# Propeller Preformance

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## I. Abstract

The influence of propeller geometry and pitch on propeller capability was explored throughout this experiment to determine how propeller performance can be best optimized. This experiment compared the performance metrics of four propellers of varying geometries and pitches in a 3x3 wind tunnel. It was found that performance metrics are dependent on propeller geometry, and more specifically, that performance metrics are dependent on the advance ratio of the propeller. The individual influences of diameter and pitch on the performance metrics could not be determined, nor could the influence of the ratio of diameter to pitch. When designing a propeller for a specific application, the geometry and pitch of the propeller will affect its capabilities. To optimize propeller performance, more analysis must be done to determine how the geometry and the pitch individually affect propellor performance.

## II. Introduction

The goal of this laboratory experiment is to measure the performance of various propeller geometries and evaluate the influence of propeller pitch on essential parameters such as power, thrust, efficiency, and torque. In order to achieve this objective, multiple measurements including propeller RPM, indicated pressure, drag, torque, and test section temperature will be taken using state-of-the-art equipment such as an electric motor, control module, six-component internal strain gage balance, differential pressure transducer, type K thermocouple, and data acquisition chassis. To conduct the experiment, a 3'x3' wind tunnel will be utilized to create a controlled airflow over the propeller, and a force/moment balance will be employed to measure thrust and torque. A motor and controller will be used to adjust the power sent to the propeller while monitoring its rotation speed. The lab procedure will involve testing two propellers from a selection of several options provided. The first propeller model is C-2, with pitch 13.5 and diameter of 13.5 inches. The second propeller model is C-2, with pitch 7, and diameter 11.0 inches. They were both manufactured at APC. The lab report will compare the results of the first and the second propeller with those of 2 other groups of propellers, analyzing how propeller power, thrust, efficiency, and torque vary with different propeller pitch and advanced ratio. This comparison will be made by examining the results for the chosen propeller against other groups' values for their respective propellers. The experiment will consist of four runs at nominal Reynold's numbers of 0, $1.20 * 10^6$, $1.65 * 10^6$, and $2.00 * 10^6$, during which continuous data will be collected. The outcome of this experiment will provide valuable insights into the performance of various propellers and their suitability for different applications.

## III. Theory

In this experiment the performance of the different propellers geometries and influence of the propeller pitch such as the power, efficiency, thrust, and torque. This will require recording the propellers RPM, indicated pressure, drag and also the test section. Starting with equation 1, pitch ratio where P is the power (W) and D is drag.

The performance of different propeller geometries and the influence of propeller pitch on parameters. The propeller power equation relates the power produced by the propeller to its thrust. Where P is the power (W), T is the thrust (N), and n is the revolutions per second. The power coefficient is calculated from equation 2.

$$p = \frac{P}{D} \quad (1) \qquad\qquad P = 2\pi n T \quad (2)$$

The propeller advance ratio, equation 3, relates the efficiency of the propeller to the velocity of air and the propeller's rotation speed. Where J is the efficiency (dimensionless), V is the air velocity (m/s), T is the thrust (N), P is the power (W), n is the propeller rotation speed (rpm), and D is the propeller diameter (m).

$$J = \frac{V}{nD} \quad (3)$$

Thrust is given by equation 1, and relates the thrust produced by the propeller to the air density, the propeller disk area, and the air velocity. Where T is the thrust (N), n is the propeller rotation speed (rpm), A is the propeller disk area ($m^2$), $\rho$ is the air density (kg/m$^3$), and V is the air velocity (m/s). Now this leads to the thrust coefficient. The thrust coefficient equation relates the thrust produced by the propeller to the air density, the propeller diameter, and the propeller rotation speed. Where $C_T$ is the thrust coefficient (dimensionless), T is the thrust (N), n is the propeller rotation speed (rpm), D is the propeller diameter (m), and $\rho$ is the air density (kg/m$^3$)

$$T = \frac{\rho}{2} A V^2 \quad (4) \qquad\qquad C_T = \frac{T}{\rho n^2 D^4} \quad (5)$$

Equation 6 relates the torque produced by the propeller to the thrust and the propeller radius. Where Q is the torque (Nm), T is the thrust (N), and r is the propeller radius (m). This leads to the torque coefficient, equation 7, which relates the torque produced by the propeller to the air density, the propeller diameter, and the propeller rotation speed.

$$Q = Tr \quad (6) \qquad\qquad C_Q = \frac{Q}{\rho n^2 D^5} \quad (7)$$

Now the efficiency of the propellers will ultimately contain the propulsive power out which will be the thrust coefficient and the propeller advance ratio. Over the shaft power in which is the torque coefficient. where $C_Q$ is the torque coefficient (dimensionless), Q is the torque (Nm), n is the propeller rotation speed (rpm), D is the propeller diameter (m), and $\rho$ is the air density (kg/m$^3$).

$$\eta_{prop} = \frac{C_T}{C_Q} \frac{J}{2\pi} \quad (8)$$

## IV. Methods and Procedure

The experiment was conducted in the 3x3 wind tunnel using a Scorpion S-4020-16 electric motor, a Phoenix HV85 Castle control module, an Able Corporation series D six-component internal strain gage balance, an Omega PX653-10D5V differential pressure transducer, a type K thermocouple, and a NI PXIe-1073 Data Acquisition Chassis. The LabVIEW software collected the following data parameters: time, indicated pressure (psf), motor speed(RPM), drag (indicated as “axial force”)(lb), torque (indicated as “roll-moment”) (in-lb), test section temperature (○C), measured to uncertainties of ±0.01sec, ±0.00001psf, ±0.00001rpm, ±0.00001lb, ±0.000001in-lb, ±0.00001°C respectively. Two propellers of different pitches and diameters were tested from their minimum to maximum rpm at four other indicated pressures turning the experiment. The rpm was controlled by a multi-turn potentiometer. The experimental set-up can be seen in Figure 1. The experimental procedure followed is below:

1. Recorded the atmospheric pressure
2. Determined the propeller diameter, pitch, manufacturer, and model
3. Followed the LabVIEW procedure for data collection
4. Set the wind tunnel to the desired indicated pressure starting with 0 psf
5. Slowly varied the propellor rpm over the course of three minutes from the minimum rpm value to the maximum rpm value, indicated by a flashing red light
6. Reduced the propellor speed to zero while the tunnel was kept running and saved the data
7. Repeated steps four through six for indicated pressure values of 4 psf, 8 psf, and 12 psf
8. Repeated steps one through seven for the second propeller

Data processing was done in MATLAB. Propeller off-tares were corrected. The shaft power and the power coefficient were determined. The non-dimensional thrust and torque coefficients, the propeller advance ratio, and the propeller frequency were calculated. Plots were then created to compare the thrust, torque, and efficiency versus the propeller advance ratio of four different propellers.

## V. Results and Discussion

During this lab the measured thrust was always greater than the tare thrust. This at first makes this seem reasonable since it is expected that the propellers will generate positive thrust, but examining the trends further by looking at 2 the expected trends shown in 3 don’t appear. This could indicate that that the thrust data is not a reasonable amount more than the tare data. Either of these interpretations can be considered reasonable as its possible their is inaccuracy with 2 and the fact that positive thrust is observed does make these results reasonable.

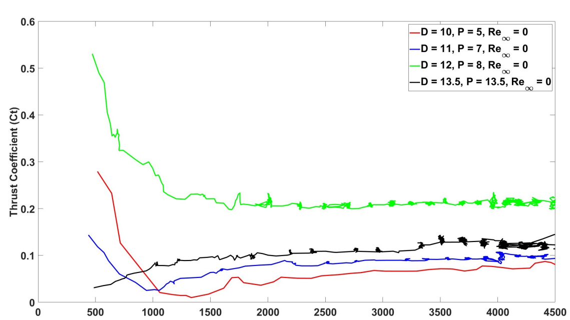


**Fig. 1:** Coefficient of Thrust vs. RPM

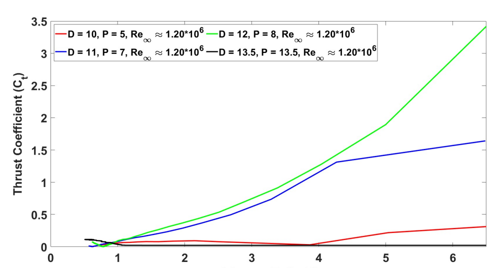


**Fig. 2:** Coefficient of Thrust vs. Advance Ratio where Reynolds number equals 1.20e6

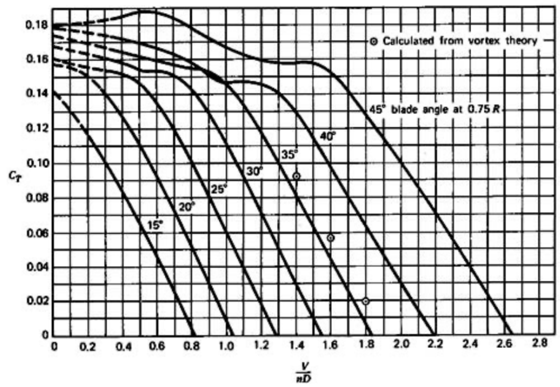


**Fig. 3:** Coefficient of Thrust vs. Advance Ratio

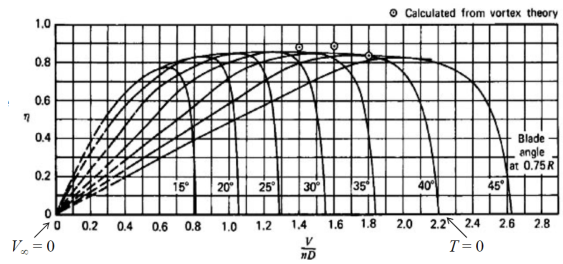


**Fig. 4:** Efficiency of a Propeller vs. Advance Ratio

**Fig. 3 and 4:** Figures 6.15 and 6.13, respectively, from B.W. McCormick's Aerodynamics, Aeronautics, and Flight mechanics, $2^{nd}$ ed., John Wiley & Sons.

The error in the data continues with efficiency as 6 does not resemble 4. The error in this data has a number of possible sources. The calculation for efficiency involves the thrust data, the torque data, the advance ratio calculations, which involve the indicated pressure data. Error in any of these data sets will propagate throughout and its possible that these sources are where the error comes from. It is also possible that these errors are due to the processing done in Matlab where because of the wrong things being done to the data the error was created in the analysis process. Unfortunately combing through each data set and the process done to them to identify exactly where this error is coming from is outside the scope of this lab especially due to time constraints. Perhaps with enough time to comb through all of the data and to have outside help examine the code used the source of the error could be identified.

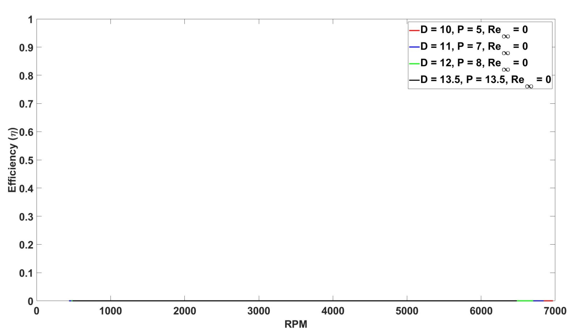


**Fig. 5:** Reynolds Numbers Equal to Zero

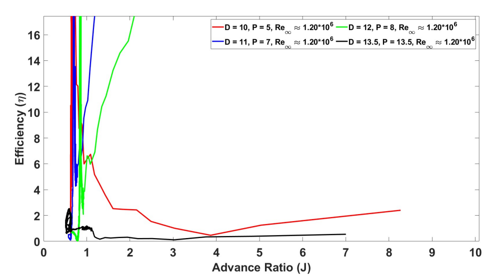


**Fig. 6:** Reynolds Number equals 1.20e6

**Fig. 5 and 6:** Efficiency as a propeller is taken through the RPM or Advance ratio range.

To understand what would happen at low and high values of the advance ratio it is necessary to examine an outside source. For this the trends shown in 3 and 4 can be examined. For thrust 3 shows a decline which is mostly two linear sections, the first being not as steep as the second. For most pitch values there is a slight dip and then peak before the second linear section begins. 4 shows a linear increase until max efficiency before a section of exponential decrease. Neither of these trends is apparent in the plots created by the data in this experiment which further supports either some source of error in the data or in the analysis.

Examining 1 and 7 both appear to increase as pitch increases, with 1 displaying a greater increase. This difference in amount they increase does suggest that as the pitch increases the advance ratio will increase. 4 agrees with this conclusion suggesting that this trend isn't just an error in the data. 9 agrees with this conclusion as the most notable spikes occur at increasing advance ratios as the pitch increases. However, examining 10 it would be expected that the propeller with a pitch of 13.5 would have the highest coefficient of thrust at each advance ratio, this is not what is observed though. Examining 1 this trend is also observed there suggesting that this is less likely to be a mistake and more likely to be an error with the data collected.

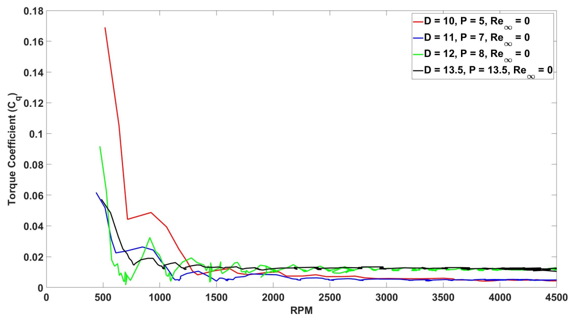


**Fig. 7:** Reynold's number is zero

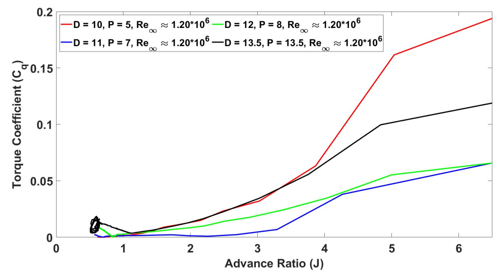


**Fig. 8:** Reynold's number equals 1.20e6

**Fig. 7 and 8:** Torque coefficients as propeller is taken through the rpm or advance ratio range

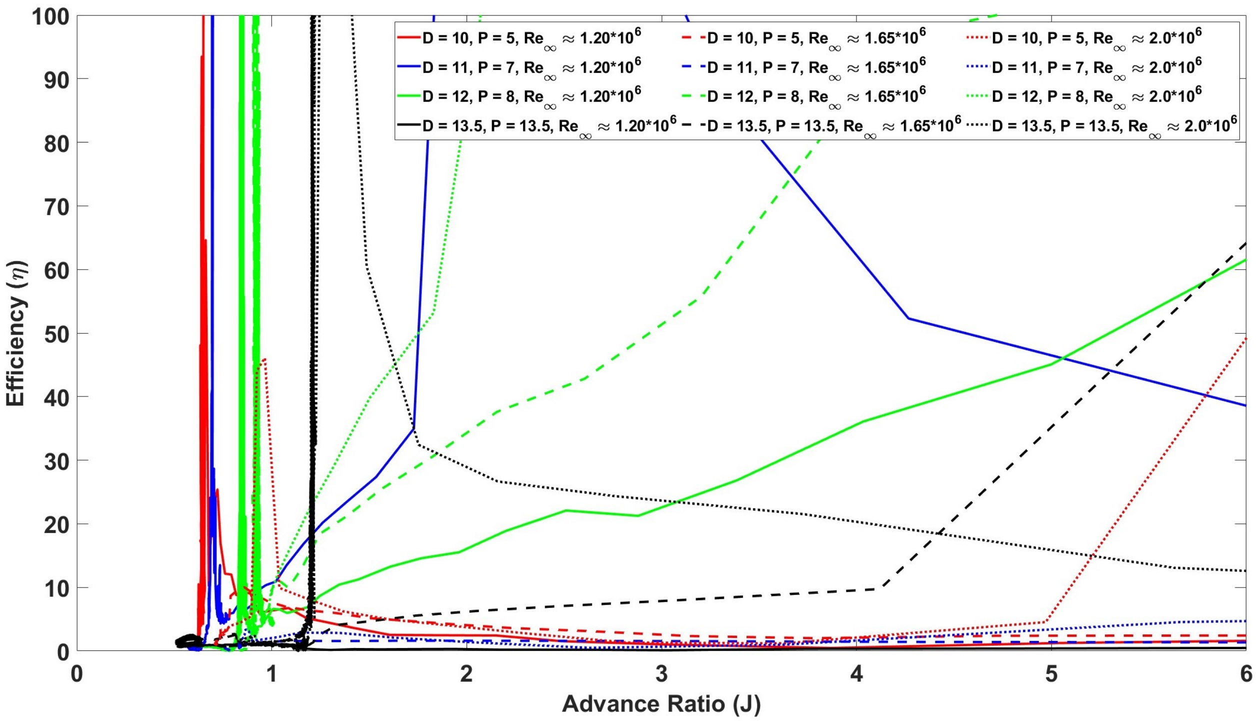


**Fig. 9:** Efficiency vs Advance Ratio for all non-Zero Reynolds numbers

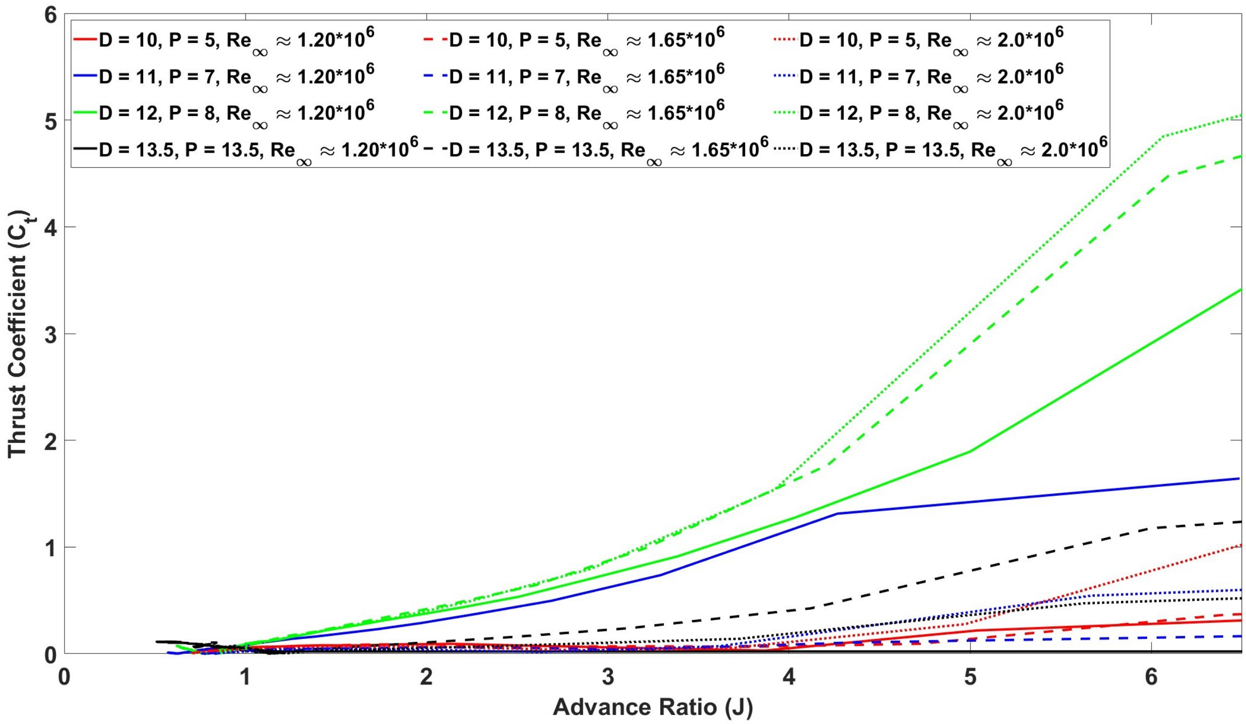


**Fig. 10:** Thrust vs Advance Ratio for all non-Zero Reynolds numbers

## VI. Conclusion

There were two objectives to this experiment: to explore how propeller power, thrust, efficiency, and torque vary with advance ratio for different propeller geometries, and to determine the influence of propeller pitch. These objectives were approached by comparing the performance metrics of four propellers of different diameters and pitches at four different free-stream Reynold's numbers within the 3x3 wind tunnel. As seen in figures 1 and 2, as the advance ratio increased, the thrust of the propeller increased for all propeller geometry and for all values of Reynolds number. This was unexpected, as thrust should decrease with advance ratio, as seen in figure 3. Figures 5 and 6 show that as the advance ratio increased, the efficiency of the propeller increased or decreased, depending on propeller geometry and Reynolds number. However, how the geometry and Reynolds number together or individually affected whether the efficiency increased or decreased was unclear. This increase or decrease was unexpected because as advance ratio increased, the efficiency should have increased steadily, peaked, then rapidly decreased, as seen in figure 4. Figures 7 and 8 show that as the advance ratio increased, the torque of the propeller increased for all propeller geometry and for all values of Reynolds number. How propeller diameter and pitch individually contributed to the magnitude of the change in thrust, efficiency, and torque cannot be commented on, as both quantities change for each propeller. Furthermore, there is no relationship between the ratio of diameter to pitch and the magnitude of the changes of the aforementioned quantities.

As previously mentioned, the results of this experiment were unexpected. It is reasonable to conclude that the limitations of the potentiometer led to these unexpected results. The multi-turn potentiometer had to be physically turned to adjust the motor speed. It was not possible to increase the motor speed smoothly and at a slow constant rate. Due to this, the data collected from the experiment was significantly distorted. A smoothing function was applied to the distorted data to correct this, minimizing the distortion while still capturing the general trend of the data. The smoothing greatly increased the uncertainty of the experimental results. For future experiments, a digital method of controlling the motor speed would significantly reduce or potentially eliminate the amount of data distortion by providing a way to linearly increase the motor speed. Another major limitation of this experiment was that the dimensions for the diameter and for the pitch of each propeller varied. As no one quantity was consistent throughout the entirety of the experiment, it could not be said how propeller diameter or propeller pitch individually affected the performance metrics of the propeller. For future experiments, one of these quantities must be kept constant, while the other is varied, eliminating the influence of the change in both diameter and pitch from propeller to propeller. This would allow one to compare how both the propeller geometry and the propeller pitch individually affect its performance.

# VII. Appendix

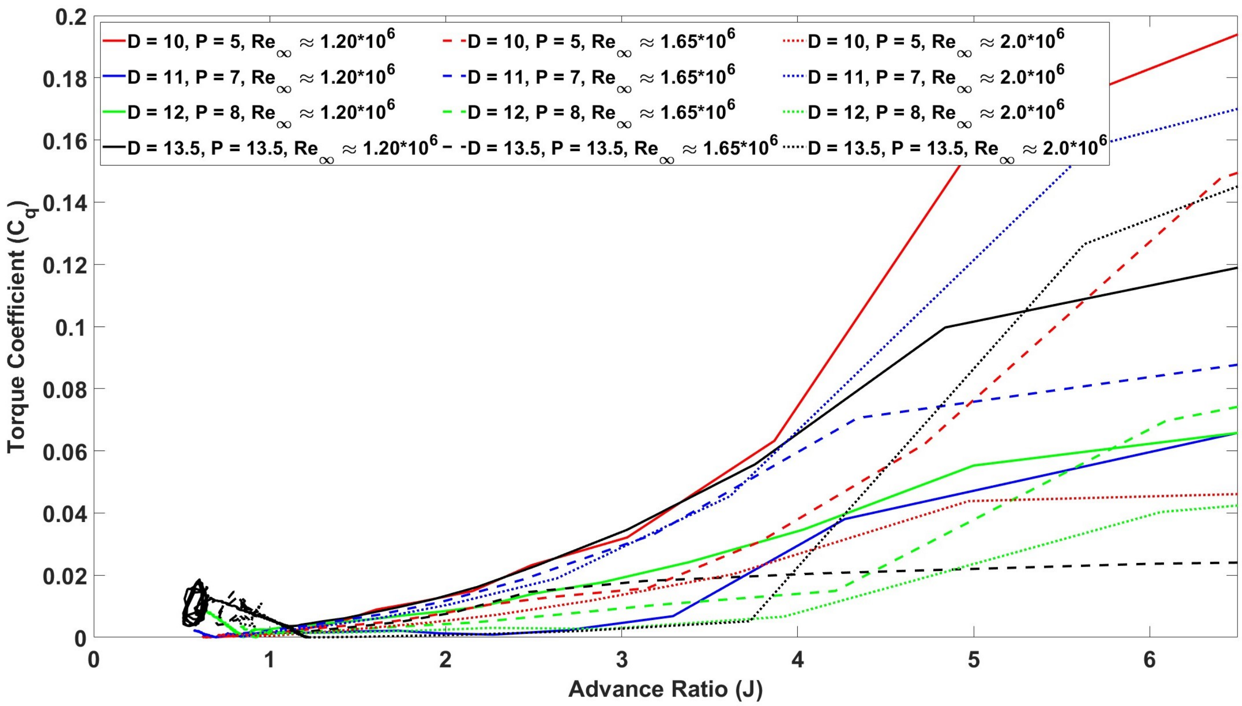


**Fig. 11:** Torque vs Advance Ratio for all non-Zero Reynolds numbers

# VIII. References


1. B.W. McCormick's Aerodynamics, Aeronautics, and Flight mechanics, $2^{nd}$ ed., John Wiley  Sons.
2. Department of Atmospheric Sciences, 2023, https://atmos.uw.edu/current-weather/.

# IX. Acknowledgments

Peer review of the full report -

| | Who | Internal deadlines | Deadline Achieved? | Time Commitment |
|---|---|---|---|---|
| Abstract | Angelina | Monday | Yes | 0.8 hours |
| Intro | Felicity | Finish by Friday | Yes | 1.5 hrs |
| Theory | Felicity | Finish by Friday | Yes | 2 hrs |
| Methods/Procedure | Angelina | Monday | Yes | 1.2 hours |
| Results/ Discussion | Kyle | Monday | Yes | 5 hrs |
| Conclusion | Angelina | Monday | Yes | 1.7 hours |
| Data Analysis | Peter | Weekend | Yes | $>$ 10 hours |
| Proof-Reading | Peter | Monday | Yes | 1 hour |