysis

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Purpose

The purpose of this propeller design project was to compare two major design components of propellers and how they affect thrust, torque, and efficiency. The first design component to test was physical size. To test this, a 10x5 propeller, and an 8x4 propeller were designed. Both propellers have the same cross-sectional airfoil, and pitch. Because they have the same airfoil shape and pitch, these propellers should only differ in their geometric scaling. This allows for comparisons to be made about the effect of diameter and chord length on thrust and torque. The second design component that was changed was the pitch and the cross-sectional airfoil. To do this, a 10x3 propeller was designed so it had the same diameter as the 10x5. Unfortunately chord length is slightly different as the 10x3 has a different airfoil cross section which ultimately decides chord length.

To perform these two comparisons, analytical calculations described in Aeronautics 1 and Aeronautics 2 taught by Professor Gallo at George Mason University were utilized to predict performance for each propeller. Next, the propellers were modeled and manufactured by 3D printing to experimentally test them using an RC benchmark 1580 series thrust stand. Once the data was collected, the experimental data was compared to the analytical predictions. Finally, once all of the data was validated from experimental and analytical predictions, comparisons were made between the different design parameters as described before to further understand how each design parameter affects propeller performance.

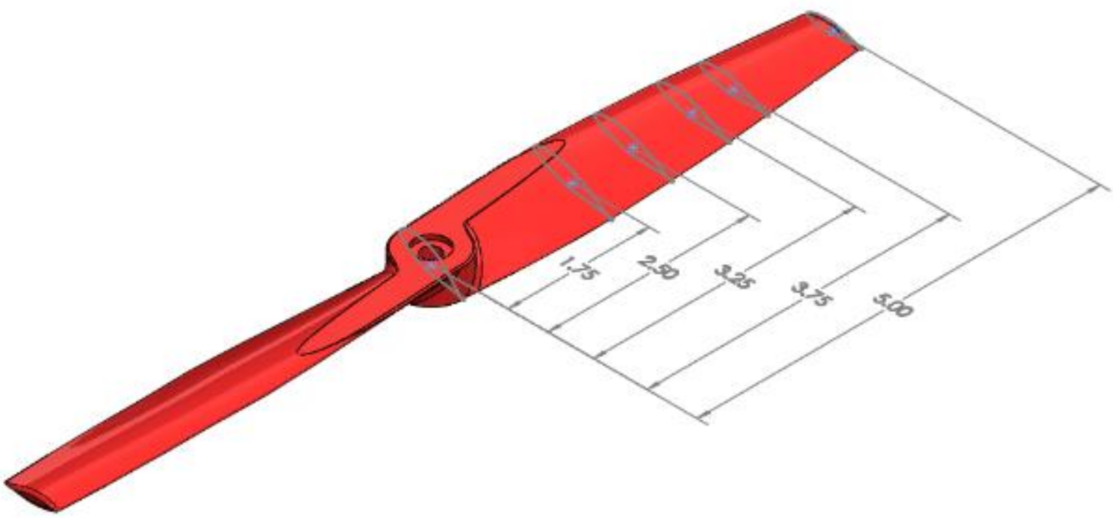
Procedure

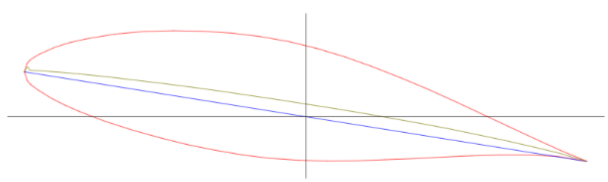
A. Design Configurations

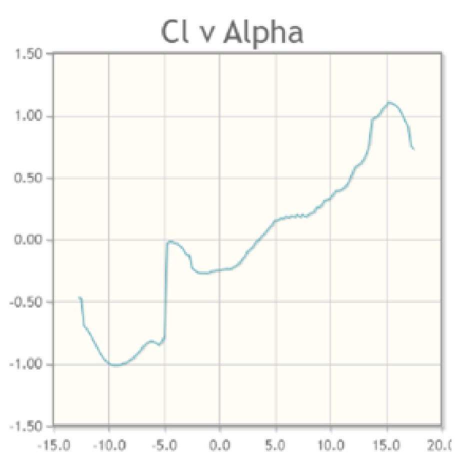
Each propeller was designed using a tabulation of what the angle was at each station, as well as the distance to said station. Each propeller used the same airfoil for the whole blade. From the airfoil information, the chord length, coefficient of lift, and coefficient of drag can be determined. Finally, angle for the first station was selected from the coefficient of lift graph so that the first station had the highest coefficient of lift. After that, every other station's angle was chosen such that the lift generated at each station would be equal to the 1st station's lift. Additionally, the station at the hub of the propeller had an increased thickness to help increase durability of the blades and fillets were used to smooth the transition between the hub and the blade itself.

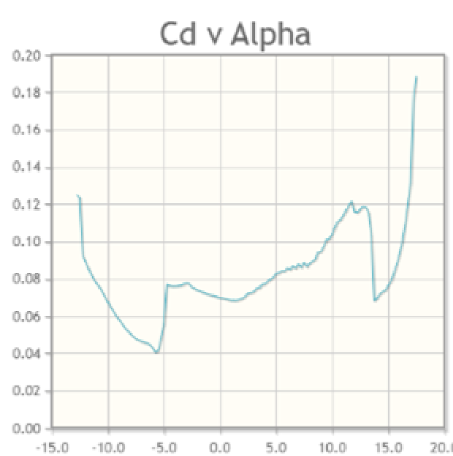
a. 10x5

10x5 - NACA 65(4)-421 AIRFOIL						
Station	0	1	2	3	4	5
Distance (in)	0	1.75	2.5	3.25	3.75	4
Chord (in)	0.85	1	0.98	0.91	0.85	0.536
Angle		17.5	13.5	12	9.04	3
CL		0.95625	0.796875	0.609354	0.35	0.174837
CD		0.19	0.08	0.115	0.1	0.07



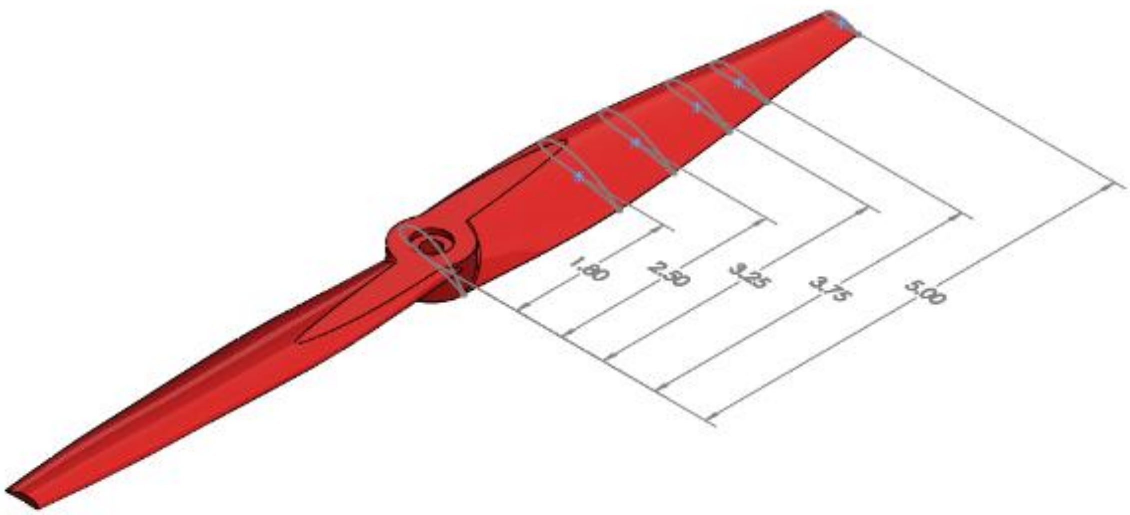


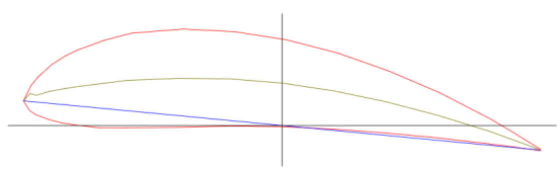


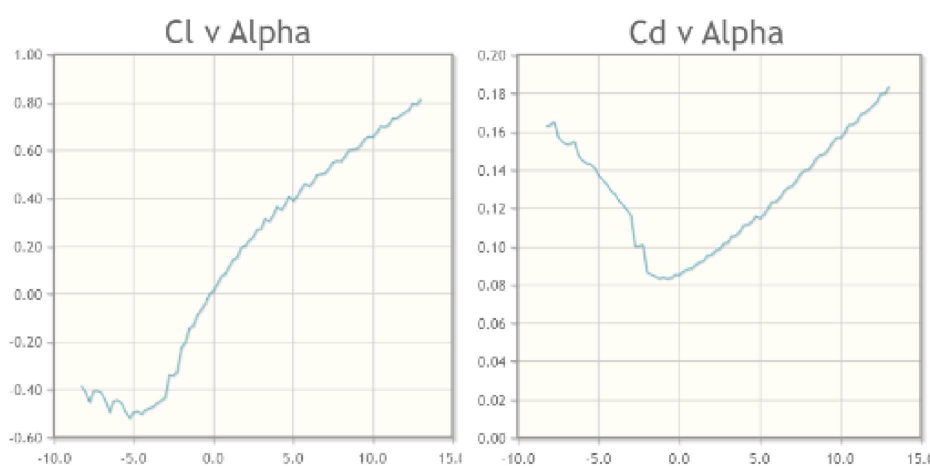


b. 10x3

10x3 - GOE 421 AIRFOIL						
Station	0	1	2	3	4	5
Distance (in)	0	1.8	2.5	3.25	3.75	5
Chord (in)	0.8327	1	0.92	0.78	0.68	0.41
Angle		13	12	9.5	5.455	2
CL		0.826389	0.802849	0.649977	0.4	0.26122
CD		0.18	0.17	0.15	0.115	0.09

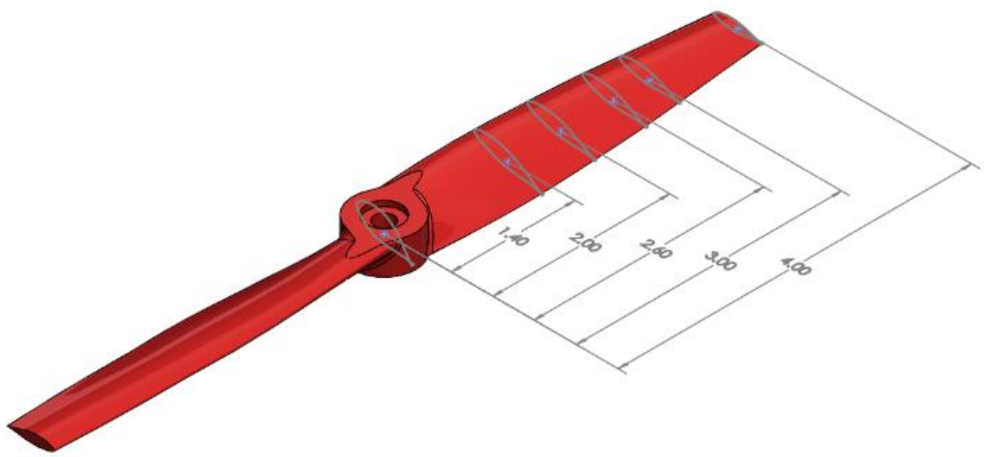


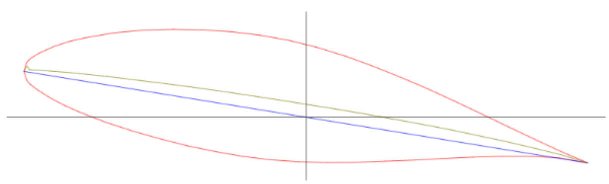


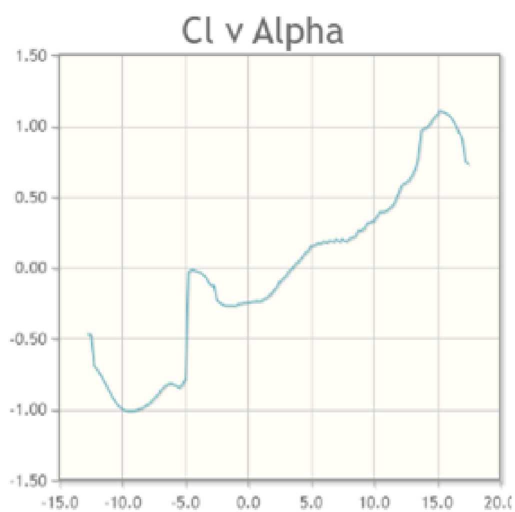


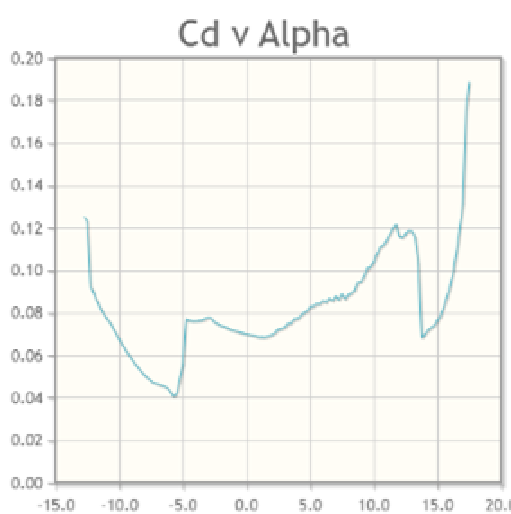
c. 8x4

8x4 - NACA 65(4)-421 AIRFOIL						
Station	0	1	2	3	4	5
Distance (in)	0	1.4	2	2.6	3	4
Chord (in)	0.68	0.8	0.784	0.728	0.68	0.536
Angle		17.5	13.5	12	9.04	3
CL		0.95625	0.796875	0.609354	0.35	0.174837
CD		0.19	0.08	0.115	0.1	0.07









B. Analytical method used to predict performance

a. Thrust

As this test was a static test, thrust and lift are equivalent. To calculate lift, one blade of the propeller was initially split into its respective stations. Once this was done, each station was treated as a wing cross section with uniform angle. Using the website Airfoil Tools, the specific coefficient of lift versus angle of attack graph was used to graphically find coefficient of lift. Then, using the lift equation (Eq. 1) the analytical lift for that specific station was solved for. This entire process was repeated for each station of the propeller. Finally, the lift values were summed together, and multiplied by two to account for the propeller having two blades.

$$\boldsymbol{L = \frac{1}{2} C_l \rho A V^2} \qquad \text{(Eq. 1)}$$

b. Torque

Torque was calculated from multiplying the drag at each station by the distance from the hub to the station. Drag was calculated in the same manner as lift, but used the drag equation (eq. 2) with the coefficient of drag. After all of the torques had been calculated, they were summed up and multiplied by two to account for both blades.

$$\boldsymbol{D = \frac{1}{2} C_D \rho V^2} \qquad \text{(Eq. 2)}$$

c. Efficiency

Propeller Mechanical Efficiency was calculated using a modified version of the efficiency equation (eq. 3). For moving propellers, efficiency relies on axial speed to obtain the propellers power. As this was a static test, there is no axial speed, because of this, propeller mechanical efficiency was used instead and is referred to as efficiency in this report.Due to this change with the static test, the axial speed is left out of equation 3, leaving the units as pound force per watt, which is what the test stand records in.

$$\eta = \frac{\boldsymbol{thrust * axial\ speed}}{\boldsymbol{resistance\ torque * rotational\ speed}} \qquad \text{(Eq. 3)}$$

C. Table of analytically predicted values

a. Thrust

Thrust (lbf)			
RPM	10x5	10x3	8x4
2500	0.13	0.13	0.07
5000	0.51	0.46	0.22
7500	1.14	1.04	0.47
10000	2.15	1.79	0.85

b. Torque

Torque (in*lbs)			
RPM	10x5	10x3	8x4
2500	0.09	0.10	0.04
5000	0.37	0.37	0.13
7500	0.83	0.83	0.27
10000	1.57	1.44	0.50

c. Efficiency

Efficiency (lbf/W)			
RPM	10x5	10x3	8x4
2500	0.05	0.04	0.05
5000	0.02	0.02	0.03
7500	0.02	0.01	0.02
10000	0.01	0.01	0.01

D. Processes and Inputs for 3D printing

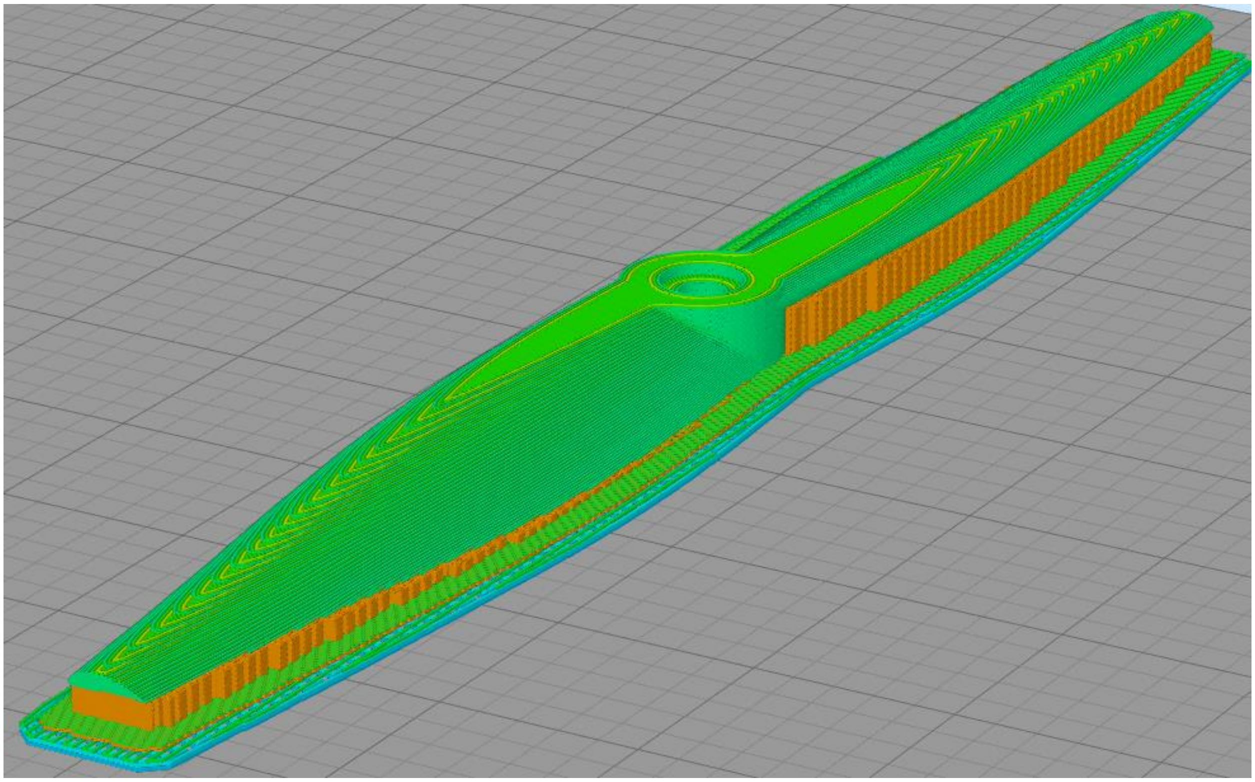


Figure 1: 3D Printed Propeller Model

Propeller designs were converted to a .stl file to be sent to a slicing software that creates the gcode, instruction process, for the 3D printer. Within the slicing software there are parameters that need to be adjusted depending on the model being printed. For a propeller a layer height of 0.2mm would provide sufficient strength without sacrificing a significant amount of dimensional accuracy.

Another important parameter is infill. In most instances an infill of over 30% is redundant, but because propeller blades are thin infill was chosen to be 60%. Having a higher infill adds some additional resistance to deflection and also decreases the chance of the blade snapping.

The exterior of the print was done in 4 shells. These shells are the equivalent of having 4 solid exterior layers, totaling approximately 1.6mm thick, surrounding the infill.

Finally, because the propeller does not lie flat on the print bed a raft and supports had to be used to support the underside of the propeller.

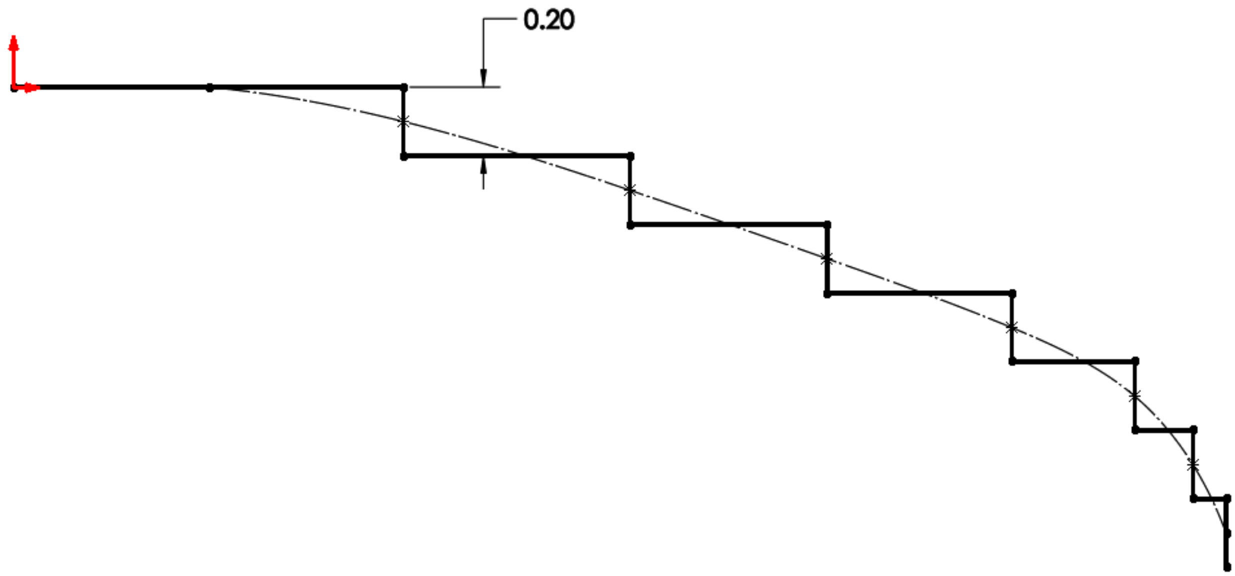


Figure 2: Wet Sanding Profile Shown by Dashed Line

3D printing creates a “stair step” effect on parts, in an attempt to minimize any effect this would have on the collected data the propellers were all wet sanded with 320 grit sandpaper. Additionally, removing the supports from the underside of the propeller left some very rough edges that needed to be smoothed out.

Sanding on any 3D printed part is risky, but even more so with something as thin as a propeller blade. Wet sanding, as opposed to dry sanding, is crucial to prevent sandpaper from clogging and also dissipates some of the heat from friction to prevent melting the heat sensitive plastic.

E. Test procedures propeller performance

The RC benchmark 1580 series thrust stand was used to accurately measure thrust, torque, propeller mechanical efficiency, acceleration, and vibration. This was all accomplished using a high rpm 12 pole motor connected to a powerful electrical power supply. As the tests went up to 10000 rpm's, safety was a major concern during all of the tests. First, a wire mesh cage surrounded the entire test stand to ensure the safety of all using the equipment. Whenever the cage was open, the power supply was turned off so there was no possible way for the motor to start up. Finally, safety glasses were worn at all times when the motor was turned on.

Initially, when the test stand was first set up, it was accurately calibrated according to the instructions on the software. This involved putting the test stand in different positions to make sure the thrust and torque load cells were calibrated. Before any individual test was started, the load cells were tared to ensure that every recording would be accurate.

Procedure

1. Ensure the power supply has been turned off so the motor is not powered.
2. Attach the propeller to the test stand using a nut driver (as depicted in figures 3-5)
3. Close the cage and secure the latch so it may not swing open.
4. Turn on the power supply and connect a computer to the test stand.
5. Tare load cells.
6. Set safety cutoffs.
7. Begin recording data.
8. Use manual control of ESC slider to control the rotational speed of the propeller.

9. Once all the data has been recorded, spin the propeller down till it stops.
10. Disconnect the power supply.
11. The cage may be opened, and the test stand can be accessed for any additional tests.

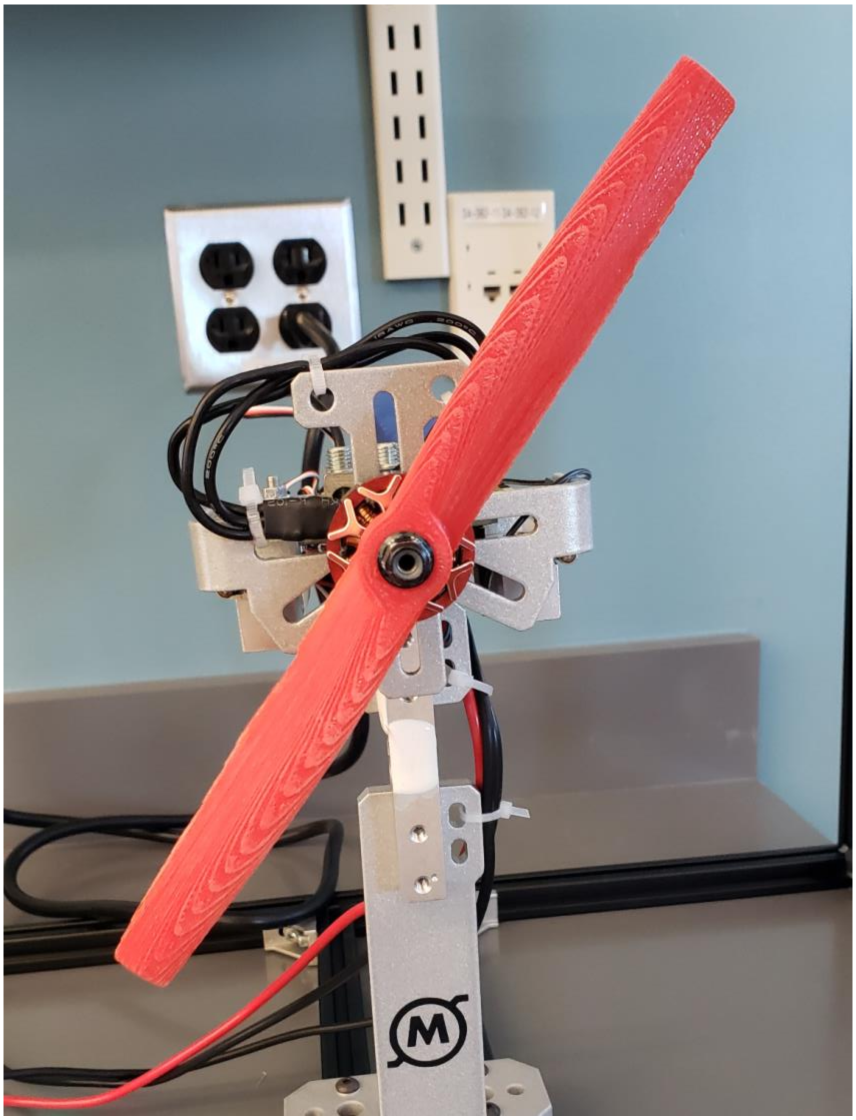


Figure 3: 10x5 Propeller on test stand

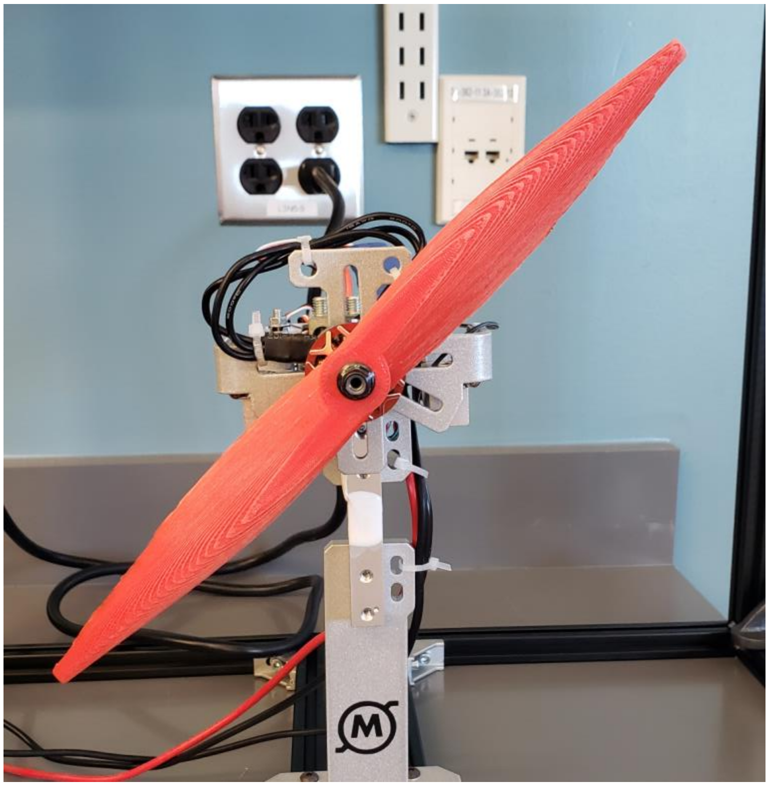


Figure 4: 10x3 Propeller on test stand

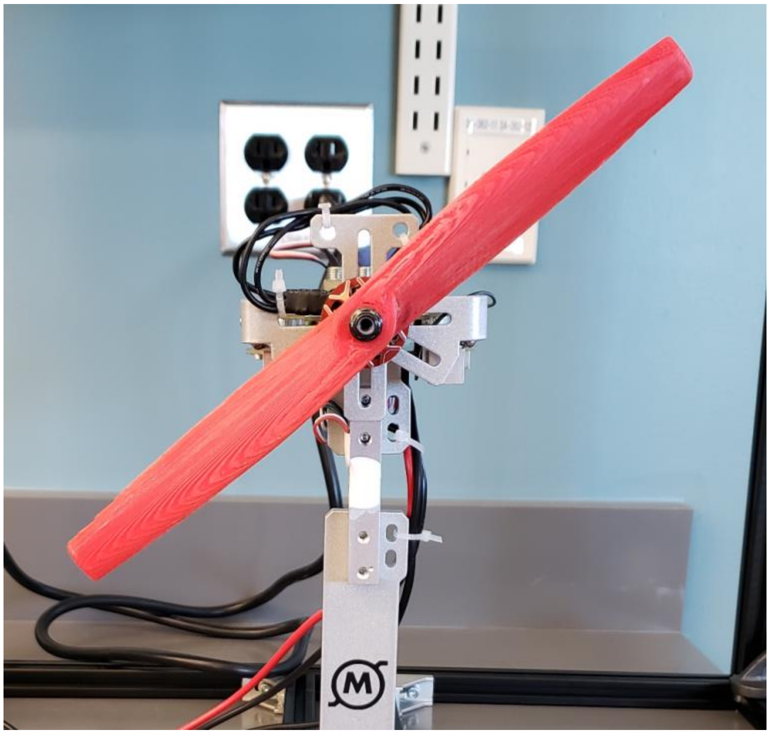


Figure 5: 8x4 Propeller on test stand

Testing Results

A. Methodology

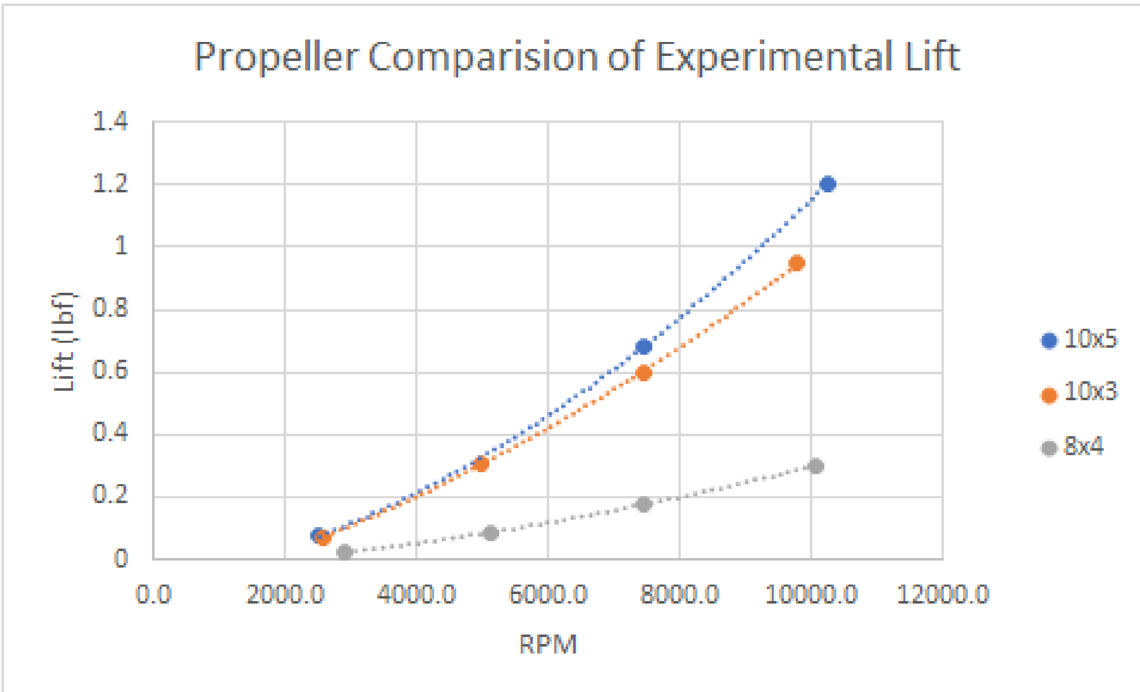
To record the three main outputs, thrust, torque, and efficiency at each major rpm goal, the RPM's were held steady to ensure good data was captured. Holding the rpm constant leads to an excess of data points compared to other rpm values. Any attempt to plot this data would lead to an unreadable mess of points. To clean the graphs up and to reduce the chance of random error, every point around the desired rpm was averaged together. For the other two parameters, vibration and acceleration, this made more sense to analyze as a transient response, so it was not averaged out. Also, as acceleration constantly changed between positive and negative values evenly, averaging it would result in a near 0 value.

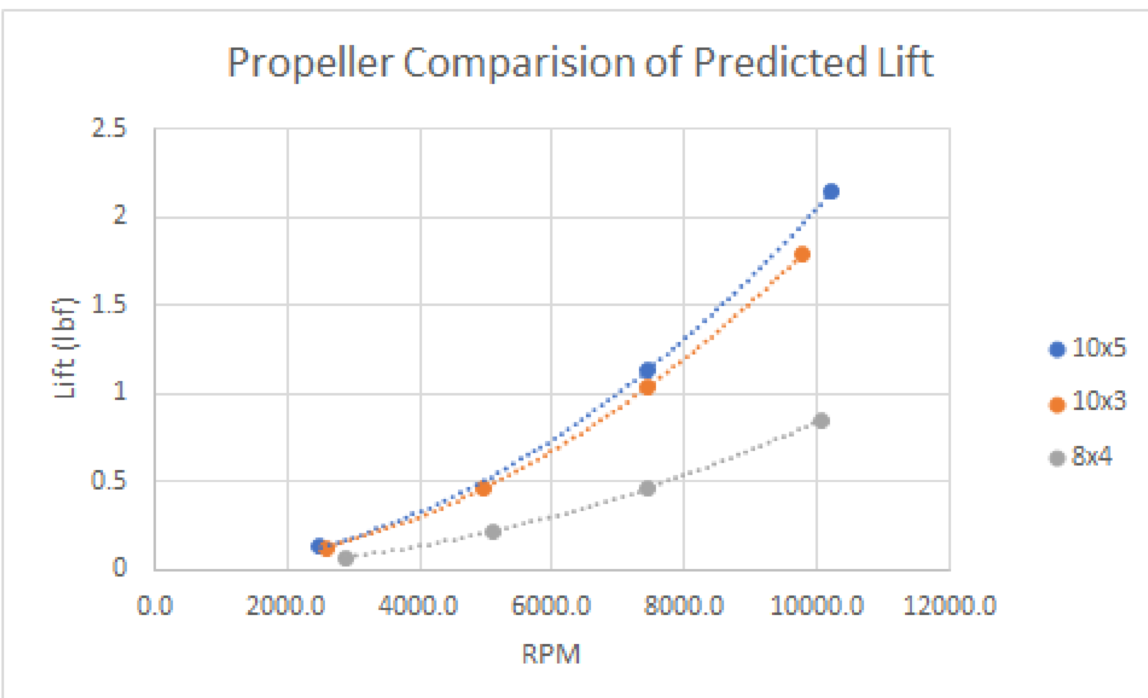
B. Analysis of Rotational Velocity

The initial plan was to test at 2500, 5000, 7500, and 10000. There were a few exceptions to this. First, for the 8x4, the slowest the propeller would spin at was 3000 RPM, so this was used instead of 2500. Similarly, for the 10x5 propeller, it produced massive resonance vibrations around the 5000 RPM mark, thus this data was omitted as the software would not record data at that point.

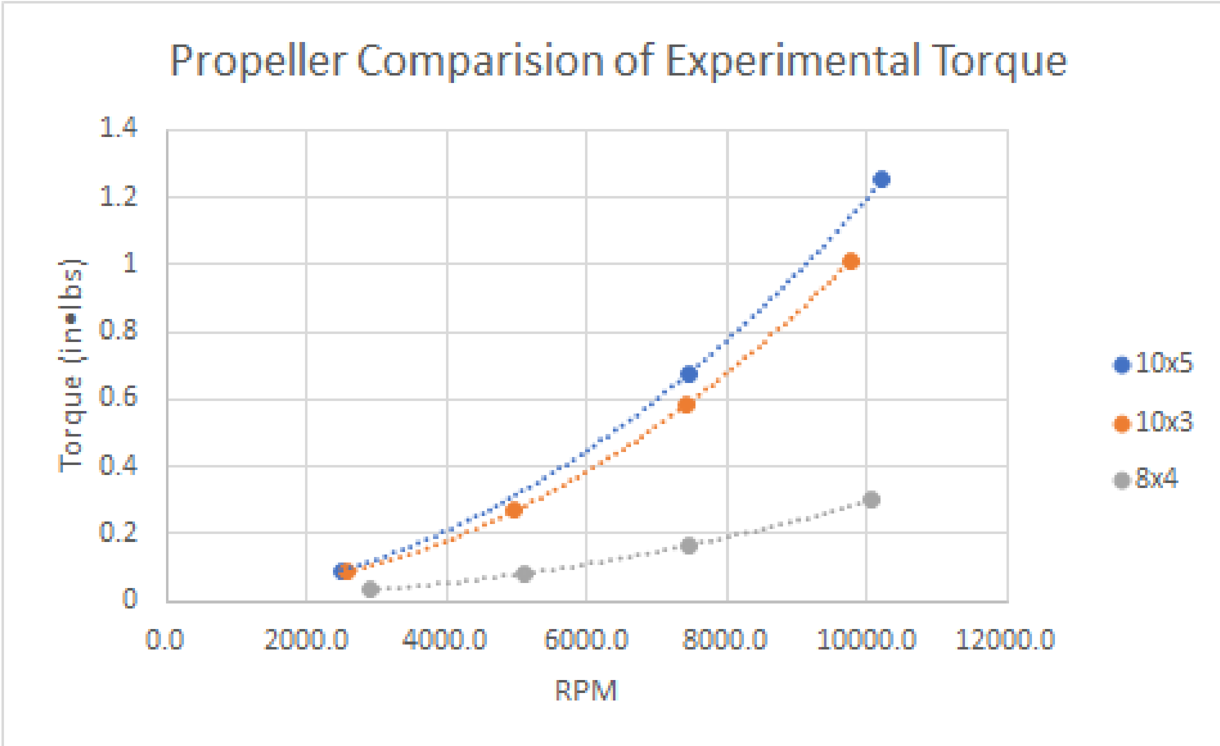
C. Propeller Comparisons

a. Lift

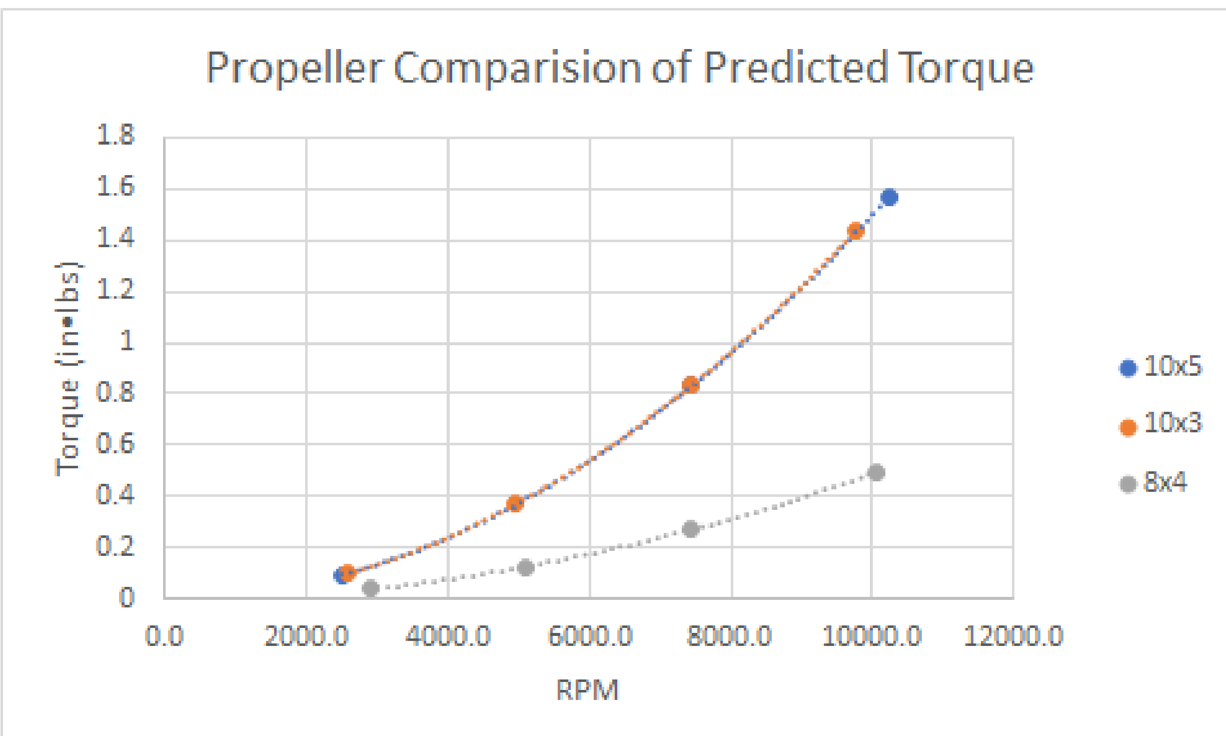




b. Torque

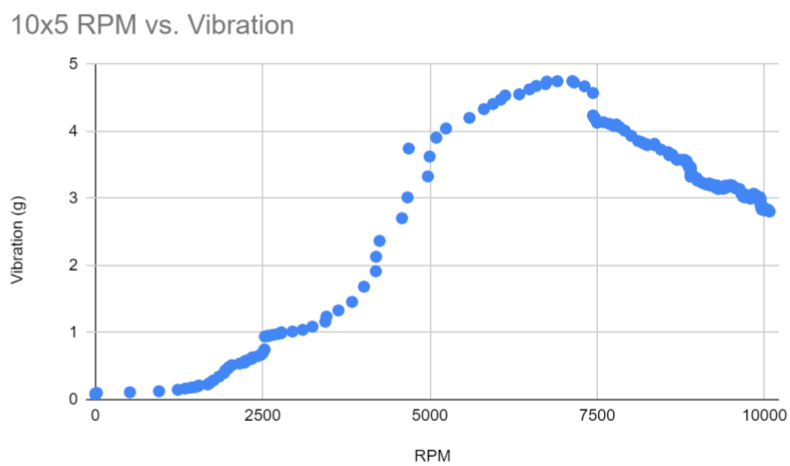


Propeller Comparision of Experimental Torque
Torque (in•lbs)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
2000.0
4000.0
6000.0
8000.0
10000.0
12000.0
RPM
10x5
10x3
8x4

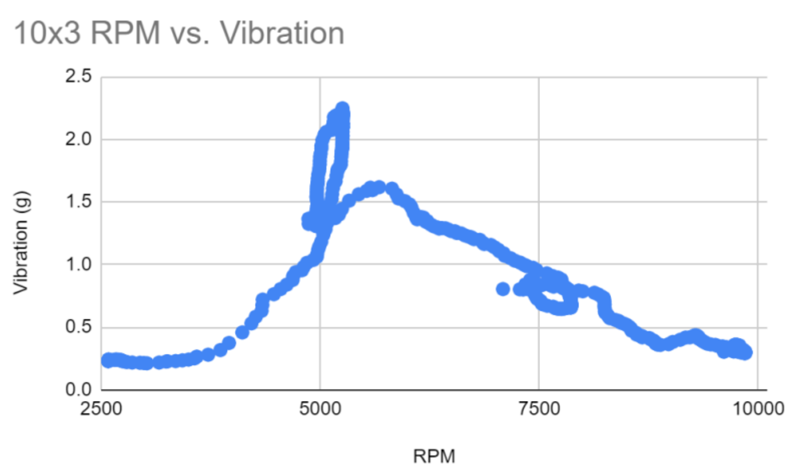


Propeller Comparision of Predicted Torque
Torque (in•lbs)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
2000.0
4000.0
6000.0
8000.0
10000.0
12000.0
RPM
10x5
10x3
8x4

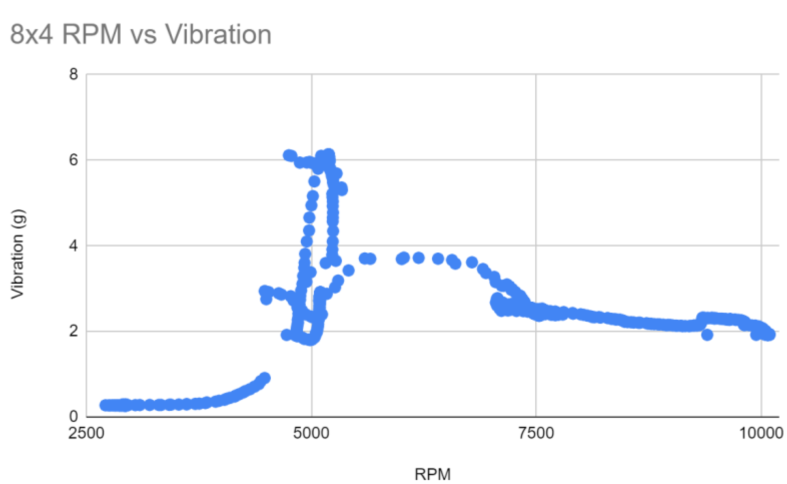
c. Vibration



10x5 RPM vs. Vibration
Vibration (g)
RPM
0
1
2
3
4
5
0
2500
5000
7500
10000

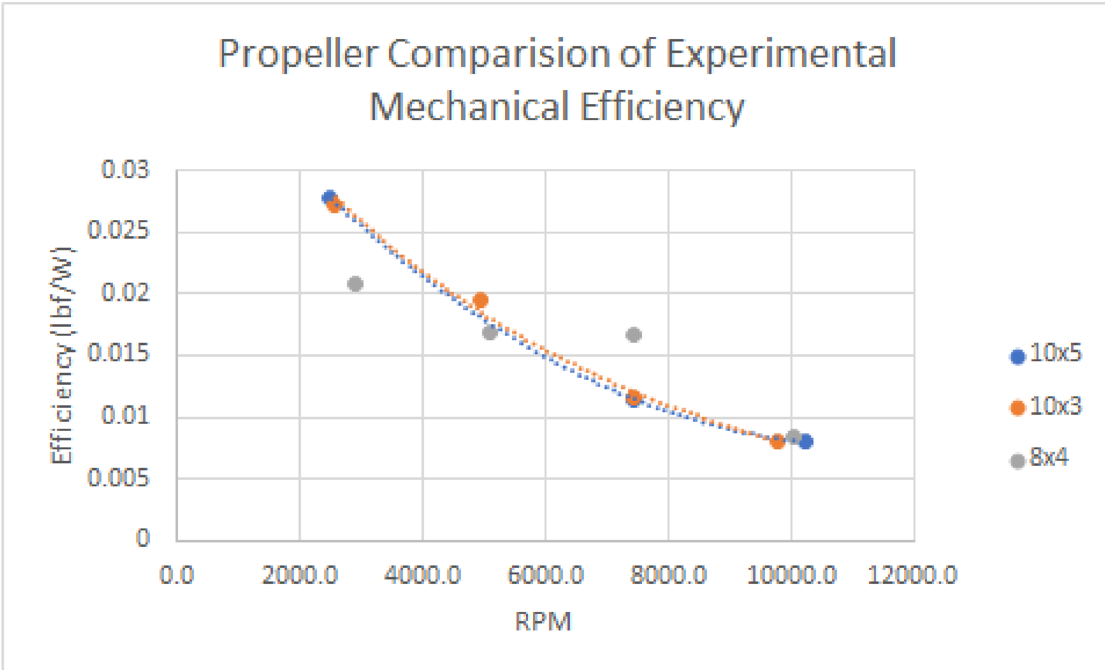


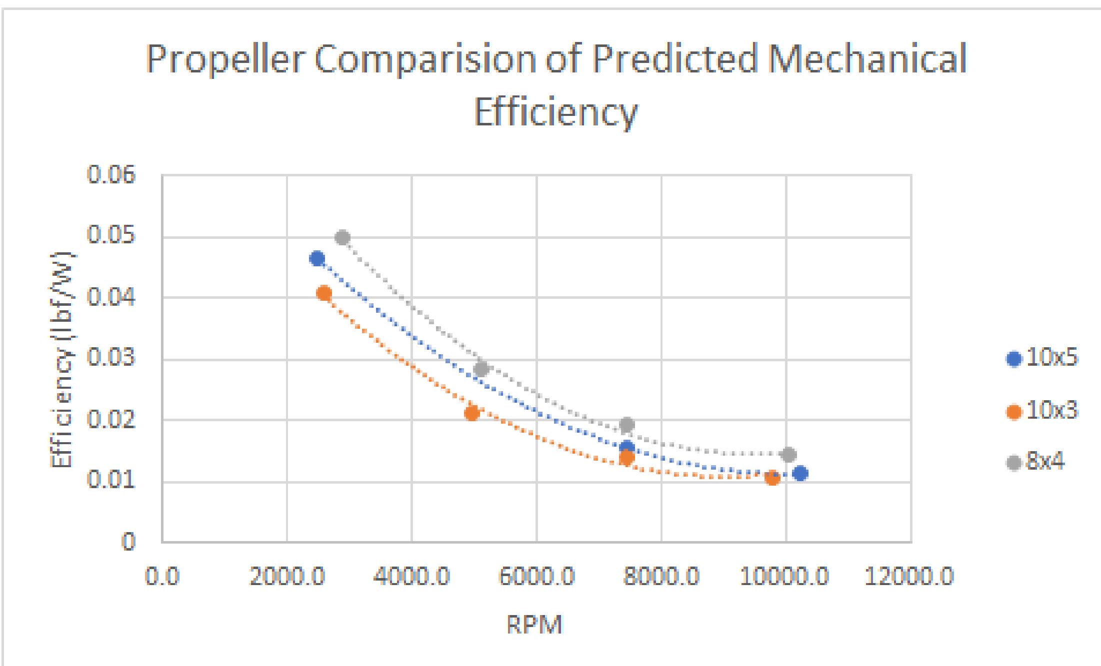
10x3 RPM vs. Vibration
Vibration (g)
RPM
0.0
0.5
1.0
1.5
2.0
2.5
2500
5000
7500
10000



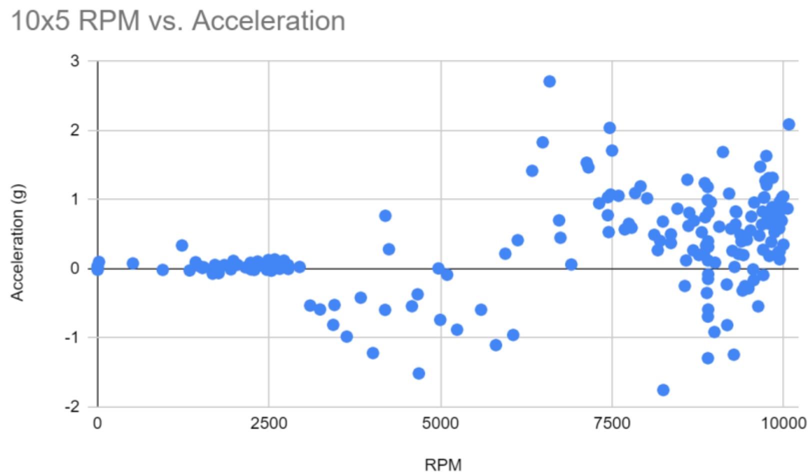
8x4 RPM vs Vibration
Vibration (g)
RPM
0
2
4
6
8
2500
5000
7500
10000

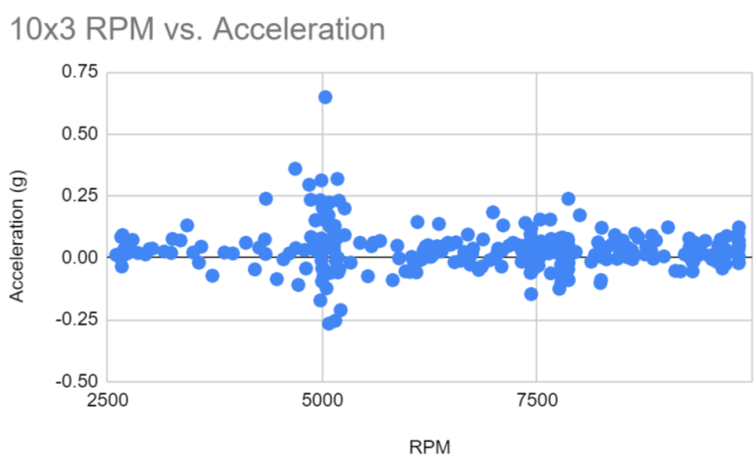
d. Efficiency

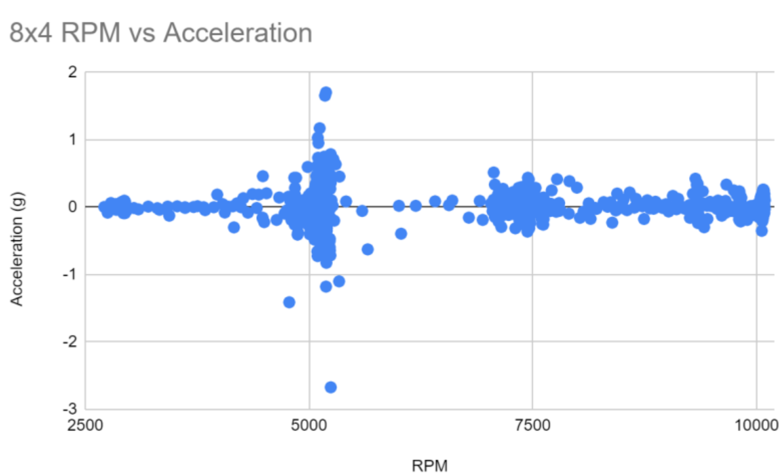




e. Acceleration



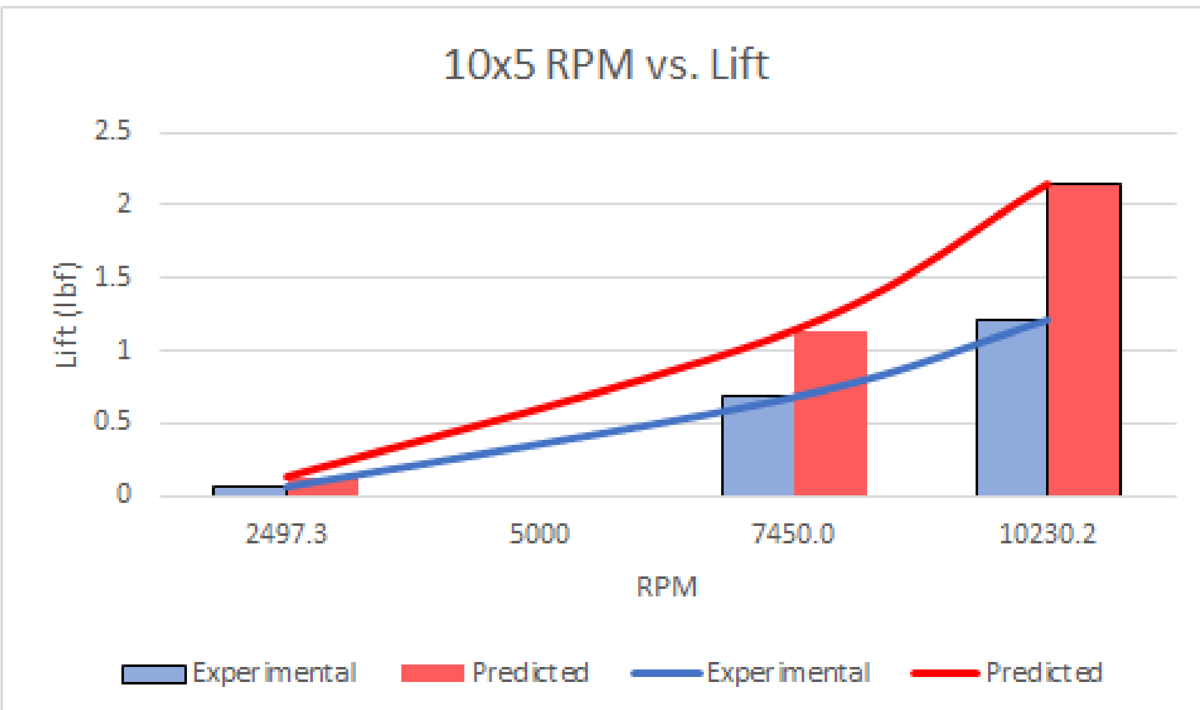


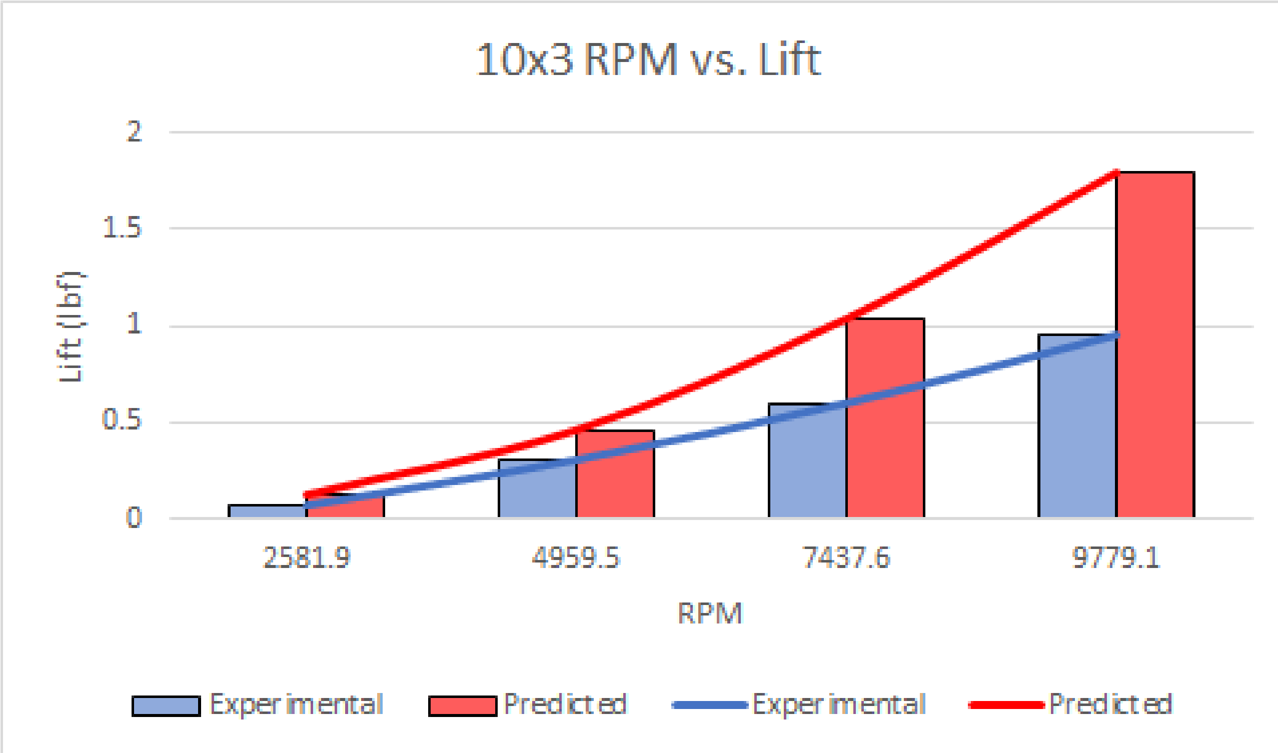


Findings

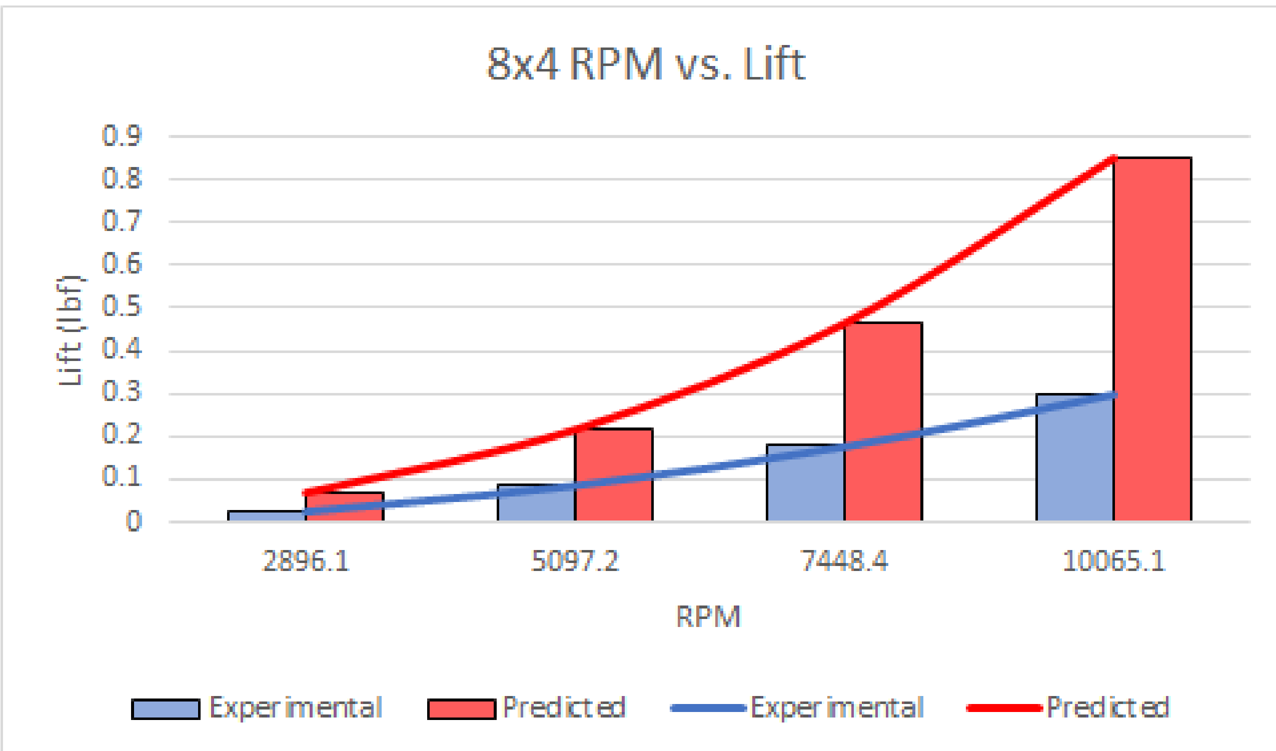
A. Thrust

Experimentally collected thrust was significantly lower than predicted values at all RPM ranges and with all propellers. There is a clear upwards nonlinear trend between RPM and lift as expected as the lift equation is related to the square of linear velocity. Also, the 10 in diameter propellers performed much better than the 8 in one.





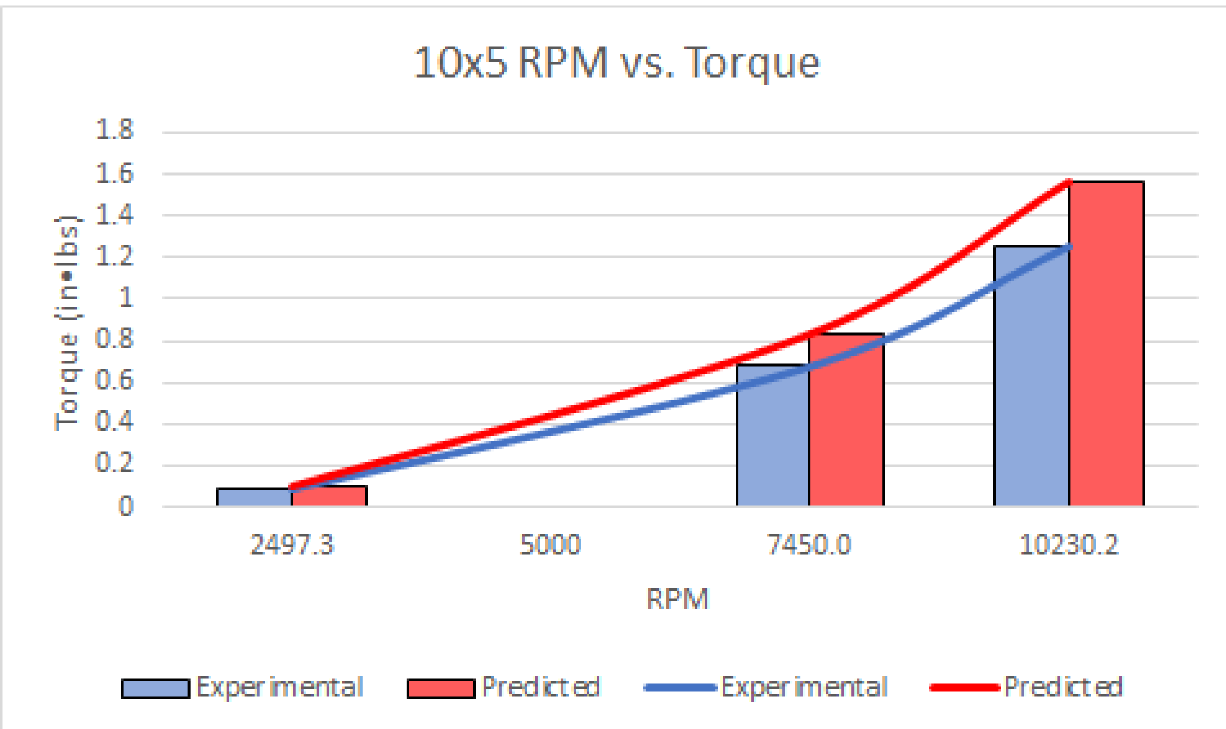
10x3 RPM vs. Lift
Lift (lbf)
2
1.5
1
0.5
0
2581.9
4959.5
7437.6
9779.1
RPM
Experimental
Predicted
Experimental
Predicted

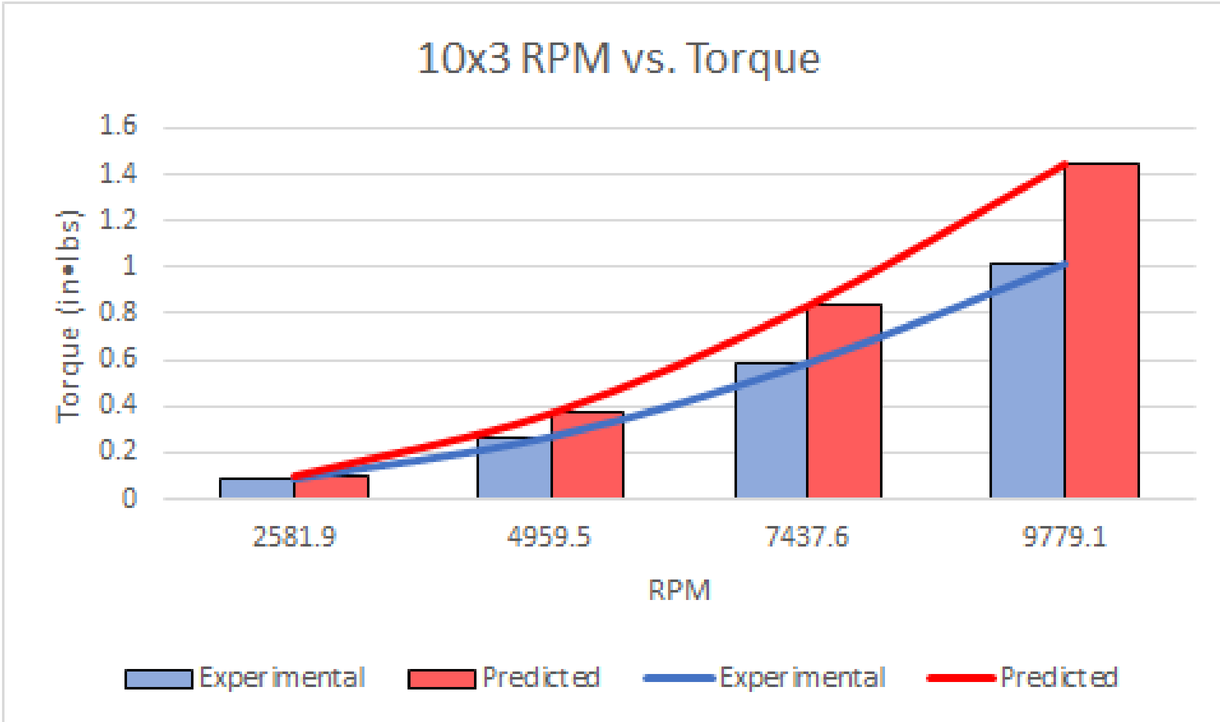


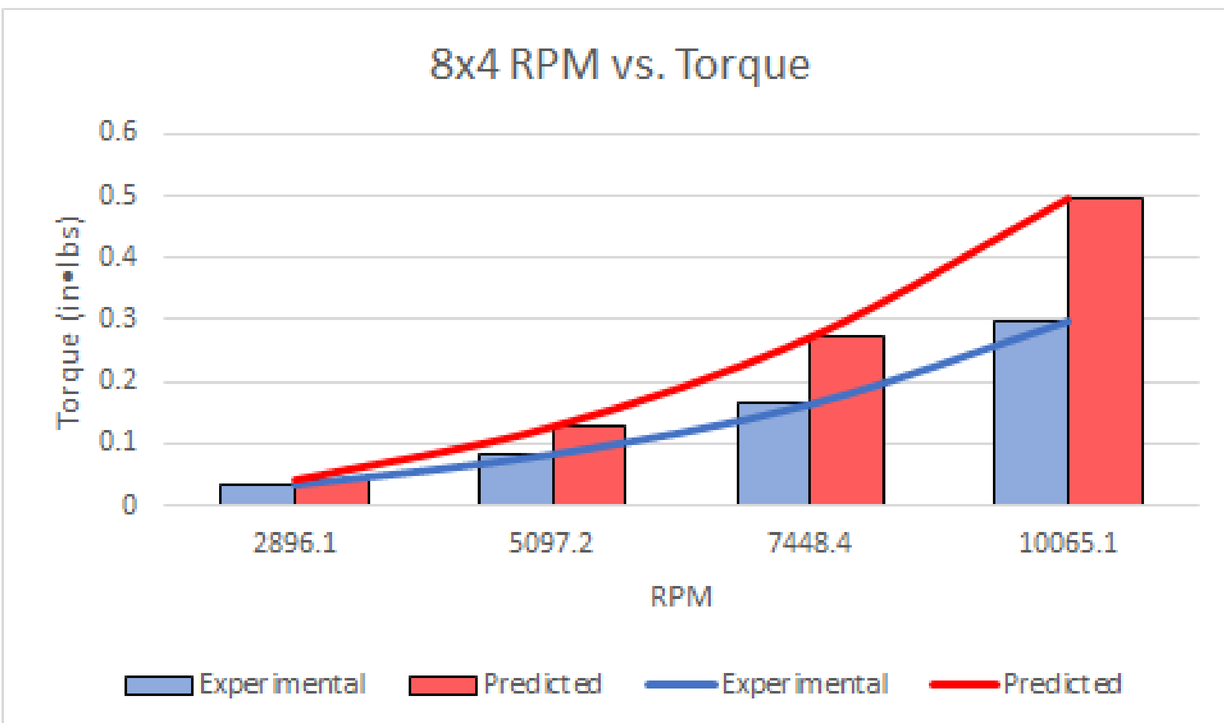
8x4 RPM vs. Lift
Lift (lbf)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2896.1
5097.2
7448.4
10065.1
RPM
Experimental
Predicted
Experimental
Predicted

B. Torque

Torque induced by drag was also a positive trend similar to lift. Experimental values for the 10x5 propeller were significantly higher than the 8x4 propeller. Predictions for the 10x5 propeller were by far the best of the torque predictions. The torque values seem to be more dependent on diameter of the propeller than any other design parameter because both the experimental and predicted values for the 10x5 and the 10x3 were somewhat close, while the 8x4 propeller had significantly less torque.

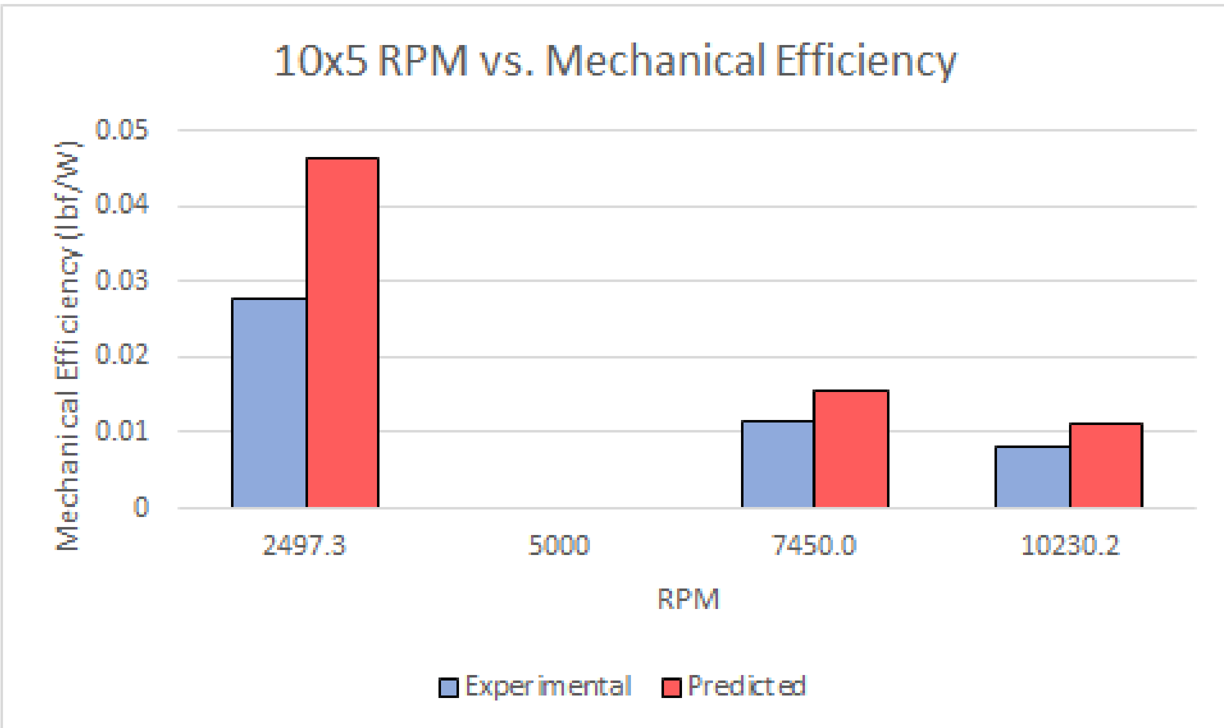


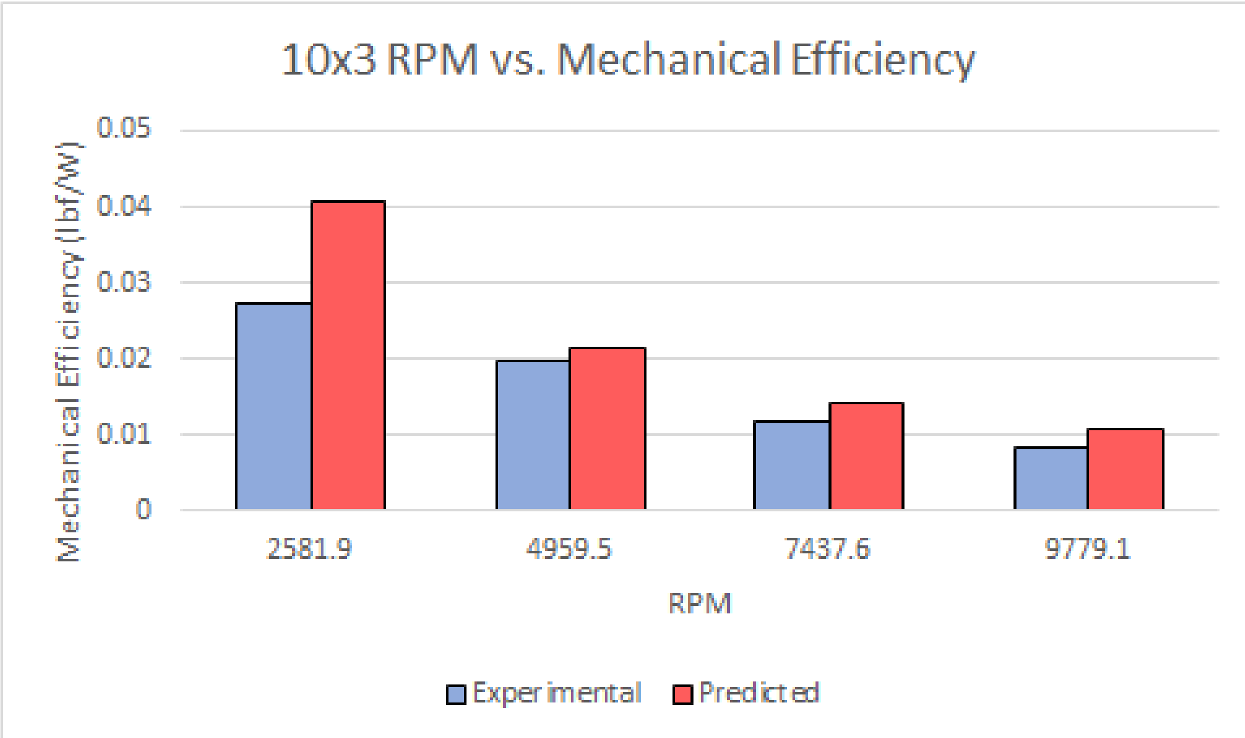

10x3 RPM vs. Torque
Torque (in•lbs)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2581.9
4959.5
7437.6
9779.1
RPM
Experimental
Predicted
Experimental
Predicted

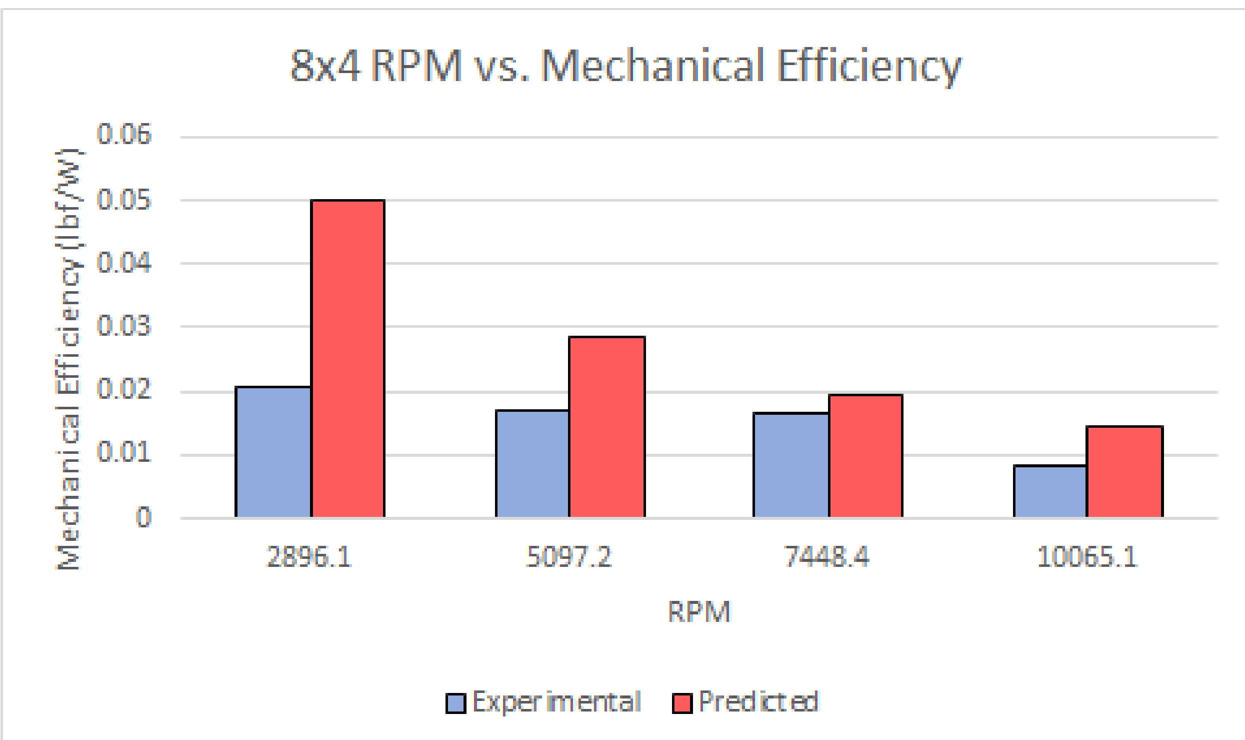

8x4 RPM vs. Torque
Torque (in•lbs)
0.6
0.5
0.4
0.3
0.2
0.1
0
2896.1
5097.2
7448.4
10065.1
RPM
Experimental
Predicted
Experimental
Predicted

C. Efficiency

Like the previous two variables, efficiency had a clear trend related to rpms. And each propeller size had different values. Unlike thrust and torque, efficiency had a negative relationship with rpm. Also, unlike the previous two, the smaller propeller performed worse at low rpms, but then performed better at high rpms. Analytically it was calculated to be better at all rpms.




10x3 RPM vs. Mechanical Efficiency
Mechanical Efficiency (lbf/W)
0.05
0.04
0.03
0.02
0.01
0
2581.9
4959.5
7437.6
9779.1
RPM
Experimental
Predicted


8x4 RPM vs. Mechanical Efficiency
Mechanical Efficiency (lbf/W)
0.06
0.05
0.04
0.03
0.02
0.01
0
2896.1
5097.2
7448.4
10065.1
RPM
Experimental
Predicted

D. Vibration and acceleration

Higher levels of vibration were observed on the thicker propellers, the 10x5 and the 8x4, this suggests that a thinner blade will have better practical applications. Along with this, the 10x3 and the 8x4 both had a spike in vibration around 5000 rpm. This was due to the propellers hitting a resonant frequency. Designing propellers to avoid any potential resonant frequencies was not within the scope of this project, but would be a major design consideration in the real world as a full-scale propeller would not be able to function at the observed vibration levels. Another thing to note is the vibration observed on the 10x5 propeller at around 5000 rpm is not accurately depicted in the plot; due to resonance the 5000 rpm range was quickly bypassed to prevent hitting the vibration safety cutoff.

The acceleration graphs were generally inconclusive for the performed tests. They are similar to the vibration graphs, except have positive and negative values. First, the thicker propellers, the 10x5 and 8x4 had a much higher magnitude of acceleration than the 10x3. The 10x3 and 8x4 acceleration graphs had a spike at 5000 rpm, where they hit their resonant frequency. Finally, the 10x5 had a gentle climb as it went from 5000 to 10000 rpm, again matching the vibration graph.

E. Final Conclusions

The purpose of this report was to research two aspects of propeller design and how they affect performance. The size of the propeller, and the cross-sectional airfoil and pitch were selected as the two design choices to analyze. From analyzing all of the data, analytical and experimental, it was determined that the airfoil and pitch have some effect on performance, while the size of the propeller matters much more. In many cases, the results for the 10x5 and 10x3 were nearly identical, while the 8x4 was noticeably different. A great example of this is the graphs of analytical torque and experimental. The analytical data had the exact same torque for 10x5 and 10x3, while the 8x4 was much lower. This was validated with the experimental data as the 10x5 and 10x3 were very similar, and the 8x4 was a much lower value. There are additional factors that could be impacting the performance that were unable to be measured. For example, the tips of the 10x5 and 8x4 propellers were more square than the 10x3 propeller which could be causing higher tip vortices. In conclusion, diameter is the most important parameter in propeller design when it comes to thrust, but for a more mechanically efficient propeller a small diameter may be a better option.

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