THE EFFECTS OF SWEEP AND TAPER ON STATIC PERFORMANCE FOR SMALL PROPELLERS

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THE EFFECTS OF SWEEP AND TAPER ON STATIC PERFORMANCE FOR SMALL PROPELLERS

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To the students of the Georgia Institute of Technology

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NOMENCLATURE

β_r	Root Twist Angle
β_t	Tip Twist Angle
Λ	Sweep Angle
β_r	Root Twist Angle
C_T	Coefficient of Thrust
C_P	Coefficient of Power
C_Q	Coefficient of Torque
D	Propeller Diameter
n	Revolutions per Second
P	Induced Power
P_{amb}	Ambient Pressure
P_{da}	Dry Air Partial Pressure
P_{sat}	Saturation Pressure of Water Vapor
P_v	Water Vapor Partial Pressure
Q	Torque
R	Blade Radius
$\bar{R}$	Specific Gas Constant
rc	Root Chord
R/C	Radio Controlled
R_{da}	Gas Constant for Dry Air
RH	Relative Humidity
ρ	Density
RPM	Revolutions per Minute

R_v	Gas Constant for Water Vapor
S	Propeller Blade Planform Area
T	Thrust
T_{amb}	Ambient Temperature
tc	Tip Chord
t/c	Thickness to Chord Ratio
TR	Taper Ratio
UAV	Unmanned Aerial Vehicle

I. INTRODUCTION

These past few years have been the years of the UAV. UAVs, also called drones, now have the friendly tasks of filming sports or movie scenes, civilian surveillance, and simple general aviation. Some companies see a future where UAVs are delivering pizza or packages. All of this shows a demand for civilian UAVs, typically in the form of quadcopters, but can also be small R/C planes. These aircraft are usually powered by small propellers and the design for propellers has not changed much despite the recent wave of UAV popularity. Two universities have made serious progress in the tabulation of small and micro propeller performance [1, 3, 4], but the realm of small and micro propeller geometry has not been pursued. Most propellers today are classified by diameter and pitch, a measure of how far a propeller would “screw” into a solid object, only, but other geometries of the propeller may lead to enhanced performance as well.

Previous Research

Research done in the realm of propeller performance has primarily focused on data generation for small propellers [3] or performance analysis for full sized aircraft propellers [2]. A University of Illinois at Urbana-Champaign (UIUC) study looked at 20 different micro propellers to develop performance charts for micro propellers. They were trying to fill the gap of performance data for micro propellers, those used in small aircraft, but the propellers they used were store bought and had the typical geometric standards of diameter and pitch only [3]. However, they did find that “larger diameter and lower pitch for propellers of the same diameter were typically more efficient [3]”.

A 1969 study conducted by the Air Force looked into propeller geometry on full size propellers. They looked into the effects of things such as tip shape, blade cuffs, and camber. They found many useful relationships. Up to a 0.09 power coefficient, blade cuff removal improved performance but showed no different or even a reduction after; below a 0.08 power coefficient, a round tipped blade produced more thrust than a square tipped blade; and a four bladed propeller produced more thrust than a three bladed propeller of the same blade shape [2]. However, great the data and correlations, they may not directly translate down to small/micro propellers that operate at significantly lower tips speeds nowhere near Mach 1. But the study was an early one to investigate geometric propeller effects.

The 2006 study at Wichita State University (WSU) focused on over sixty propellers and their wind tunnel performance. Specifically, they looked at relationships of the coefficients of thrust, torque, and power, and propeller efficiency against the advance ratio. They were able to set the foundation for a collection of data that applied to small aircraft propellers [4]. The 2011 UIUC study went even further in the realm of small propellers testing 79 propellers to see a relationship between the coefficients and propeller efficiency versus advance ratio. They found that usually that propellers performed better at higher rpms in all respects [1].

However, what each of these studies did not investigate was the propellers deeper geometric considerations. Diameter and pitch play an important role, but little can be said for the taper or sweep of each propeller. Those studies allow for one to buy a propeller that should fit their needs, but cannot help one design a propeller to fit one’s needs.

Purpose and Focus of this Study

The geometric aspects of propellers that are the focus of this study are sweep and taper. Sweep is a measure of the angle between the propeller tip and root and comes from the idea of wing sweep found on most jets today and even some propellers today [7]. Sweeping the wings provides better characteristics once a jet enters into the supersonic regime by delaying the formation location of shock waves, which generate a lot of additional drag on the aircraft. In terms of propeller sweep, a swept propeller could delay the formation of tip shocks, similar to the shock waves on wings, which occur at high RPM. Taper is the ratio of the tip chord to the root chord and is a measure of how rectangular a wing planform is, a ratio of one being a rectangle. Tapered wings provide a better distribution of lift which improves the capabilities of the wing without changing the airfoil. In terms of propellers, this effect would translate into additional thrust.

This study will create several control propeller geometries and vary the sweep and taper ratio linearly to see the baseline effects of each independent variable. Each propeller will be 3-D printed and run in a test rig designed to measure thrust, torque, and power which can then be turned into dimensionless coefficients that will be used to compare propellers to one another. The data generated could be used to explore other geometric concepts of micro propellers to improve performance for modern day small civilian UAVs.

II. EXPERIMENTAL SETUP

A. Propeller Design and Fabrication

Each of the propellers was designed using a custom MATLAB program that applied taper, sweep, and thickness distributions to an airfoil along the radius of the propeller. Table I shows all of the test cases that were analyzed in this study. For all cases, the thickness to chord ratio was kept constant at .15 and the twist distribution varied linearly between 30° at the root and 0° at the tip. The sweep angles were selected to capture the potential benefits of both aft and forward sweep, where the sweep direction is in the plane of the propeller disc. The taper ratios were selected to encompass a good range greater than and less than 1. The respective root and tip chords were solutions to the system of equations, Equations 1 and 2, involving the equations for taper ratio and planform area with the planform area being held constant. All of the propellers have a nominal diameter of 9 in.

Table I. Experiment Test Cases

	Sweep Variation								
	Case 1	Case 2	Case 3	Case 4	Control	Case 5	Case 6	Case 7	Case 8
rc (in.)	1	1	1	1	1	1	1	1	1
tc (in.)	1	1	1	1	1	1	1	1	1
β_r (°)	30	30	30	30	30	30	30	30	30
β_t (°)	0	0	0	0	0	0	0	0	0
Λ (°)	-20	-15	-10	-5	0	5	10	15	20
t/c (~)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Taper Variation								
	Case 1	Case 2	Case 3	Case 4	Control	Case 5	Case 6	Case 7	Case 8
rc (in.)	0.714	0.769	0.833	0.909	1.000	1.111	1.250	1.429	1.667
tc (in.)	1.286	1.231	1.167	1.091	1.000	0.889	0.750	0.571	0.333
TR (~)	1.8	1.6	1.4	1.2	1	0.8	0.6	0.4	0.2
β_r (°)	30	30	30	30	30	30	30	30	30
β_t (°)	0	0	0	0	0	0	0	0	0
t/c (~)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

$$TR = \frac{tc}{rc} \quad (1)$$

$$S = (\frac{rc+tc}{2})R \quad (2)$$

All of the propellers used in this study were printed from a Cubify CubePro Duo 3-D Printer using a nylon material cartridge, shown in Figure 1. The print settings were kept the same for every print and are as follows in Figure 2. All of propeller sets are shown in Figure 3.

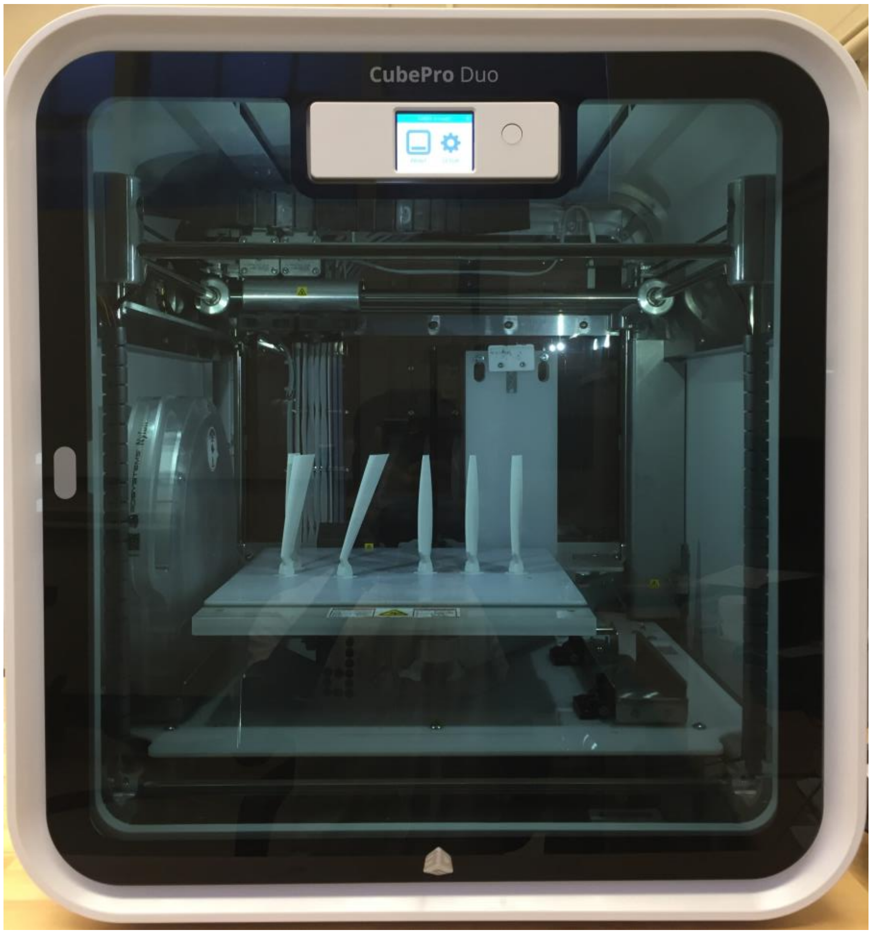

Figure 1. Cubify CubePro Duo 3-D Printer with nylon cartridge and some of the propeller prints.

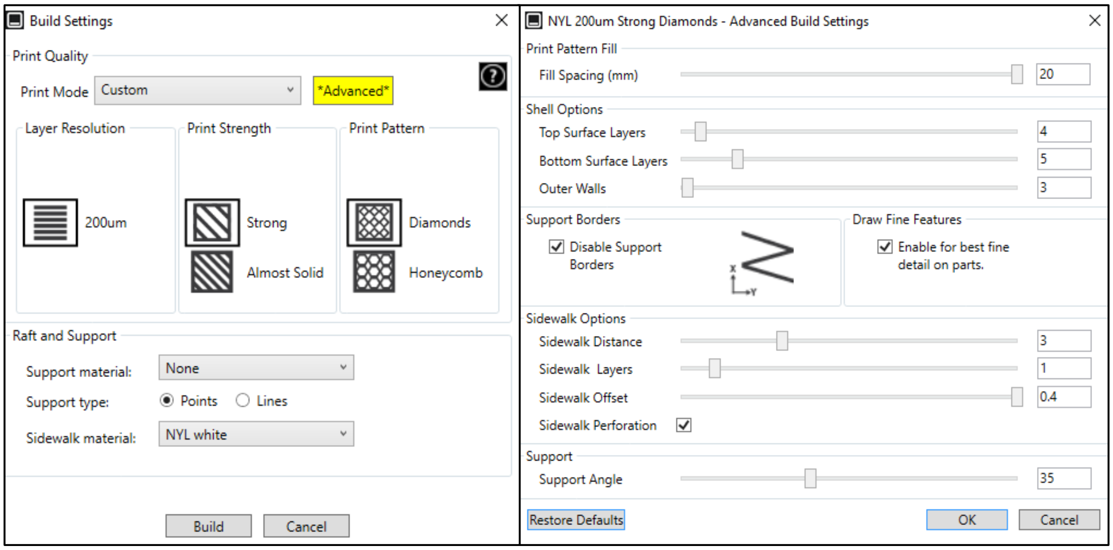

Figure 2. 3-D Print settings.

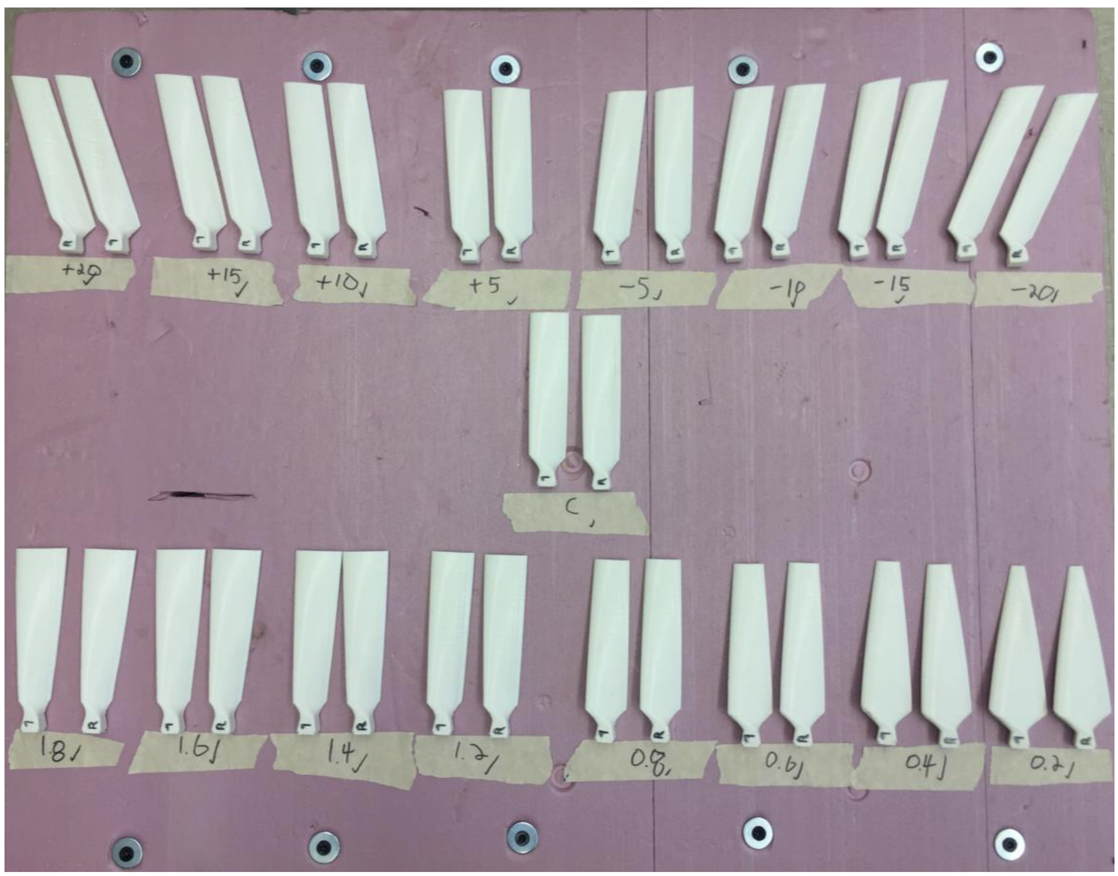

Figure 3. Sets of Test Propeller Blades *Top*: Swept propellers. *Middle*: Control Propeller. *Bottom*: Tapered Propellers.

B. Testing Apparatus

The custom testing apparatus is shown in Figure 4. Key components include the lubricated shaft which is held by two coaxial Linear Rotary Bearings Inc. LR-12W linear-rotary bearings to properly transfer the loads from the propeller driven by an E-Flite Power 25 BL (870Kv) motor to the two Measurement Specialties FC22 (10lb) compression load cells. There were two power plants for the system. The first one was a Circuit Specialists CSI3003XIII DC regulated power supply used to power the load cells and a servo tester, which was used to control the RPM of the motor. The second one was a Volteq HY5050EX DC regulated power supply used to power the motor.

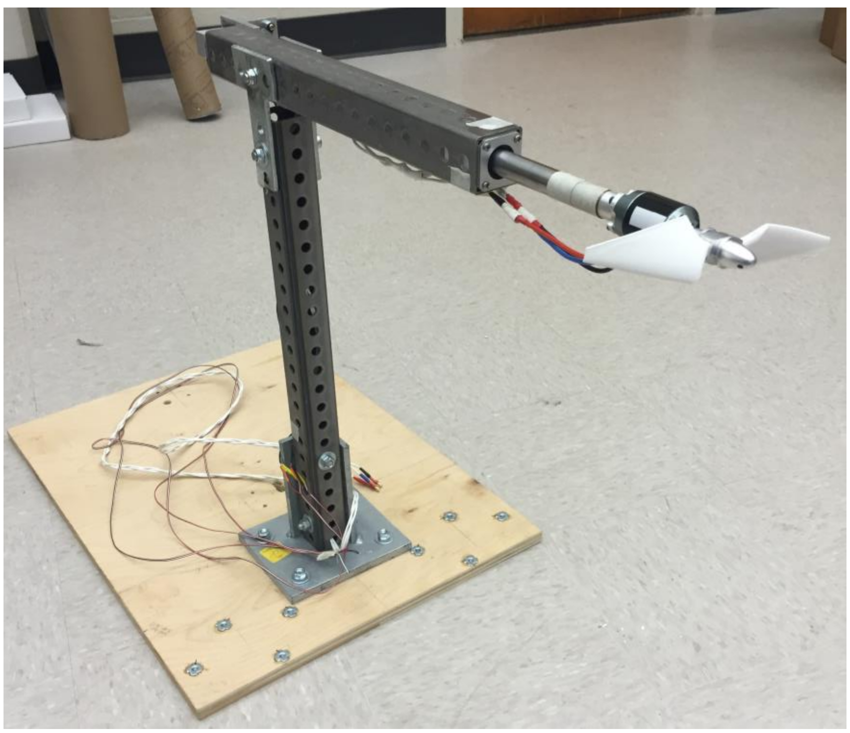

Figure 4. Testing Apparatus

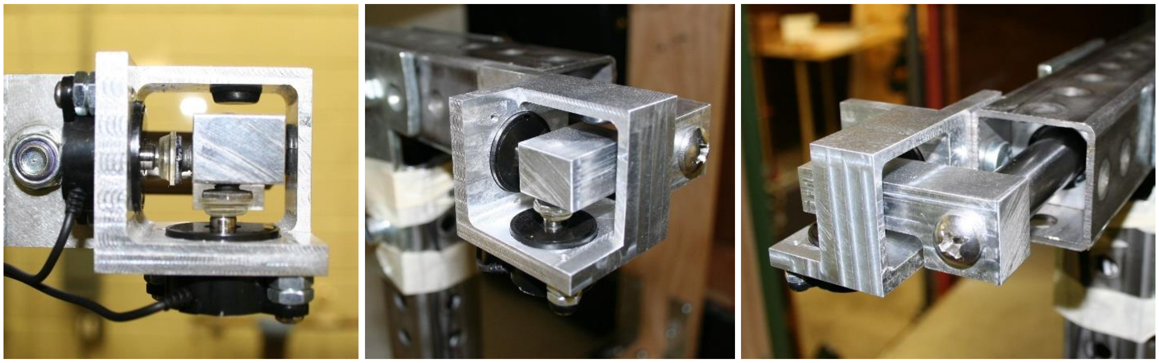

Figure 5. Views of the load cells and the load transfer beam

C. Data Acquisition

Data acquisition for the thrust, torque, and propeller RPM measurements was performed using a custom LabView program coupled with data samples taken by a National Instruments USB-6002. Thrust and torque measurements are taken as averages of their respective samples while RPM was determined by measuring the frequency of the pings that the Castle Phoenix Edge HV60 speed control output for each motor cycle. Independent verification using a photo-tachometer showed that the RPM measurement was accurate. Ambient condition data was taken by an Extech Instruments datalogger.

III. DATA REDUCTION

The data reduction process begins by converting the measured voltages into the physical quantities of thrust and torque. Those values were determined from calibration data, shown in Figures 6 and 7, that were created using known weights, moment arm for torque, and scales.

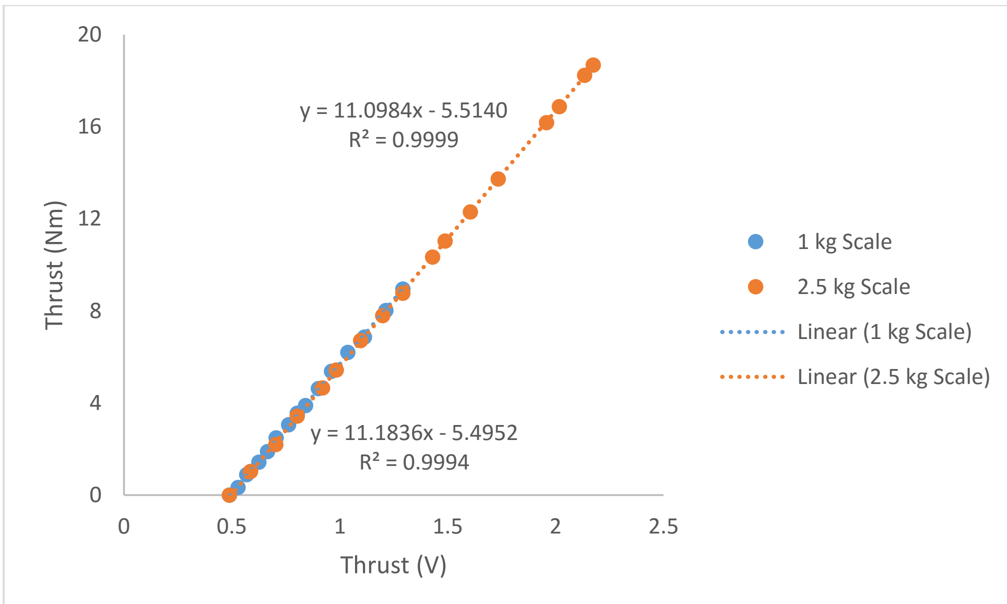

Figure 6. Thrust Calibration Curves

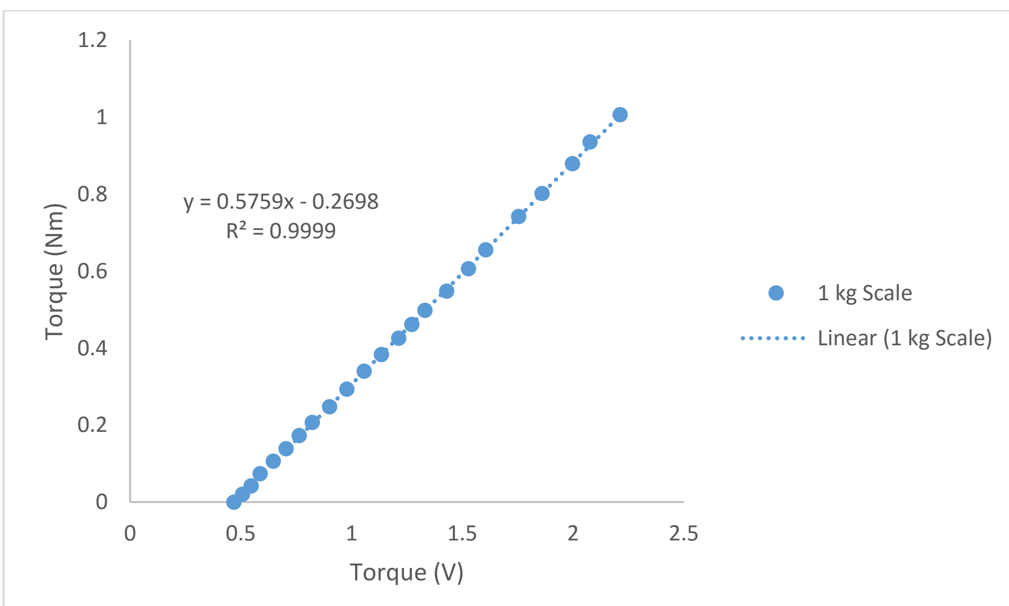

Figure 7. Torque Calibration Curve

Air density was determined using Equations 3-6 [6], based on the measured ambient conditions.

$$P_{sat} = 6.1078 \times 10^{\left(\frac{7.5 * T_{amb}}{237.3 + T_{amb}}\right)} \tag{3}$$

$$P_v = RH \times P_{sat} \tag{4}$$

$$P_{da} = P_{amb} - P_v \tag{5}$$

$$\rho = \frac{P_{da}}{R_{da} T_{amb}} + \frac{P_v}{R_v T_{amb}} \tag{6}$$

Lastly, the thrust and torque measurements were non-dimensionalized to acquire the propeller performance data in terms of the thrust and torque coefficients, found using Equations 7 and 8. The coefficients were then plotted against RPM. Additionally, the induced power coefficient was found, using Equation 9, and plotted against the thrust coefficient.

$$C_T = \frac{T}{\rho n^2 D^4} \tag{7}$$

$$C_Q = \frac{Q}{\rho n^2 D^5} \tag{8}$$

$$C_P = 2\pi C_Q \tag{9}$$

IV. RESULTS

A. Validation

In order verify the accuracy of the acquired results, a test, run in a similar fashion, was conducted for an APC 9x6 propeller. Figure 8 shows the comparison between the thrust coefficient data from APC's analytical model, the UIUC database [1], and the loading and unloading data obtained from the test run. The loading data corresponds to the data taken while RPM was being increased with the unloading data being the opposite. They differ due to frictional losses induced by the rubber dampers used to achieve clean load cell signals.

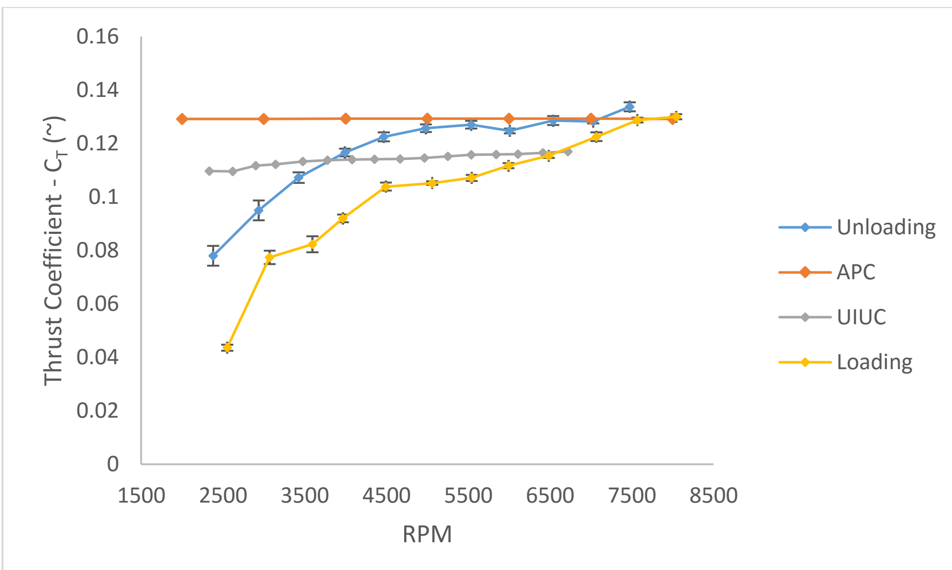

Figure 8. Validation run compared to publicly available data

The rest of the results are plotted using the unloading data since it fit best between the known data curves.

B. Sweep

For the sweep test cases, the data for each coefficient is split into forward sweep and aft sweep cases with the control included, as shown in Figures 9-14. The percent changes at maximum RPM are tabulated in Table II.

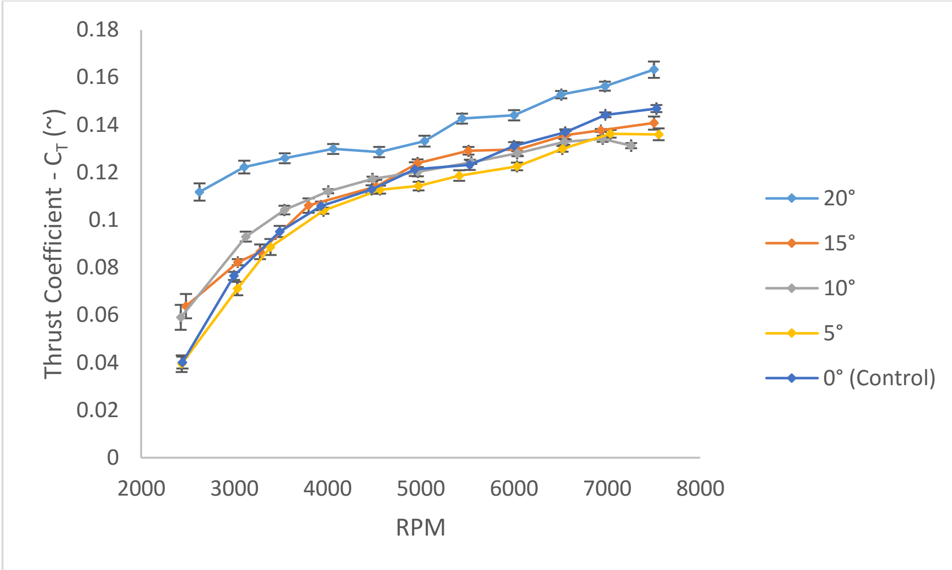

Figure 9. Forward Sweep Thrust Coefficient Data

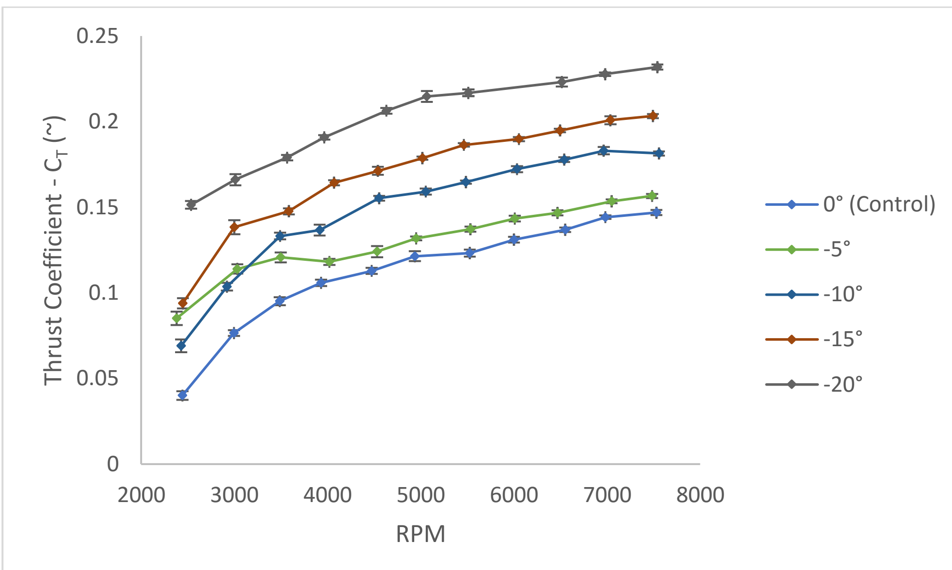

Figure 10. Aft Sweep Thrust Coefficient Data

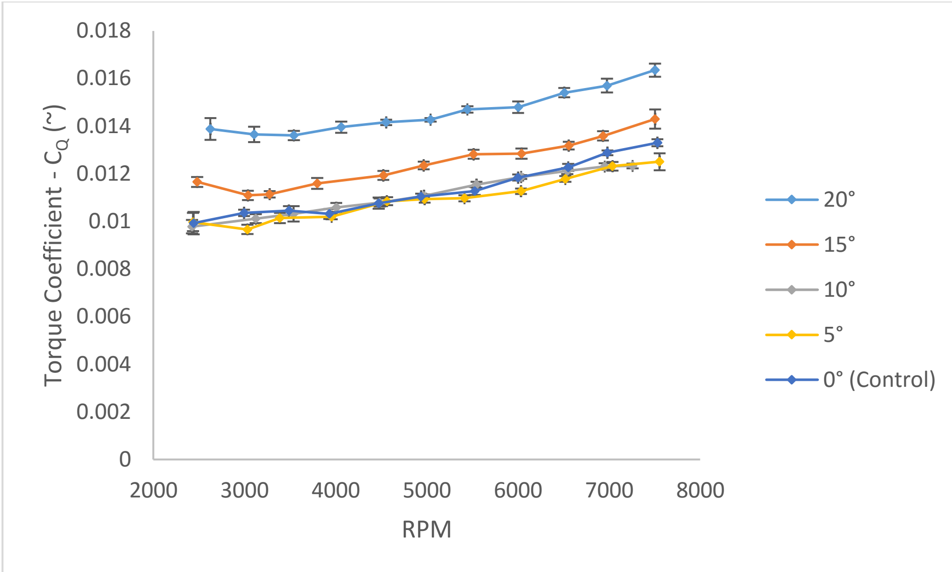

Figure 11. Forward Sweep Torque Coefficient Data

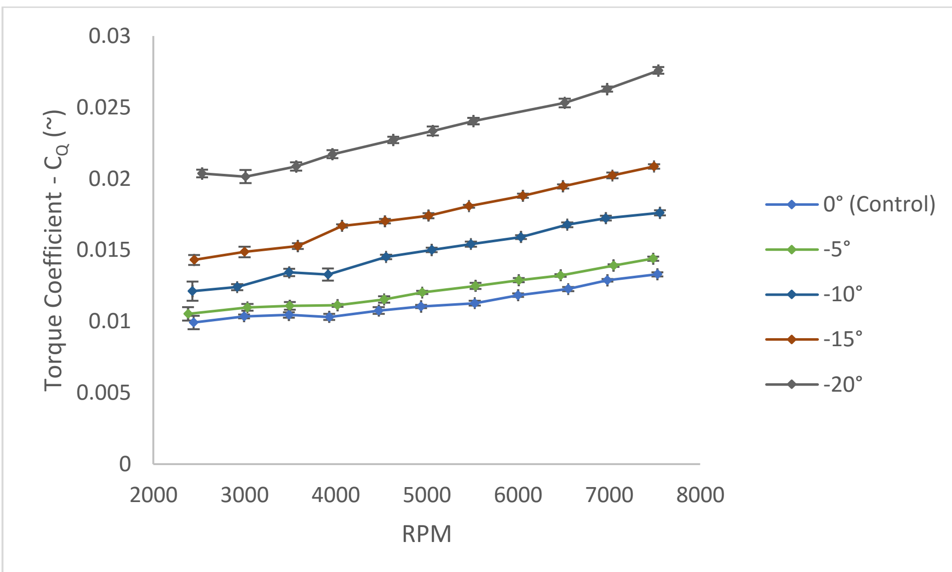

Figure 12. Aft Sweep Torque Coefficient Data

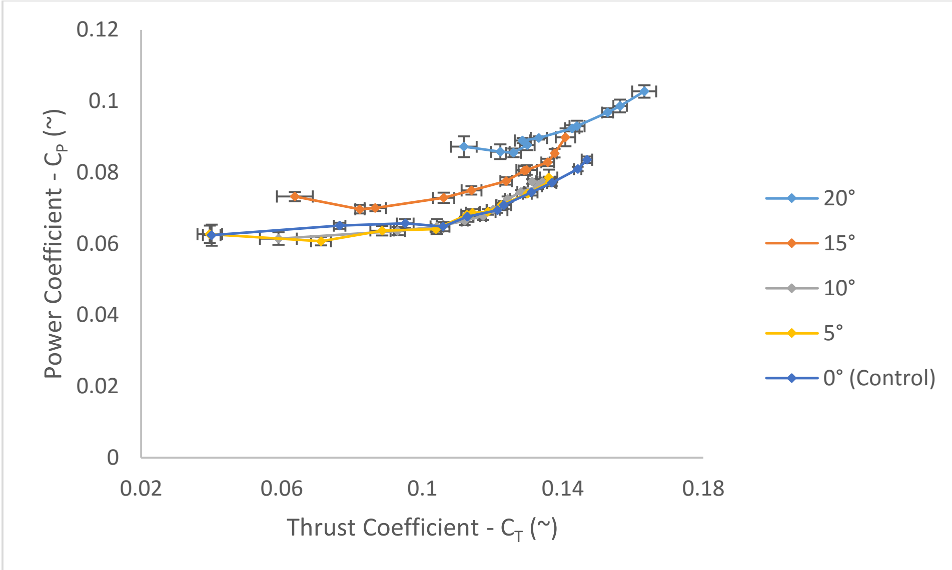

Figure 13. Forward Sweep Thrust vs. Power Coefficients Data

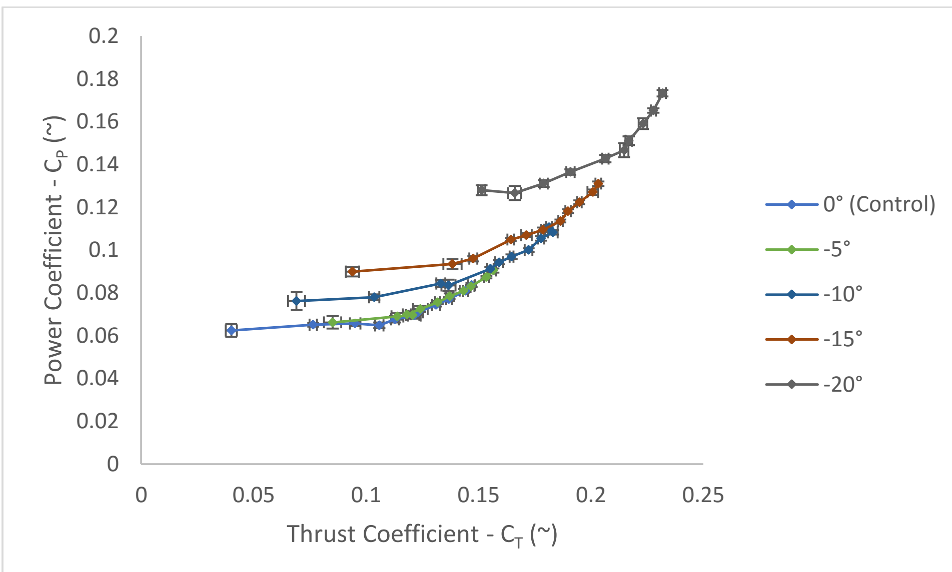

Figure 14. Aft Sweep Thrust vs. Power Coefficients Data

Table II. Sweep Angle Performance Changes ***measured at maximum RPM**

Sweep Angle (°)	ΔC_T (%)	ΔC_Q (%)
20	11%	23%
15	-4%	1%
10	-11%	-7%
5	-7%	-6%
-5	7%	8%
-10	24%	32%
-15	38%	57%
-20	58%	107%

C. Taper

For the taper test cases, the data for each coefficient is split into taper ratio greater than and less than 1 with the control included, as shown in Figures 15-20. The percent changes at maximum RPM are tabulated in Table III.

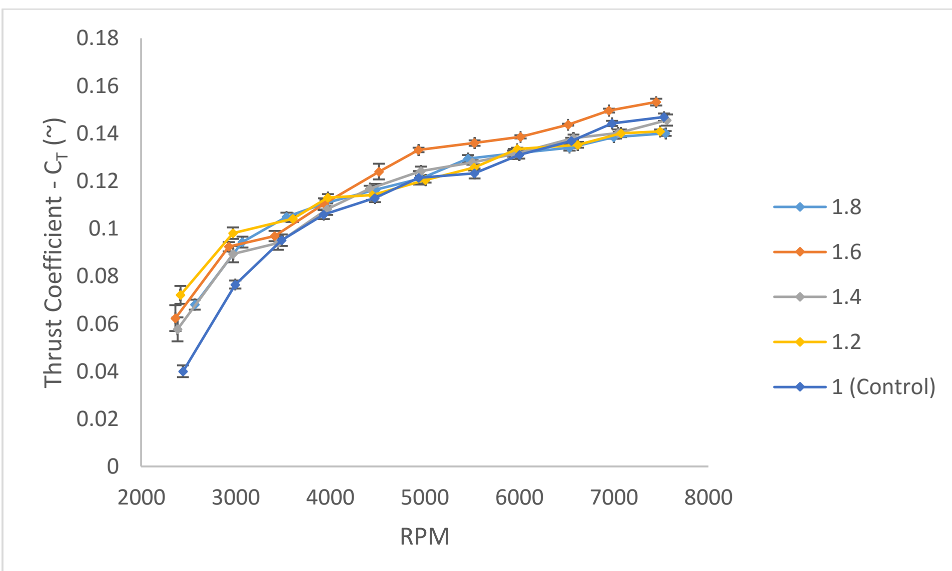

Figure 15. TR>1 Thrust Coefficient Data

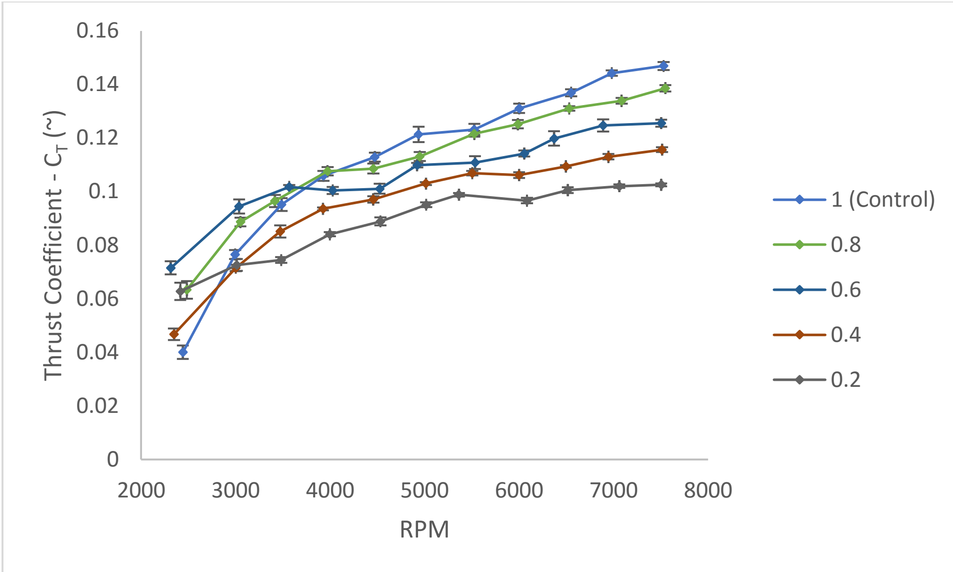

Figure 16. TR<1 Thrust Coefficient Data

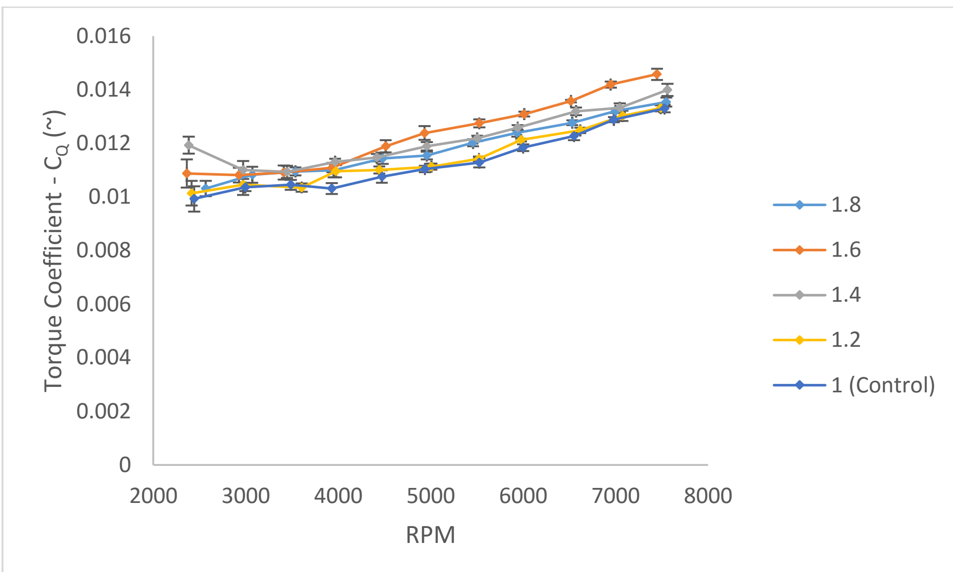

Figure 17. TR>1 Torque Coefficient Data

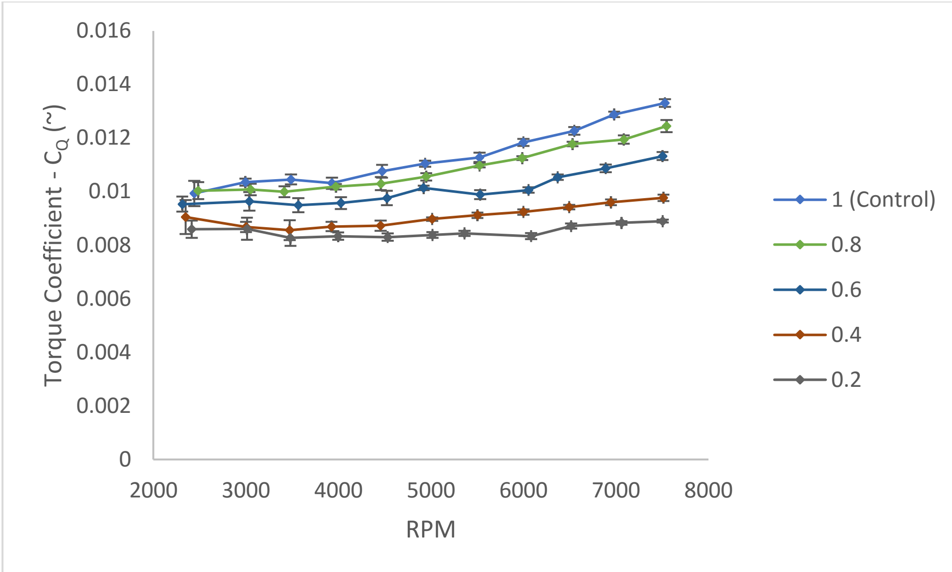

Figure 18. TR<1 Torque Coefficient Data

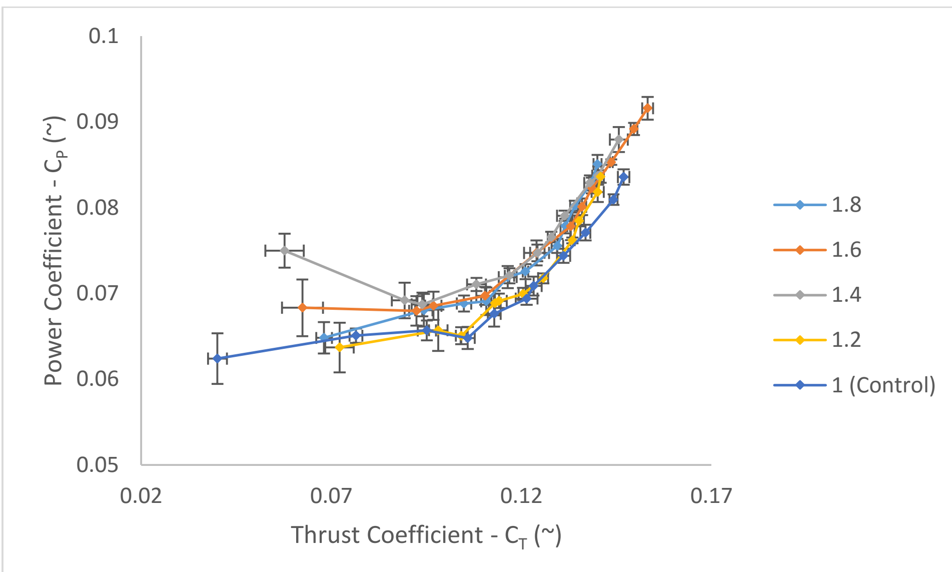

Figure 19. TR>1 Thrust vs. Power Coefficients Data

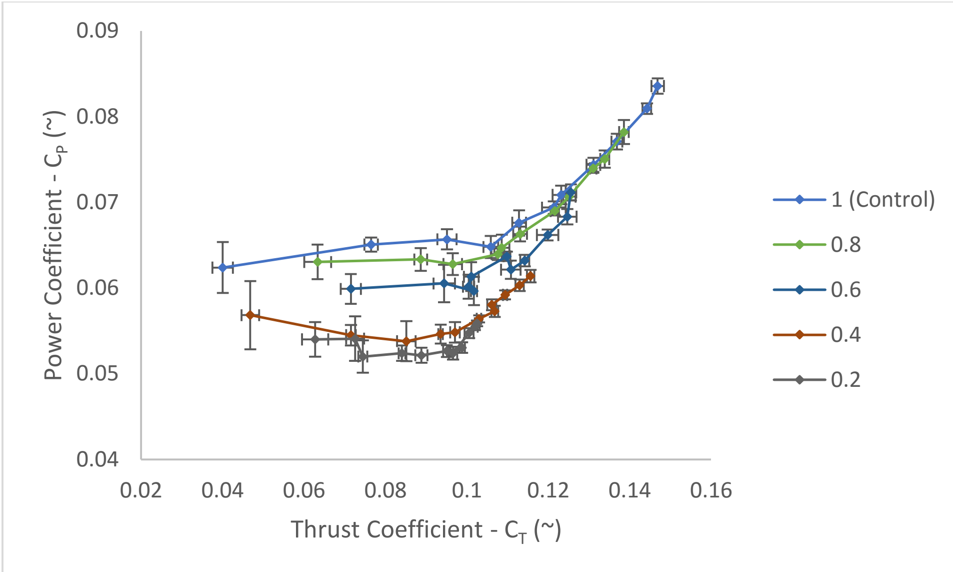

Figure 20. TR<1 Thrust vs. Power Coefficients Data

Table III. Taper Ratio Performance Changes ***measured at maximum RPM**

Taper Ratio	ΔC_T (%)	ΔC_Q (%)
1.8	-5%	2%
1.6	4%	10%
1.4	-0.8%	5%
1.2	-4%	0%
0.8	-6%	-6%
0.6	-15%	-15%
0.4	-21%	-27%
0.2	-30%	-33%

V. DISCUSSION

A. Thrust Coefficient

Based on the results, it could be said that forward sweep has a small effect on thrust, since the maximum improvement from the control was about 11% for the 20° case. Most of the other cases matched or performed worse. The trend seems to show that a significant amount of forward sweep is necessary to see heightened performance, but without data further than 20° it cannot be justified. Aft sweep showed great improvements at all the levels with the maximum being about 58% for the -20° case. However, it is difficult to say whether the improvement with significant sweep angles was due to sweep alone or coupled with the effects of increased planform area.

The taper ratio cases were slightly different. For a ratio greater than 1, which is fairly unconventional, the maximum improvement from the control was only 4% at 1.6. All of the other cases underperformed, which suggests that a root chord smaller than the tip is impractical. For a ratio less than 1, which is more conventional, performance actually decreased in all cases. This phenomenon could be due to the fact that a typical propeller has a taper ratio that initially increases and then decreases along the radius of the blade, which is not captured by the solely linear increase *or* decrease variation conducted in this experiment.

B. Torque Coefficient

Based on the results, it could be said that forward sweep also has a sizable effect on torque. The maximum improvement from the control was about 23% for the 20° case. The other cases varied from outperforming to underperforming. The data, like the thrust coefficient, could suggest that a significant amount of forward sweep is necessary to see heightened performance. Aft sweep again, showed great improvements in performance at all levels with the maximum improvement from the control being 107% for the -20° case.

The taper ratio results exhibited behavior similar to the thrust coefficient. For a ratio greater than 1, the maximum improvement from the control was only 10% at 1.6. For a ratio less than 1, performance decreased for all cases.

C. Power Coefficient

Based on the results, it could be said that sweeping either direction allows higher thrust coefficients albeit at higher induced power coefficients. Negative sweep outperforms positive sweep in the power regime as well.

Small taper appears to reduce the achievable maximum thrust coefficient most likely due to the fact that the area is held constant while more area is being allotted to the root, which spins slower than the lesser area tip. Conversely, it is also worth noting that the achievable thrust coefficients cost less power when compared to the control prop. Large taper appears to have the opposite or no noticeable effect on the required power.

VI. CONCLUSIONS AND FUTURE WORK

Overall, in this report, seventeen 9 in. propellers were fabricated and tested. Thrust and torque coefficients were plotted against RPM since the tests were conducted statically. Forward sweep has adverse effects on both thrust and torque with only a hint that a higher sweep magnitude might yield significant performance improvements. Aft sweep yields substantial increases in thrust and torque, at the expense of higher power, and should qualify as a viable parameter for propeller manufactures to include in designs. A taper ratio greater than 1 has negligible increases in both thrust and torque while a taper ratio less than 1 has adverse effects on both. Varying taper ratio, at least solely from root to tip, is therefore not an effective strategy for thrust or torque augmentation, however small taper does reduce the induced power for a given thrust.

One of the limitations to this study is the static nature of the experiment. Static propeller data is really only useful for very low speed or takeoff conditions. Dynamic tests would actually show how efficient varying either sweep or taper could be. Another limitation, at least for the sweep cases was the fabrication process. The more the propeller blades were swept, the less stable they were while printing which limited the maximum magnitude of sweep angle. The work around would be printing with supports, but that would require additional studies to see how much support was needed and how to minimize the added time that supports would add to the printing time. The last limitation is that our test rig, in order to reduce vibrations and produce cleaner signals, has rubber dampers which then cause friction between themselves and the load cells. Loading and unloading data captures part of this effect; the loading curves were always lower in magnitude since the friction is opposing the forces, however the unloading curves were always higher in magnitude since the friction is then aiding the forces.

Potential facets to continue this research include expansion into the dynamic regime and determining if propeller efficiency increases with changes to sweep and taper. That would provide a measure of how the propellers would perform in flight for driving aircraft, whereas the static regime is closer to a hover state. Another avenue is the consideration of Reynolds Number and how it changes with RPM to get a better idea of how the propellers affect the air itself. Another concept is varying taper ratio but with the maximum being at a quarter or half radius, to emulate a typical chord distribution for a stock propeller. The swept propellers could be fabricated in some different way such that sweep angles past 20° could be tested. And lastly, additional analytical comparison could made for different stock propellers to get a better idea of the accuracy of these results.

APPENDIX: ERROR ANALYSIS

The error analysis for this experiment was performed using equations derived from the root-sum-square method [5]. The measured quantities for the experiment were ambient temperature, ambient pressure, relative humidity, thrust, torque, and RPM. The former three measurements went into the air density formulation and the latter three went into the non-dimensional performance parameters. The error associated with the density formulation quantities is difficult to quantify as the formulas used do not fall under the necessary product form and was thus neglected. Instead, the tolerances for the measurements are listed in Table IV.

Table IV. Tolerances for Quantities Used for Density Formulation

Measured Quantity	Tolerance
Temperature	±0.8 °C
Pressure	±2 hPa
Relative Humidity	±4 %

Equations 10-12, which were used to find the error associated with the non-dimensional performance parameters, based on Equations 7-9, are listed below. The error quantities were plotted on each respective graph

$$\delta C_T = C_T\sqrt{(\frac{\delta T}{T})^2 + (-2\,\frac{\delta n}{n})^2} \tag{10}$$

$$\delta C_Q = C_Q\sqrt{(\frac{\delta Q}{Q})^2 + (-2\,\frac{\delta n}{n})^2} \tag{11}$$

$$\delta C_P = 2\pi\delta C_Q \tag{12}$$

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