

DEVELOPMENT OF A MICROSOFT EXCEL BASED  
UAV PROPELLER DESIGN AND ANALYSIS TOOL

By

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DEVELOPMENT OF A MICROSOFT EXCEL BASED  
UAV PROPELLER DESIGN AND ANALYSIS TOOL

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Abstract: QPROP/QMIL were developed by Professor Mark Drela at MIT for use in designing propellers and windmills for various flow conditions. These tools have been used by other graduate students with varying degrees of success, however there has not been a formal comparison of the QPROP results to experimental wind tunnel data. The goals of this thesis are to provide a software tool to assist in operating QPROP and QMIL in order to design UAV propellers for the Minimum Induced Loss (MIL) condition for a given flight condition and to perform a comparison of QPROP results to experimental wind tunnel results.

A Microsoft Excel based Visual Basic tool (PROPDES) was developed and utilized to automate the use of QPROP and QMIL. Verification of PROPDES is presented to show that it does not adversely change the QPROP/QMIL results. PROPDES is then used to attempt to validate QPROP's prediction methods and QMIL's design capabilities by running various test cases for ranges of RPM, velocity, diameter, and number of blades that are typical for small UAV propellers. The QPROP predictions are then compared to published wind tunnel data and the results are discussed.

Finally, improvements are made to allow multiple iterations of QMIL to be used for the design case as well as including an APC chord and beta distribution for use when QMIL fails to provide an output. The PROPDES designs are compared to commercially available propellers to show that PROPDES designed propellers are able to obtain much better performance characteristics than commercially available propellers for the particular design condition.

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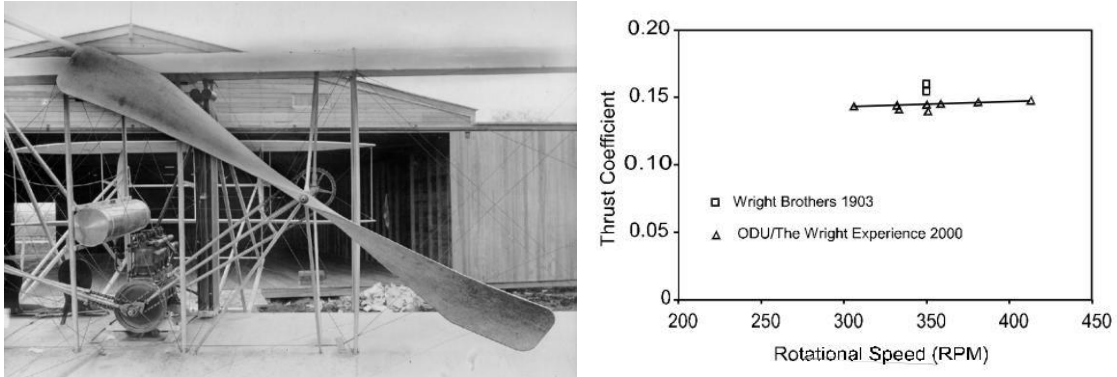
## CHAPTER I

### INTRODUCTION

Aircraft propeller research has been ongoing for over 100 years. The Wright Brothers completed the first powered flight on December 17, 1903 using a propeller that the brothers designed and built themselves. The Wrights originally thought that they could use the same theory that was used by marine engineers to develop ship propellers. However, after finding that marine engineers at the time were using a trial-and-error approach the Wrights decided that they needed to develop new theory to help them understand the propeller mechanics and create designs prior to building and testing.

The Wright brothers theorized that propellers could be thought of simply as rotating wings. They desired to calculate the thrust that the propeller would produce, however that problem was much harder to visualize. Orville stated in *Flying Magazine*, “It is hard to find even a point from which to make a start; for nothing about a propeller, or the medium in which it acts, stands still for a moment. The thrust depends upon the speed and the angle at which the blade strikes the air; the angle at which the blade strikes the air depends upon the speed at which the propeller is turning, the speed the machine is travelling forward, and the speed at which the air is slipping backward; the slip of the air backward depends upon the thrust exerted by the propeller and the amount of air acted upon. When any of these changes, it changes all the rest, as they are all interdependent upon

one another.” (<http://wrightstories.com/propeller-design-demonstrates-the-genius-of-the-wright-brothers/>).



**Figure 1: (Left) Wright Brother's 1910 Bent End Propeller, (Right) CT Data for Wrights' 1903 Propeller**

The brothers went on to use momentum theory, blade element theory and their previous airfoil tests to design a propeller that had a maximum efficiency of nearly 70%. The Wrights continued to improve their design in 1905 and ultimately increased the propeller maximum efficiency to 81.5% in 1905 (Koehersberger, Wald, & Hyde, 2000). Their work is truly amazing considering that modern wooden aircraft propellers have efficiencies of around 85%.

(<http://wrightstories.com/propeller-design-demonstrates-the-genius-of-the-wright-brothers/>)

The science of propellers, how they work, and how to design them has been well understood for full scale aircraft for several decades now. Rankine and Froude separately developed similar momentum theories based on the momentum and kinetic energy that is imparted to the air mass in which the propeller rotates. Froude is also credited with developing the idea of analyzing the forces on elementary strips of propeller blades in 1878. Drzewiecki independently published his Blade Element Theory (BET) in 1885. BET suggests that a blade element works as a single lifting surface that moves through the air in a helical path; the forces on each element can be summed up to find the total forces acting on the propeller blades. (Weick, 1930) As previously discussed, Orville and Wilbur Wright created the first useful aircraft propellers by combining their knowledge of airfoils with both momentum theory and blade element theory.

Several others have made significant contributions to aircraft propeller technology. In 1919, Albert Betz published a paper describing an extension of the momentum theory in which rotational effects were included and in which he identified the conditions for minimum induced loss for the case of a lightly loaded propeller. The minimum induced loss (MIL) condition consists of a propeller load distribution that results in the shed vorticity forming regular undeformed helicoidal vortex sheets which move backward from the propeller. (Helmbold, 1931, Wald, 2006) Prandtl developed a 2-dimensional approximation for the flow in the MIL conditions.

Sydney Goldstein later provided his Vortex Theory where he expanded Betz's approximation by solving exactly for the case of a frictionless, lightly loaded propeller with minimum loss of energy to the slipstream, assuming that the induced velocity is normal to the resultant velocity. (Goldstein, 1929) Theodorsen analyzed the vortex sheets far behind the propeller and showed that Goldstein's solution does not need to be limited to only lightly loaded propellers. In 1964, Tibery and Wrench Jr. provided tables of the Goldstein function over a wide range of parameters. (Tibery and Wrench Jr, 1964)

Larrabee later presented a method for the practical design of propellers, however this method assumes a lightly loaded propeller and does not take into account the additional change in velocity due to self-induction. (Wald, 2006; Larrabee, 1979) More recently, Mark Drela provided a computer code, QPROP, which followed the methods published by Larrabee but also included a radially-varying self-induction velocity term in order to give consistency with the heavily-loaded actuator disk limit. (Drela, QPROP User Guide)



**Figure 2: Example of UAV Propellers from APC, XOAR, and UAV Prop (Not to Scale)**

The primary area of propeller research in recent years has focused around Unmanned Aircraft Vehicles (UAVs) or Unmanned Aerial Systems (UASs). Even during the recent years of constrained US Government spending, unmanned technology and advances to UAVs is still a priority for the United States' defense leadership. The Honorable Frank Kendall, US Defense Secretary for Acquisition, Logistics and Technology, recently stated the following in an interview: "There's a general need to move technology more quickly and effectively and to push technology forward. So while our investments are constrained now, there are some things we can do, if we prioritize, that will accomplish that goal in general. The areas we're looking at in the technological offset strategy include things like autonomy, unmanned systems in [different] domains, ways to extend our range capabilities so we can operate and generate effects and generally control forces farther away."

<http://archive.defensenews.com/article/20140922/DEFREG/309220017/Interview-Frank-Kendall-US-DoD-Acquisition-Chief>

There have been many analytical models developed that attempt to solve for common variables such as Thrust provided and Power required to drive the propeller at some known flight conditions. A few software program designers have even attempted to solve design problems by producing the necessary propeller blade geometries for given in-flight conditions. While these

tools can be very useful to propulsion system designers, there is a great need to validate these tools to ensure that they remain accurate for the flight regimes of interest to the designers.

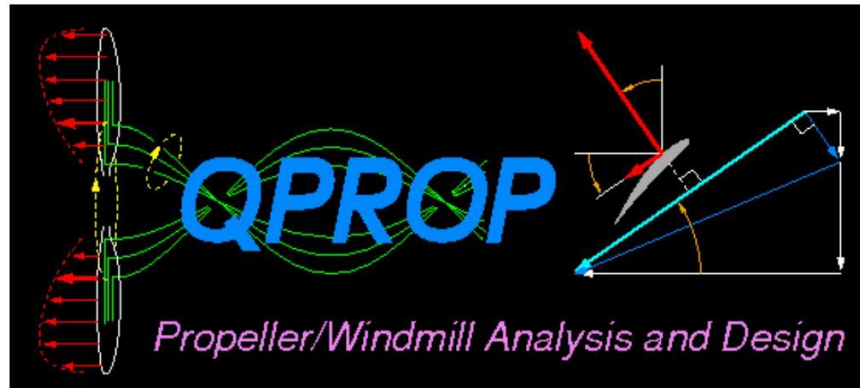


Figure 3: QPROP Logo

QPROP is an example of a software code that can be used to aid aircraft propulsion designers.

QPROP is designed to be used to predict the performance of various propeller-motor combinations. It has a relatively sophisticated propeller model and also allows for both brushed and brushless motors to be used in the analysis. Its companion program, QMIL, generates propeller geometries for the Minimum Induced Loss (MIL) condition. QPROP and QMIL can be used to complement one another during the design process for both aircraft propellers and windmills however, for the purposes of this thesis, only the propeller code is explored in detail. (Drela, QPROP User Guide)

Multiple papers have been published which either use QPROP as part of the author's analysis (Hrad, Pederson, Rotramel, Turan) or perform limited comparisons of QPROP to experimental data (Short, Silvestre, Morgado, Pascoa, Turan). However, the author was unable to find any extensive validation of QPROP in which QPROP results were directly compared to experimental data for a wide range of propeller diameters and Reynolds Number conditions. Due to QPROP's relatively sophisticated structure and robust handling of multiple design cases, it has become a popular tool for UAV propulsion designers which creates a great need for validation to ensure that the tool's limitations are well understood and documented.

The need for validation of propeller codes becomes particularly necessary when a tool is desired for use across a wide range of Reynolds numbers. Reynolds number effects are well documented, particularly for smaller, lightly loaded propellers. (Borst, 1977). UAVs vary greatly in size and therefore also vary greatly in size of propellers and cruising velocities. UAV propellers can vary from a few inches in diameter to over 9 feet in diameter and cruising velocities range from 20 feet per second to over 400 feet per second. (2010 UAV Roundup – need better citation?) Therefore, UAVs at cruise conditions can experience Reynold’s numbers from under 100,000 to well over 20,000,000. Because of this vast Reynold’s number range, it is extremely important to understand any software tool limitations; particularly when estimating low Reynold’s number performance



**Figure 4: Examples of Propeller Driven UAVs**  
**(From Top Left, Clockwise: Predator, Raven, Scan Eagle, Wasp III, Reaper, Altair)**

The primary objective of this thesis is to properly validate QPROP over a range of design cases (to include Reynold’s number, number of blades, and size of propellers) using experimental data obtained from wind tunnel testing. The validation includes an analysis on the accuracy of QPROP over the range of design cases in an effort to better understand its limitations. The secondary objective is to develop a Graphical User Interface (GUI) that facilitates running multiple design and analysis cases utilizing QPROP and QMIL. The third objective is to use the GUI tool to design a propeller for use on a UAV as an example case.

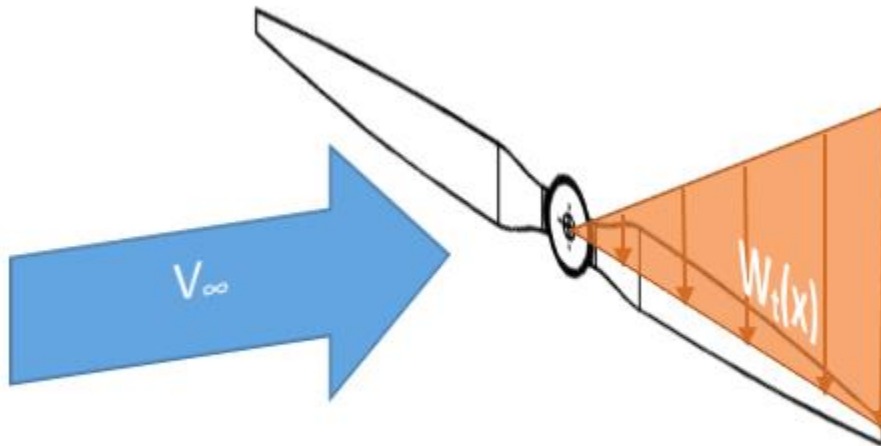
## CHAPTER II

### PROPELLER THEORY

There are three primary theories regarding the mechanics and performance of aircraft propellers, Momentum Theory, Blade Element Theory, and Vortex Theory. (Nelson, 1944; Glauert, 1947; Weick, 1930; Wald, 2006) The following section will discuss these theories and provide the necessary framework for discussing QPROP and QMIL.

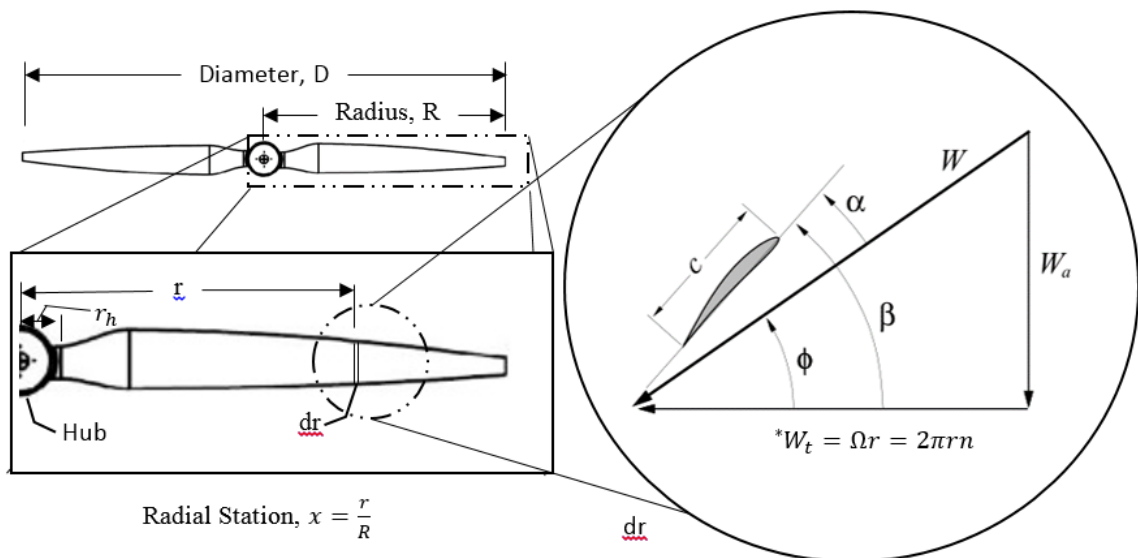
#### 2.1 – Basic Principles

A propeller is a device consisting of lifting surfaces connected at a central hub which rotates in order to produce a forward force or thrust. These lifting surfaces are basically wings with much more twist and variation in chord as a function of the radial station. The chord and twist variation is necessary to ensure that each blade section operates at a favorable angle of attack since the local velocity vector will vary due to the rotation of the propeller. By examining a simple sketch of the spinning propeller, one can see that the propeller experiences velocities from 2 primary sources: the forward velocity of the aircraft,  $V_{\infty}$ , and the rotational velocity caused by the propellers rotation about its axis,  $W_t$ . This principle is shown in Figure 5.



**Figure 5: Primary Velocities Acting on a Rotating Propeller**

In reality, there are additional induced velocities present which contribute to the airflow at the propeller but these velocities will be discussed in later sections. Some of the important geometric parameters of the propeller are discussed below and shown in Figure 6.



**Figure 6: Propeller Geometry and Blade Element Velocities (Gamble, Drela)**

\*The equation for  $W_t$  holds true only for the case of the induced velocity,  $v = 0$ .



On the top left of the above figure is a standard 2 bladed propeller with an overall Diameter,  $D$  and Radius,  $R$ . The exploded view shows the hub, the radius of the hub,  $r_h$ , and a particular radial station,  $x$ , at some value of  $r$ , where  $x = \frac{r}{R}$ . The exploded view of the blade element,  $dr$ , shows the cross-sectional view at  $x$ . From this view, it is evident that the cross-section of the propeller is a 2-dimensional airfoil with chord,  $c$ . The geometric pitch angle,  $\beta$ , the local flow angle,  $\phi$ , the local angle of attack,  $\alpha$ , and the tangential velocity,  $W_t$ , all vary with the radial station and are demonstrated in Figure 6. Additionally, the local total velocity relative to the blade element at station  $x$ ,  $W$ , is shown along with the axial and tangential components of  $W$ ,  $W_a$  and  $W_t$  respectively.

It is important to understand the difference between the geometric pitch angle,  $\beta$ , and the local flow angle,  $\phi$ . The geometric pitch,  $p$ , is the advance per revolution of a propeller blade element moving along a helix whose angle equals the propeller geometric pitch angle,  $\beta$ . This concept is best understood by visualizing the propeller rotated through a gelatin fluid where no slip occurs. The geometric pitch is then equal to the distance that the propeller moved forward in the fluid in a single revolution.

$$p = \pi D \tan(\beta)$$

**Equation 1: Geometric Pitch**

However, propellers operate in a fluid which does allow slip and therefore the propeller will not obtain the full geometric pitch in one revolution under normal conditions. Therefore, the effective pitch,  $p_e$ , is defined as the distance that the airplane advances along its flight path for one revolution of the propeller.

$$p_e = \pi D \tan(\phi)$$

**Equation 2: Effective Pitch**

Slip is defined as the difference between the geometric pitch and effective pitch and will vary with the forward velocity of the airplane,  $V_\infty$ . Generally, small UAV propellers are designated by giving the geometric pitch of the propeller at the  $\frac{3}{4}$  radius.

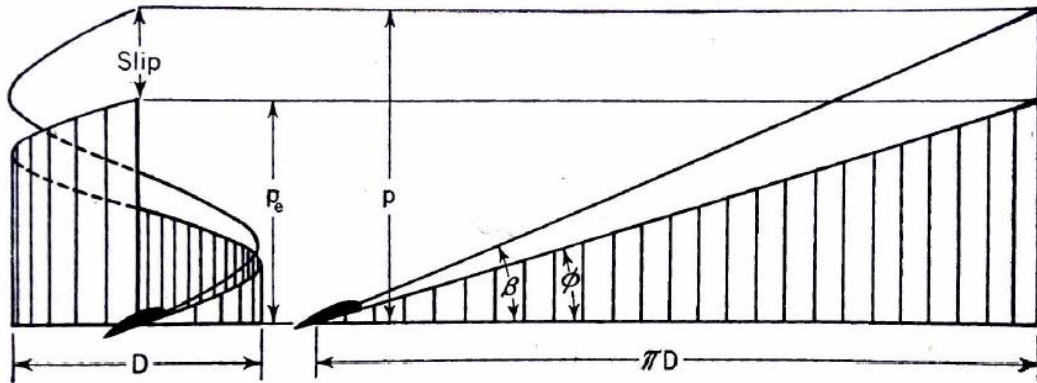


Figure 7: Slip, Geometric Pitch, and Effective Pitch (Nelson, 1944)

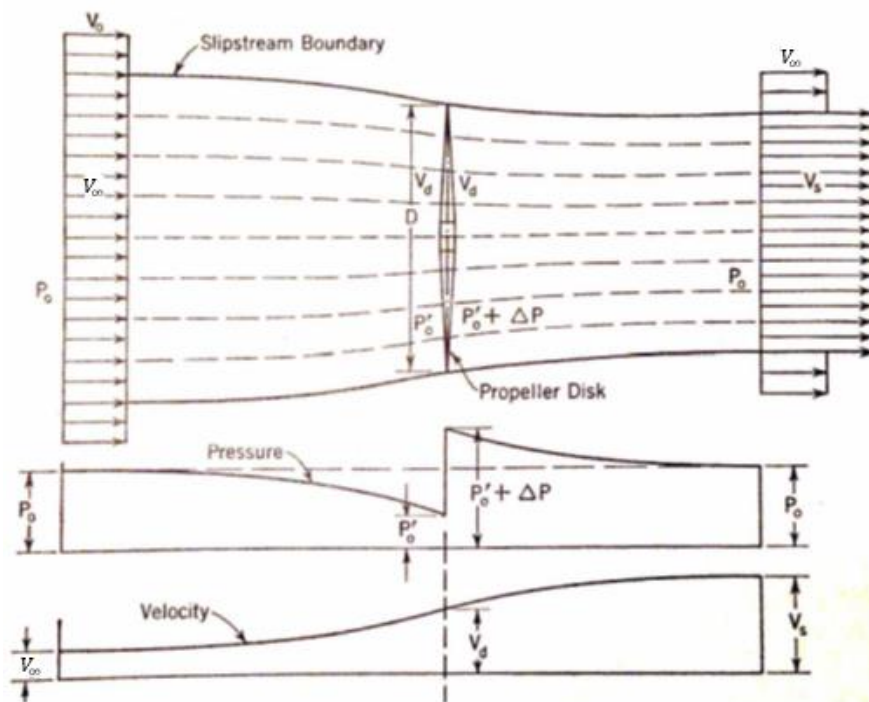
## 2.2 – Momentum Theory

The first theory regarding the mechanics of a fluid around a propeller was developed by Rankine and Froude and is called the momentum theory (or sometimes called the actuator disk theory).

The momentum theory treats the propeller as an actuator disk that produces a uniformly distributed thrust (which is created by a difference in pressure between the front and the back of the disk). The disk can be thought of as a propeller having an infinite number of blades. It is also assumed that the thrust is uniformly distributed over the entire area of the disk. Additionally, it is assumed that the airflow is streamline in character on both sides of the disk and are continuous through the propeller. As a result of this assumption, the axial velocity is equal immediately in front of and immediately behind the propeller disk (Notice  $V_d$  shown on each side of the disk in Figure 8). It is important to note that the actuator disk as described here does not provide a true mathematical limit for the propeller properties, however it does provide an overall general representation of the propeller properties. (Theodorsen, )

In the simplest form of the momentum theory, the torque on the propeller disk and the rotation imparted to the airstream by the propeller is ignored. The theory relies on Bernoulli's theorem

that states the total energy is a constant along a given stream line, which is true for incompressible and inviscid flow conditions. The stream tube of interest is chosen such that it encloses the propeller disk as demonstrated in Figure 8. (Nelson, 1944; Weick, 1930; Glauert, 1943)



**Figure 8: Momentum Theory Stream Tube and PV Relationships (Nelson, 1944)**

Figure 8 also shows the general relationships of pressure and velocity near the propeller disk.

Notice that  $V_\infty$  designates the velocity of the freestream (the air well ahead of the propeller disk that is unaffected by the propeller). Likewise,  $P_0$  or  $P_\infty$  designates the pressure of the freestream.

From the P-V charts above, it is evident that the pressure is reduced from  $P_0$  in the freestream to  $P'_0$  directly in front of the propeller and the propeller adds a pressure increment  $\Delta P$ . The pressure then returns to its original value,  $P_0$ , in the slipstream. Additionally, the propeller causes the velocity to increase from  $V_\infty$  in the freestream to  $V_d$  at the propeller and reaches a final, increased, value of  $V_s$  in the slipstream. (Nelson, Weick)

Bernoulli's equation shows that the total head of a fluid is constant along a stream tube and that the total head is given by

$$H = P + \frac{1}{2}\rho V^2 = \text{constant}$$

**Equation 3: Bernoulli's Equation**

Bernoulli's equation may be applied in front of the disk and behind the disk but it cannot be used across the disk since energy is added to the flow by the actuator disk. (Nelson) Using the General Thrust Equation (John, 1984), gives

$$T = \dot{m}\Delta V = (A\rho V_d)(V_s - V_\infty)$$

**Equation 4: General Thrust Equation**

The thrust, T, can also be calculated using only the disk area, A, and the difference in total head pressure on either side of the disk ( $\Delta P$ ). Using Bernoulli's equation to solve for the pressure on each side of the disk gives

$\Delta P = \text{head pressure after the disk} - \text{head pressure before the disk}$

$$\Delta P = \left(P_0 + \frac{1}{2}\rho V_s^2\right) - \left(P_0 + \frac{1}{2}\rho V_\infty^2\right)$$

$$\Delta P = \frac{1}{2}\rho(V_s^2 - V_\infty^2)$$

Therefore, the thrust calculated by using the pressure difference is

$$T = \frac{1}{2}A\rho(V_s^2 - V_\infty^2)$$

By comparing the two expressions for thrust, one can show that:

$$T = (A\rho V_d)(V_s - V_\infty) = \frac{1}{2}A\rho(V_s^2 - V_\infty^2)$$

$$V_d(V_s - V_\infty) = \frac{1}{2}(V_s^2 - V_\infty^2)$$

$$V_d = \frac{1}{2}(V_s + V_\infty)$$

In other words, half of the velocity added by the propeller disk is imparted before the propeller disk and half is imparted after the disk. This relationship is shown above in Figure 8. (Nelson)

Momentum theory also provides a means for estimating the ideal efficiency for a given propeller. Efficiency is simply the output energy divided by the input energy and in the case of the propeller disk the input is simply the total work done by the propeller whereas the output is defined as the thrust multiplied by the velocity.

The input energy is defined by the change in kinetic energy in the flow:

$$\Delta KE = \frac{1}{2} \dot{m} (\Delta V)^2 = \frac{1}{2} (A \rho V_d) (V_s^2 - V_\infty^2)$$

**Equation 5: Input Energy for a Propeller System**

The ideal efficiency can then be estimated by

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Thrust} \times \text{Velocity}}{\text{KE Increase}} = \frac{T V_\infty}{\frac{1}{2} (A \rho V_d) (V_s^2 - V_\infty^2)}$$

**Equation 6: Ideal Efficiency Using Momentum Theory**

Where  $V_d = \frac{1}{2} (V_s + V_\infty)$  and  $T = \frac{1}{2} A \rho (V_s^2 - V_\infty^2)$ , therefore

$$\begin{aligned} \eta &= \frac{\frac{1}{2} A \rho (V_s^2 - V_\infty^2) V_\infty}{\frac{1}{2} \left( A \rho \left( \frac{1}{2} (V_s + V_\infty) \right) \right) (V_s^2 - V_\infty^2)} \\ &= \frac{2 A \rho (V_s^2 - V_\infty^2) V_\infty}{A \rho (V_s + V_\infty) (V_s^2 - V_\infty^2)} \\ &= \frac{2 V_\infty}{V_s + V_\infty} = \frac{2}{1 + V_s / V_\infty} \end{aligned}$$

$$\therefore \eta_{ideal} = \frac{2}{1 + V_s / V_\infty}$$

**Equation 7: Ideal Efficiency of a Propeller**

The efficiency expressions above represent the ideal efficiency of a propeller which cannot be obtained in reality. Remember, this expression for ideal efficiency has been obtained by assuming that the only loss of energy is given by the change in kinetic energy of the axial velocity in the slipstream. However, there are several other factors that are ignored, such as aerodynamic drag on the blades, energy loss due to rotation in the slipstream, compressibility losses, blade interference, and loss of thrust due to the periodic thrust variation (thrust is not uniform across the disk area).

(Nelson)

The benefit of the equations derived from the momentum theory is that they are quick and easy to use and give a propeller designer a rough estimate of the maximum thrust and efficiency limits. In most cases, the actual efficiency is roughly 85% of the ideal efficiency. The figure below shows the actual and ideal efficiency variation based on a NACA propeller.

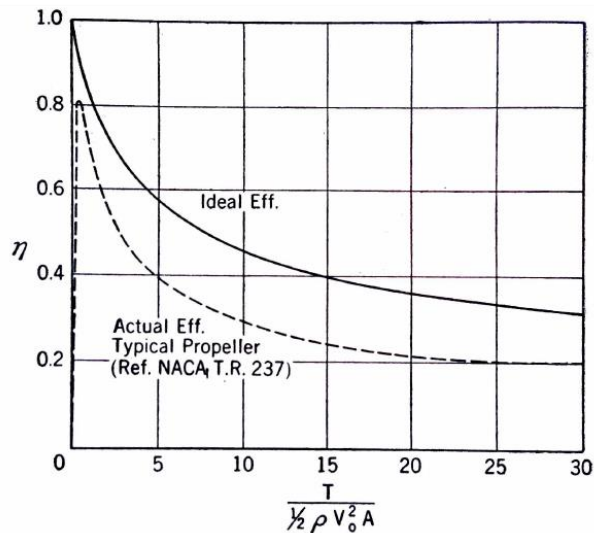


Figure 9: Ideal Efficiency Compared to Measured Efficiency (Nelson, 1944)

Some important relationships can be seen from Figure 9 above. In general, an increase in thrust, a decrease in velocity, or a decrease in propeller diameter all cause a decrease in efficiency.

Therefore, when designing a propeller, it is prudent to choose as large a diameter as possible, keep the forward velocity as high as possible (without inducing separation issues), and try to

minimize the thrust required. These conditions should provide the best ideal efficiency. In practice however, the skin friction increases with an increase in diameter so there are obviously limitations to the preceding rules of thumb. (Nelson, Weick)

## 2.3 – Blade Element Theory

Momentum theory provides a basic structure for solving the propeller problem, however it neglects several things that have a dramatic effect on the propeller's performance, such as torque, rotational effects, and aerodynamic drag on the blades. As mentioned previously, Drzewiecki is generally credited for bringing the Blade Element Theory to a practical form and used it to obtain thrust and torque values for the entire propeller by summing up the resultant forces on the individual blade elements.

Blade element theory assumes that the propeller has a certain angular velocity,  $\Omega$ , around its axis and that it is placed in a uniform airflow of velocity,  $V_\infty$  which is parallel to the axis of rotation. The propeller is then treated as a twisted wing and each blade element,  $dr$ , follows a helical path and is treated as a normal 2-dimensional airfoil. Since the airflow around each element is being considered as 2-dimensional, the adjacent parts of the blade are assumed to be unaffected by one another, which is not true in practice. It is also assumed that the angular velocity of the propeller is kept low enough that the velocity of the blade tips does not approach the speed of sound. In other words, compressibility effects due to transonic or supersonic flow are being ignored which, in the case of most UAV propellers, is a perfectly acceptable assumption. (Glauert, Weick, Nelson)

By looking at the element  $dr$ , as shown in the figure below, one can see that it is located a distance  $r$  from the axis and therefore will have a rotational velocity  $W_t = 2\pi rn$ . The forward velocity (or axial velocity) is shown as  $W_a$  and it will later be shown that  $W_a \neq V_\infty$ . When the

forward velocity is combined with the tangential velocity, the resultant velocity vector is formed and is shown below as  $W$ .

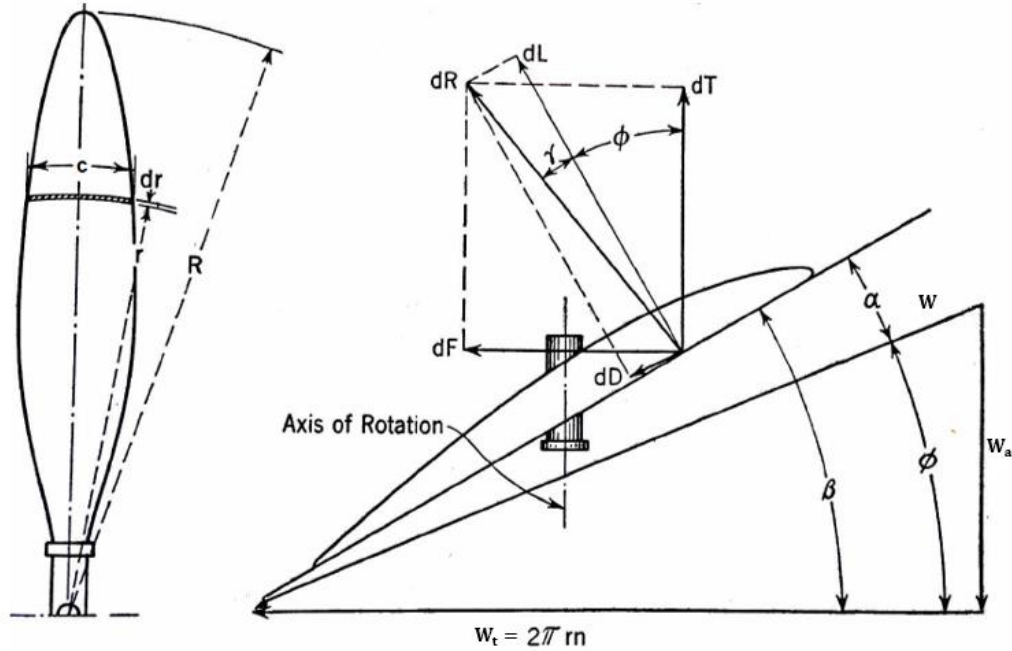


Figure 10: Blade Element Theory Relationships (Nelson)

Recall from airfoil theory (Anderson, 2007), the lift generated by an airfoil can be expressed as

$$dL = C_L \frac{1}{2} \rho V^2 dA = C_L \frac{1}{2} \rho W^2 c dr$$

Equation 8: Airfoil Lift Equation

Likewise, the drag induced by an airfoil can be expressed as

$$dD = C_D \frac{1}{2} \rho V^2 dA = C_D \frac{1}{2} \rho W^2 c dr$$

Equation 9: Airfoil Drag Equation

From Figure 10 above,  $\gamma = \tan^{-1} \frac{dD}{dL}$ , and the total resultant force on the blade element is

$$dR = \frac{C_L \frac{1}{2} \rho W^2 c dr}{\cos \gamma}$$

Equation 10: Airfoil Resultant Force



The thrust component for the given blade element,  $dT$ , is given by the component of the resultant force,  $dR$ , in the forward direction. The thrust component can be expressed as

$$dT = dR \cos(\phi + \gamma) = \frac{C_L \frac{1}{2} \rho W^2 c dr \cos(\phi + \gamma)}{\cos \gamma}$$

And from Figure 10 above, it can be shown that

$$W = \frac{W_a}{\sin \phi}$$

Therefore,

$$dT = \frac{C_L \frac{1}{2} \rho W_a^2 c dr \cos(\phi + \gamma)}{\sin^2 \phi \cos \gamma}$$

**Equation 11: Thrust of an Airfoil**

Torque is defined as the force acting on the blade element perpendicular to the propeller axis multiplied by the moment arm from the axis (i.e. the radius). Therefore, the torque component for the given blade element,  $dQ$ , can be expressed similarly as

$$dQ = dF * r$$

Where,

$$dF = dR \sin(\phi + \gamma) = \frac{C_L \frac{1}{2} \rho W^2 c dr \sin(\phi + \gamma)}{\cos \gamma}$$

Substituting for  $dF$  in the above equation, gives the following expression for the torque component in terms of the axial velocity,  $W_a$ :

$$dQ = dF * r = \frac{C_L \frac{1}{2} \rho W_a^2 c r dr \sin(\phi + \gamma)}{\sin^2 \phi \cos \gamma}$$

**Equation 12: Torque of an Airfoil**

One obvious but important concept to note is that the expressions above give the forces on a blade element and not the entire propeller. To calculate the forces on the entire propeller, one must integrate the above expressions over the entire length of the blade and then multiply by the number of blades on the propeller. The overall total values of thrust and torque for the propeller are given by:

$$T = \frac{1}{2} \rho W_a^2 B \int_0^R \frac{C_L c \cos(\phi + \gamma)}{\sin^2 \phi \cos \gamma} dr$$

**Equation 13: BET Total Thrust Equation**

$$Q = \frac{1}{2} \rho W_a^2 B \int_0^R \frac{C_L c r \sin(\phi + \gamma)}{\sin^2 \phi \cos \gamma} dr$$

**Equation 14: BET Total Torque Equation**

And the propeller efficiency can be defined as

$$\eta = \frac{\text{output}}{\text{input}} = \frac{TV_\infty}{2\pi nQ}$$

**Equation 15: BET Propeller Efficiency**

Additionally, the amount of power needed to drive the propeller for this design case is given by

$$P_{prop} = 2\pi nQ = \Omega Q$$

**Equation 16: BET Power Required**

Depending on the units of torque, one can divide Equation 16 by 550 to get horsepower (assuming torque is in English units of  $ft * lbs$ ) or leave as is for Power in Watts (assuming torque is in SI units of  $N * m$ ).

Recall the assumptions that were made while developing the BET relationships. In particular:

1. 2-Dimensional flow assumed, therefore interaction of the airflow between blade elements is ignored
2. No radial flow due to slipstream contraction

3. Increased velocity in front of the propeller (inflow velocity) is incorrect due to airfoil data only being published for a rectangular or slightly tapered wing (not accounting for taper/twist used in propeller designs) (Weick)
4. Interference between the propeller blades is ignored
5. Tip loss is ignored – thrust and torque values are calculated higher for the elements near the tip than what is shown by experimentation (Lock & Bateman)

As with the simple Momentum Theory, BET also overestimates the thrust produced and therefore provides an unrealistically high thrust estimate. Therefore the real value of the simple BET is for a relatively quick approximation (although the computations are more involved than momentum theory) or for qualitatively comparing the performance of 2 or more propellers. There are many variations to the momentum and blade element theories including accounting for some of the effects ignored by the simple BET however the momentum and blade element theories will always be limited by the basic assumption that each blade element acts independently from one another and therefore has no effect on the adjacent elements.

## 2.4 – Vortex Theory (Wald)

Once Prandtl developed the lifting line theory of wings, the modern vortex propeller theory was soon to follow. After all, the simple blade element theory had already treated the propeller problem by dissecting each propeller blade into 2-dimensional airfoils. Vortex theory expounded on the idea of treating propellers as rotating wings by considering the propeller blade as a lifting surface with a circulation associated with the bound vorticity and a vortex sheet that is continuously shed from the trailing edge. The BET uses 2-dimensional aerodynamics (airfoils) whereas vortex theory uses 3-dimensional aerodynamics (vortex system). (Wald, 2008)

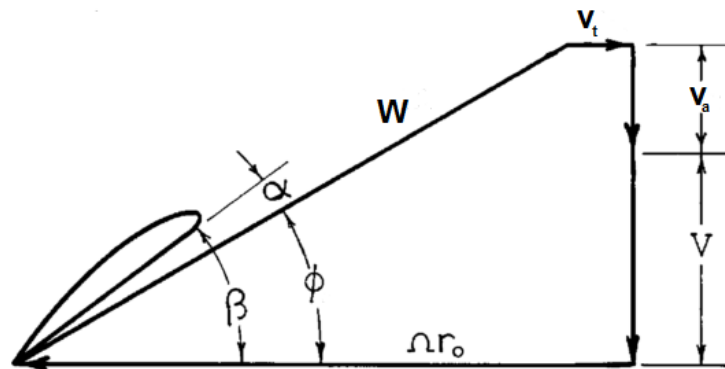
As early as 1919, it was realized that in order to truly solve the propeller problem the induced velocities along the blades had to be considered. Additionally, it was theorized that an optimum

loading must exist for a propeller with given conditions (RPM, Velocity, Diameter, Blades) analogous to the elliptical loading case on a wing. Betz developed the vortex theory which shows that the load distribution for lightly loaded propellers with minimum induced loss is such that shed vorticity forms rigid helicoidal vortex sheets moving backward behind the propeller. Around the same time, Prandtl developed a mathematical method for calculating the loading based on an infinite number of blades and then applying a tip correction factor. Prandtl's approximation is sufficient when the advance ratio is small and the number of blades is large. As the blades decrease or the advance ratio increases, the approximation deteriorates. (Wald, Theodorsen)

In 1929, Goldstein solved the potential flow and the distribution of circulation for a helicoidal vortex system for small advance ratios. Goldstein's analysis assumed the propellers were lightly loaded. This assumption was later shown to be unnecessary when Theodorsen proved that the Goldstein functions are applicable directly to all loadings, as long as the reference is made to the helicoidal sheet surface far behind the propeller and not to the surface of the propeller itself. Additionally, Theodorsen added to the theory of propellers by using the analysis of the trailing helicoidal vortex sheets to determine the conditions at the propeller and thus the necessary geometry of the propeller. (Wald, Theodorsen)

In 2006, Wald used the previous works of Goldstein and Theodorsen as well as the mathematical solutions provided by Tibery and Wrench (Tibery & Wrench, 1964) to treat the design of propellers for minimum induced loss. His analysis corrected some of the errors in previous work and expanded the coverage for the Goldstein circulation function tables for helicoidal vortex sheets. Additionally, Wald considered cases for interference effects from fuselages, nacelles, and spinners. The vortex theory as presented by Wald is given below although QPROP and QMIL do not take full advantage of the theory as described by Wald.

Wald used Theodorsen's theory which suggested that one can find the conditions at the propeller blades by first focusing on the necessary conditions in the trailing vortex system. Once the conditions in the trailing vortex system are determined, one can then compute the circulation on the propeller blades and determine the physical characteristics (chord and beta distributions, as well as the number of blades) of the propeller that would create the conditions in the vortex system.



**Figure 11: Velocity Components at a Blade Element (Wald)**

Figure 11 shows the local rotor-induced velocities ( $v_t, v_a$ ). Note that the lifting line assumption, as developed originally by Prandtl, states that if the blades are of sufficiently small chord then the induced velocity does not vary significantly along the chord. Therefore, one can assume that the lift on the blade element is related to the local angle of attack and the local relative velocity as in 2-D airfoil theory. Caution is needed here however, because if the chord is relatively wide (as is the case for MIL propellers designed for relatively high thrust production at relatively slow speeds) then the variation of induced velocity along the chord must be accounted for. (Wald)

Some important assumptions:

1. Interference of nacelles, fuselages, etc are ignored (these may be handled through variations of the fundamental vortex theory)

2. Blades are relatively narrow such that there is no variation of induced velocity along the chord.
3. Blades are equally spaced about the hub; therefore vortex lines representing each blade do not induce any velocity on any of the other lines. In other words, the effect on each blade due to the bound vorticity on the other blades is ignored and only trailing vorticity contributes to the resultant velocity at the blade.

Wald showed that the light loading restriction assumed by Betz can actually be relieved. He did this by splitting the propeller load into increments of load that lie directly on the vortex sheet behind the propeller as shown in Figure 12. He then showed that the variation of thrust and the variation of torque at each of these incremental locations must vanish if the propeller has an optimum radial distribution of load (MIL condition).

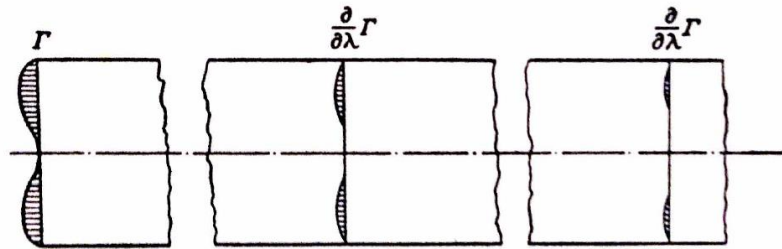


Figure 12: Load Increments on the Trailing Vortex Sheets (Theodorsen)

Additionally, Wald showed that the condition for optimum loading is:

$$r \tan \phi = \frac{r(V_\infty + v_a(r))}{\Omega r - v_t(r)} = \text{constant}$$

Equation 17: Optimal Propeller Loading Condition (Wald)

And the marginal efficiency associated with a small increment of circulation,  $d\Gamma$ , at radius,  $r$ , is:

$$\eta_m = \frac{V_\infty}{V_\infty + w} = \text{constant}$$

Equation 18: Marginal Efficiency (Wald)

The marginal efficiency is the efficiency associated with the last increment of load at an element. It is this efficiency that must be kept constant along the radius in order to obtain an optimum propeller design.

#### 2.4.1 – Basic Forces on a Propeller

In considering the propeller using vortex theory, it is necessary to first show the basic forces acting on the blade elements using the lifting line assumption. This assumption introduces the concept of vorticity into the propeller problem, which was absent from the BET.

Using the Kutta-Joukowski Theorem and the velocity components in Figure 10, one can show that the lift force on a blade element of radial thickness,  $dr$ , is

$$dL = \rho W \times \Gamma dr$$

**Equation 19: Lift Force on a Blade Element using Vorticity**

Additionally, the contribution of a blade element to thrust and torque can be shown to be

$$dT = \rho \Gamma (\Omega r - v_t) dr$$

**Equation 20: Blade Element Contribution to Thrust using Vorticity**

$$dQ = \rho \Gamma (V_\infty + v_a) r dr$$

**Equation 21: Blade Element Contribution to Torque using Vorticity**

The full thrust and torque of the propeller can be found by summing the forces of each blade element

$$T = \rho B \int_{r_{hub}}^R \Gamma (\Omega r - v_t) dr$$

**Equation 22: Total Propeller Thrust using BET and Vorticity**

$$Q = \rho B \int_{r_{hub}}^R \Gamma (V_\infty + v_a) r dr$$

**Equation 23: Total Propeller Torque using BET and Vorticity**

Using 2-D airfoil theory, one can relate the bound circulation on a blade element to the local angle of attack of the blade element by the following:

$$dL = c_l \frac{\rho}{2} W^2 c dr = cl_a (\alpha - \alpha_{L_0}) \frac{\rho}{2} W^2 c dr$$

**Equation 24: Blade Element Lift in terms of Local Angle of Attack**

From Figure 10, recall that  $\alpha = \beta - \phi$ . Also recall from Prandtl's Lifting Line Theory that  $dL = \rho W \Gamma dr$  (Anderson, Eq 5.20). Therefore:

$$\Gamma = \frac{1}{2} cl_a (\alpha - \alpha_{L_0}) W^2 c$$

**Equation 25: Circulation in terms of the Local Angle of Attack**

$$\phi = \tan^{-1} \frac{V_\infty + v_a}{\Omega r - v_t}$$

**Equation 26: Pitch Angle of the Relative Wind at a Blade Element**

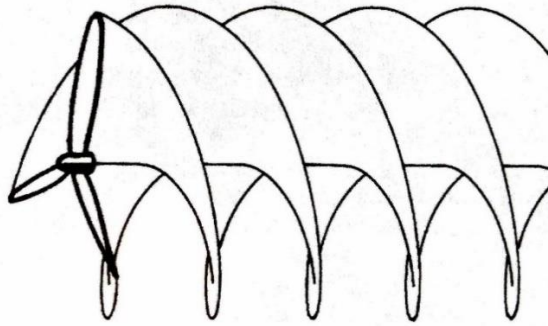
These equations provide the fundamental relationships of the mechanics at the propeller which will be used to solve for the propeller design problem.

#### 2.4.2 – Trailing Vortex System and Goldstein Circulation Function

Up to this point in the presentation of vortex theory, there has not been any attention on the trailing vortex system. This section focuses on the trailing vortex system and how it can be related to the conditions at the propeller.

First, the vortex sheet concept must be well understood. The vortex sheet does not contain any fluid particles. Instead, it is a sheet of velocity discontinuity within the fluid. Because of this principle, it does not matter if one considers the vortex sheet system (far behind the propeller) to be rotating about an axis, moving backward in the fluid, or both simultaneously – the vortex sheet will appear identical in each case. Figure 13 shows the vortex sheet system behind a propeller where the vortex sheet is actually twisted into a helicoidal vortex sheet. (Wald)





**Figure 13: Trailing Helicoidal Vortex Sheets (Wald)**

The Helmholtz vortex theorem states that a vortex cannot end in a fluid. Therefore, when the bound vorticity on a wing or propeller blade varies along the span, a free vortex filament must propagate from the trailing edge with a magnitude equal to the change of the bound vorticity. Wald showed that the shed vortex filaments constitute the trailing vortex sheet that must exist wherever bound vorticity is not constant along the span. He also gave the following expression showing that the derivative of the strength of the vortex sheet in the spanwise direction must be equal to the negative of the derivative of the strength of bound vorticity in the spanwise direction ( $\Gamma_B$  is the magnitude of the bound vorticity and  $\Gamma_F$  is the magnitude of the free vorticity):

$$\frac{d\Gamma_F}{dr} = -\frac{d\Gamma_B}{dr}$$

**Equation 27: Relationship between Bound Vorticity and Free Vorticity (Wald, Section 3.3)**

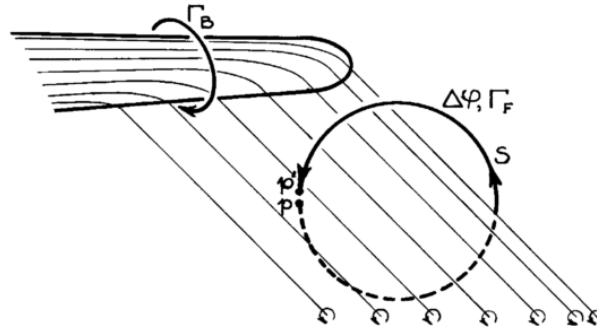
The vortex sheet may be imagined to be drifting with the fluid. There are no forces acting on it, no discontinuity of pressure, and no discontinuity of normal velocity. There can only be a discontinuity of tangential velocity whose magnitude gives the vortex strength of the sheet. (Wald)

Figure 14 below shows the free and bound vorticity as well as the trailing vortex sheet. If a point on the lower surface (p) is considered along with an adjacent point on the upper surface (p'), one can connect the 2 points by an arbitrary path, S, which contains all of the vortex filaments from point p to the edge of the vortex sheet.

One can show that

$$\Delta\phi = \Gamma_F$$

Which indicates that the potential difference across a vortex sheet at any point on the sheet is equal to the total circulation between the point and the edge of the sheet. (Wald)



**Figure 14: Bound and Free Vorticity on a Lifting Surface (Wald)**

Additionally, one can look at the bound vorticity of the vortex elements that are contained within S (See  $\Gamma_B$  on Figure 14) and will find that

$$\Gamma_F = \Gamma_B$$

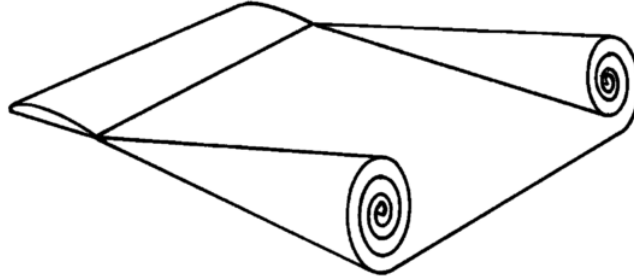
Therefore,

$$\Delta\phi = \Gamma_B$$

In other words, the bound circulation on a lifting surface is equal to the potential difference across the trailing vortex sheet at a corresponding point. (Wald)

Wald also demonstrated that the plane vortex sheet model trailing a lifting surface as discussed above requires that a very large singularity force exist in the velocity field for the vortex sheet to remain flat and not rollup on itself. Since there is no rigid body for such a point force to act and the vortex sheet cannot support tension, the example model of the vortex sheet cannot exist for

any length of time but it does serve as an idealistic model which provides a means of connecting the induced velocity at the propeller with the propeller loading. (Wald)



**Figure 15: Rolling Up of the Vortex Sheet behind a Lifting Surface (Wald)**

Moving now from discussing vortex sheets behind a lifting surface to the case of helicoidal vortex sheets behind a propeller, it is required to determine the distribution of vorticity on the trailing vortex sheet and then deduce the bound circulation on the propeller. This situation requires that one determine the potential function,  $\phi$ , which describes the flow in the surrounding fluid. (Wald)

The partial differential equation that must be satisfied by  $\phi$  is

$$\nabla^2 \phi = 0$$

And the boundary condition is that the normal velocity everywhere on the surface of the helicoidal vortex sheet  $\left(\theta - \frac{\Omega}{V+w}z - 2\pi \frac{n-1}{B} = 0\right)$  is  $\frac{\delta\phi}{\delta n} = w \cos \tau$ . ( $\tau$  is the pitch angle of the helicoidal sheet and  $w$  is the axial velocity of the helicoidal vortex sheets) (Wald)

The circulation  $\Gamma(r_1)$  is the strength of the vortex sheet downstream from the propeller. It then becomes a separate problem to trace the vortex filaments back to the propeller to determine the point on the propeller radius where the circulation at the propeller is equal to the circulation in the vortex sheet ( $\Gamma(r_0) = \Gamma(r_1)$ ), thus defining the bound circulation and the loading on the propeller blade.

It is worth mentioning that the notation used for the subscripts is as follows:

- 0 – at the propeller plane
- 1 – on the helicoidal trailing vortex system

Goldstein defined the Goldstein function as a dimensionless factor given by

$$G(r_1) = \frac{\Gamma(r_1)}{hw}$$

**Equation 28: Goldstein Function**

Where h is the axial distance between adjacent turns of the helicoidal sheets and w is the backward velocity of the vortex system with respect to the surrounding fluid.

$G(r_1)$  is dependent on the geometry of the vortex system as defined by  $\lambda_1$ , the pitch of the helicoid, and B, the number of interleaved sheets (which relates to the number of blades on the propeller). The term h is defined by:

$$h = \frac{P}{B} = \frac{2\pi(V + w)}{\Omega B}$$

**Equation 29: Axial Distance between Turns of the Helicoidal Vortex Sheets**

Therefore,

$$G(r_1) = \frac{B\Gamma\Omega}{2\pi w(V + w)}$$

**Equation 30: Goldstein Function in terms of h**

NOTE: Goldstein assumed light loading and therefore wrote V where Wald has  $V+w$ . (Wald)

For convenience, a new form of the advance ratio may be defined as  $\lambda_2 = \frac{V+w}{\Omega R_1} = (1 + \bar{w})\lambda_1$

where  $\bar{w}$  is simply the ratio of w to V or  $\left(\frac{w}{V}\right)$ . It is important to note that the new advance ratio

used here,  $\lambda_1$ , is the advance ratio for the trailing helicoidal vortex system – not the propeller itself.

Substituting gives the following expression:

$$G(r_1) = \frac{B\Gamma}{2\pi R_1 w \lambda_2}$$

**Equation 31: Modified Goldstein Function for All Loading Cases**

Accurate tables of the Goldstein function were developed by Tibery and Wrench. These tables give accurate solutions for all numbers of blades from 2 to 10 and for  $\lambda_2$  values from 1/12 to 4.0. Tibery and Wrench actually defined the function slightly different in that they presented their results as a ratio of the circulation  $\Gamma(r)$  to the circulation that would be obtained if there were an infinite number of blades. They designated their tabulated function as  $K(r)$  and defined it in such a way that

$$K(r_1) = G(r_1) \left( 1 + \frac{\lambda_2^2}{x_1^2} \right)$$

Therefore,

$$G(r_1) = \frac{(K(r_1))}{\left( 1 + \frac{\lambda_2^2}{x_1^2} \right)}$$

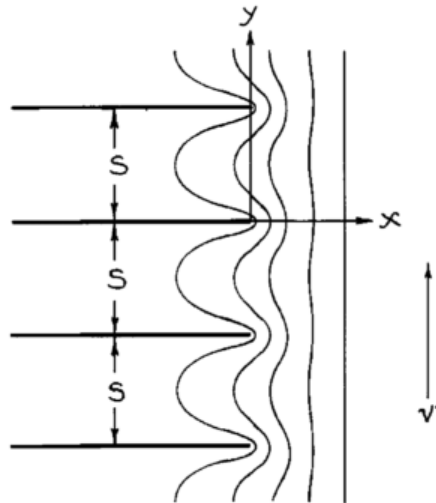
In other words, the tabulated values must be divided by  $\left( 1 + \frac{\lambda_2^2}{x_1^2} \right)$  to find the Goldstein function.

Wald has already performed the division and presented the Goldstein function for blades 2 through 6. (Wald)

### 2.4.3 – Prandtl’s Approximation

Prandtl developed a method for approximating the solution for the potential flow around a set of translating helicoidal surfaces by comparing the flow around the edges of a lifting surface to the

flow around a 2-D set of semi-infinite lamina that are equally spaced. This idealization is shown below in Figure 16. (Wald)



**Figure 16: Flow around 2-D Equally Spaced Lamina (Wald)**

Prandtl's approximation for the potential flow provides a decent estimate of the circulation distribution for the outer sections of the propeller blade. His approximation is particularly good for lower advance ratios and larger number of blades. Prandtl's approximation is still used in many applications since it is very easy to incorporate compared to the difficult mathematics involved with the Goldstein function or the use of tables to find values for the Goldstein function. (Wald)

The approximation is 2-D and therefore must be applied as a modification to a simplified 3-D representation where the fluid around the helicoidal vortex sheets is carried along without loss of velocity between the sheets. The Prandtl Factor can be found to be:

$$F = \frac{2}{\pi} \cos^{-1} e^{-f}$$

**Equation 32: Prandtl Factor**

Where

$$f = \frac{\pi a}{s}$$

Note:  $a$  is the distance from the edge of the lamina to the point of interest on the lamina,  $P$  and  $s$  is the distance between lamina sheets as shown in Figure 16. (Wald)

When the factor is applied to the case of the helicoidal vortex sheets, the distance  $a$  from the edge of the sheet is  $R - r$  or  $R(1 - x)$ .  $S$  can be shown to be equal to the linear pitch,  $P = 2\pi R\lambda_2$ , divided by the number of sheets (blades) and multiplied by  $\cos \phi$  where  $\tan \phi = \lambda_2$ . Therefore,

$$f = \frac{B}{2}(1 - x) \frac{\sqrt{1 + \lambda_2^2}}{\lambda_2}$$

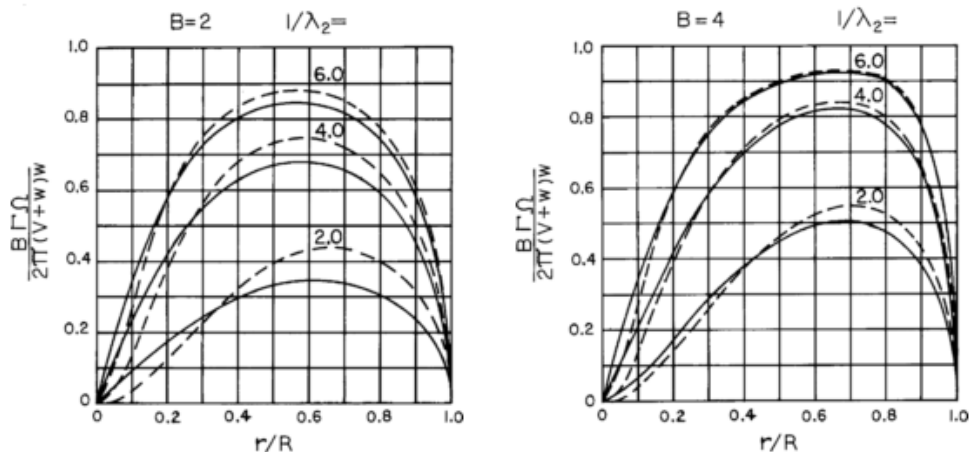
**Equation 33:  $f$  for the Case of Helicoidal Vortex Sheets**

And the approximation of the circulation function, and therefore an approximation of the Goldstein Function, is:

$$\frac{B\Gamma\Omega}{2\pi(V+w)w} \cong \frac{Fx^2}{x^2 + \lambda_2^2} \cong G(x, \lambda_2)$$

**Equation 34: Goldstein Function Approximation for the Case of Helicoidal Vortex Sheets**

The plots below show the actual Goldstein Function solutions (solid lines) compared to the Prandtl estimated solutions (dashed lines). (Wald)



**Figure 17: Comparison of Calculated Goldstein Function to the Prandtl Estimation (Wald)**

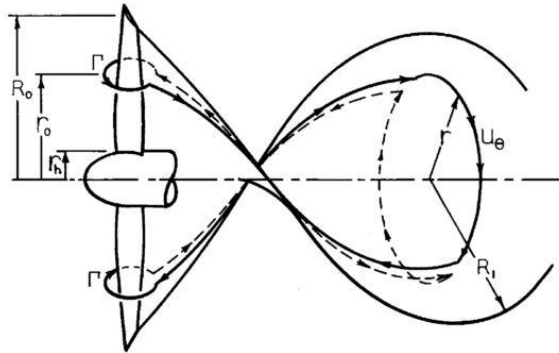
From Figure 17, one can see that the Prandtl estimate does a surprisingly good job of estimating the Goldstein function, particularly at higher blade numbers and smaller values of  $\lambda_2$ . On the

other hand, the maximum deviation shown on the above figure occurs on the 2 bladed propeller case with  $\lambda_2 = \frac{1}{2}$  between the 60% and 80% radial stations where the percent error for the Goldstein Function is roughly 33% which could greatly affect the estimated thrust, torque, and efficiency.

#### 2.4.4 – Propeller Geometry Determined by Trailing Vortex System

As previously stated, the goal of examining the trailing vortex system is to obtain a method for obtaining the propeller parameters necessary for the optimum condition, or the Minimum Induced Loss condition. The following briefly presents Wald’s discussion on obtaining the propeller geometry that satisfies the MIL condition as well as determining an accurate estimation of the thrust, torque, and efficiency of that propeller.

The bound circulation  $\Gamma(r_0)$  about an element of the propeller blade is uniquely related to the circulation at a corresponding radius,  $r$ , downstream on the trailing helicoidal vortex sheets. This condition is shown below in Figure 18.



**Figure 18: Relationship between the Propeller and the Trailing Vortex System (Wald)**

Wald showed that the line integral of the velocity taken along the path shown above is equal to zero and therefore

$$B\Gamma(r_0) = \int_0^{2\pi} u_\theta(r_1) d\theta$$

**Equation 35: Line Integral of the Velocity on the Propeller-Trailing Vortex System**



Which leads to

$$B\Gamma(r_0) = B\Gamma(r_1)$$

**Equation 36: Relation of Bound Circulation to Shed Circulation**

In other words, the total bound circulation on the propeller blades at any radius,  $r_0$ , must be equal to the total shed vorticity within a circle of radius,  $r_1$ , passing through the vortex filament shed from the elements at  $r_0$ . (Wald)

It is necessary to determine the distribution of circulation,  $\Gamma(x_0)$ , along the radial axis of the propeller blade which is dependent on the circulation distribution found on the trailing vortex sheets,  $\Gamma(x_1)$ . Wald accomplished this by considering an approximate continuity relationship between the propeller and the slipstream for the case of a propeller with an infinite number of blades. This assumption only provides the following relationships and is not used in a manner that compromises the previous discussions. The Goldstein distribution of circulation on the trailing vortex system remains in effect. (Wald)

This assumption leads to the following relationship between radial station on the propeller,  $x_0$ , and the dimensionless radial coordinate of the trailing vortex element,  $x_1$ :

$$x_0 = x_1$$

And, in the presence of a hub:

$$x_0^2 = x_h^2 + x_1^2(1 - x_h^2)$$

**Equation 37: Relationship between Propeller Radial Station and the Trailing Vortex Radial Coordinate**

The thrust and torque must also be found for the MIL case. One may begin by observing the pressure equation for unsteady incompressible potential flow in the absence of external forces (such as gravity)

$$\frac{\delta\varphi}{\delta t} + \frac{u^2}{2} + \frac{p}{\rho} = \text{constant}$$

**Equation 38: Pressure Equation for Unsteady, Incompressible Flow**

By applying this equation to the helical vortex system far behind the propeller, both  $u$  and  $\frac{\delta\varphi}{\delta t}$  must approach 0 at large distances from the axis. If the pressure in the undisturbed fluid is  $p_\infty$  at large values of radius, then the expression becomes

$$\frac{\delta\varphi}{\delta t} + \frac{u^2}{2} + \frac{p}{\rho} = \frac{p_\infty}{\rho}$$

**Equation 39: Pressure Equation Assuming Pressure is Constant Outside of the Propeller Area**

By assuming that the entire fluid moves axially with unchanging form at a velocity  $w$  in the positive  $z$  direction and by utilizing the momentum thrust equation, the axial force required to produce the continuous motion of the vortex sheet is (Wald, 2006)

$$T = \int_S \rho(V + u_z)u_z dS + \int_S (p - p_\infty) dS$$

**Equation 40: Vortex Theory Total Thrust Equation (Wald)**

Note:  $S$  is a planar surface normal to the axis of the helicoid and fixed in undisturbed fluid.

If it is assumed that density remains constant, then the equation can be written as

$$T = \rho \int_S (V + w)u_z + u_z^2 - \frac{u^2}{2} dS$$

**Equation 41: Vortex Theory Total Thrust Equation Assuming Constant Density (Wald)**

Theodorsen further developed this expression by solving for thrust as a function of 2 dimensionless variables,  $\kappa$  and  $\varepsilon$ . His work is presented well in other references (Wald, 2006 and Theodorsen, 1948) so it is not repeated here. However his result is of particular importance (keep in mind that the thrust expressed here is entirely in terms of the trailing vortex system):

Let  $\bar{w} = w/V_\infty$ ,

$$T = \kappa \rho \pi R_1^2 V^2 \bar{w} \left[ 1 + \bar{w} \left( \frac{1}{2} + \frac{\varepsilon}{\kappa} \right) \right]$$

**Equation 42: Thrust in Terms of  $\bar{w}$  (Theodorsen)**

Or expressed as a coefficient

$$K_{T1} = 2\kappa \bar{w} \left[ 1 + \bar{w} \left( \frac{1}{2} + \frac{\varepsilon}{\kappa} \right) \right]$$

**Equation 43: Coefficient of Thrust in Terms of  $\bar{w}$  (Theodorsen)**

Where  $\kappa$  and  $\varepsilon$  are given by

$$\kappa = \int_0^1 2G(x_1)x_1 dx_1 \text{ and } \varepsilon = \kappa + \frac{1}{2}\lambda_2 \frac{d\kappa}{d\lambda_2}$$

**Equation 44: Dimensionless Variables  $\kappa$  and  $\varepsilon$  (Theodorsen)**

And the ideal efficiency for the case of the “frictionless” propeller is given by:

$$\eta_i = \frac{1 + \bar{w} \left( \frac{1}{2} + \frac{\varepsilon}{\kappa} \right)}{(1 + \bar{w}) \left( 1 + \frac{\bar{w}\varepsilon}{\kappa} \right)}$$

**Equation 45: Ideal Efficiency for a Frictionless Propeller**

#### 2.4.5 – Relationship between Trailing Vortex System and the Propeller

The equations given in Section 2.4.4 for Thrust and Efficiency were derived solely for the trailing vortex system of a frictionless propeller and did not consider the relationship between the vortex and the propeller. That relationship was further explored and the results follow:

Wald showed that the representation of the vortex system behind the propeller using regular semi-infinite helicoidal vortex sheets is a simplification and thus the contraction of the trailing vortex system immediately behind the propeller must be taken into account. Wald also showed that the exception to this rule is for the case of a lightly loaded propeller where one may use a simplified treatment due to the contraction of the vortex system directly behind the propeller being very small.

Assuming a lightly loaded propeller, one can find the tangential and axial velocities at the propeller as well as the magnitude of the relative velocity at a blade element based upon the trailing vortex equations shown in Section 2.4.4:

Tangential and axial velocities at the propeller:

$$\bar{u}_{\theta_0} = \frac{\frac{1}{2}\bar{w}(1 + \bar{w})\left(\frac{\lambda}{x_0}\right)}{\left(1 + \frac{\lambda_2^2}{x_1^2}\right)}$$

**Equation 46: Tangential Velocity at the Propeller Assuming Light Loading**

$$\bar{u}_{z_0} = \frac{1}{2}\bar{u}_{z_0} = \frac{\frac{1}{2}\bar{w}}{\left(1 + \frac{\lambda_2^2}{x_1^2}\right)}$$

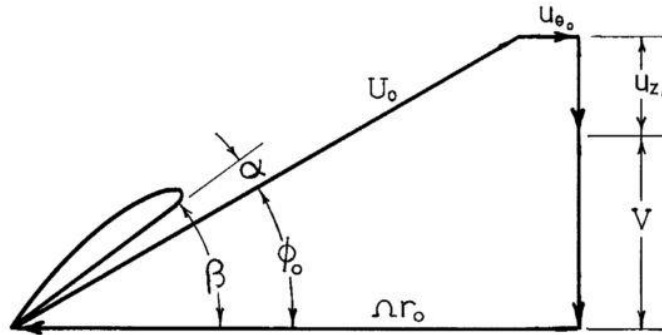
**Equation 47: Axial Velocity at the Propeller Assuming Light Loading**

$$\left(\frac{U_0}{V}\right)^2 = (1 + \bar{u}_{z_0})^2 + \left(\frac{x_0}{\lambda} - \bar{u}_{\theta_0}\right)^2$$

**Equation 48: Magnitude of the Relative Velocity at a Blade Element Assuming Light Loading**

$$\tan \phi_0 = \frac{V + u_{z_0}}{\Omega r_0 - u_{\theta_0}} = \frac{1 + \bar{u}_{z_0}}{\frac{x_0}{\lambda} - \bar{u}_{\theta_0}}$$

**Equation 49: Pitch Angle of the Relative Wind at a Blade Element Assuming Light Loading**



**Figure 19: Velocities at a Blade Element (Wald)**

Additionally, the diameter of the propeller can be shown to be:

$$D_0 = 2R_1 \sqrt{\frac{\left[1 + \bar{w} \left(\frac{1}{2} + \frac{\varepsilon}{\kappa}\right)\right] / (1 + \bar{w})}{\sqrt{(1 - x_h^2) - \frac{1}{2} \bar{w} (1 + \bar{w}) \lambda^2 I_1 / \kappa}}}$$

**Equation 50: Diameter of the Propeller based on Trailing Vortex System Assuming Light Loading**

Where  $I_1 \equiv \int_0^1 \frac{2G(x_1)x_1^3 dx_1}{(x_1^2 + \lambda_2^2)(x_1^2 + c)}$  and  $c = \frac{x_h^2}{(1 - x_h^2)}$

The lift coefficient should be chosen such that  $c_d/c_l$  is minimized. For the purposes of this thesis, the author used a standard Clark Y airfoil therefore changes to  $c_l$  and  $c_d$  are due to changes in airflow and pitch of the propeller only. No other airfoils are considered in this work.

The blade angle is simply:

$$\beta(x) = \alpha + \phi_0$$

**Equation 51: Blade Angle based on Trailing Vortex System Assuming Light Loading**

Remember that the above equations were developed assuming a lightly loaded propeller and ignoring profile drag. Profile drag can be included with relative ease since the profile drag acts in a direction normal to the lift force and does not affect the form of the trailing vortex system.

Therefore, profile drag can be treated simply as an additive force without modification of the distribution of the trailing vorticity. NOTE:  $\phi_0 = \frac{1 + \bar{u}_{z_0}}{\bar{x}_0 / \lambda - \bar{u}_{\theta_0}}$

$$dT_p = -c_d \rho U_0^2 \sigma \pi R^2 \sin(\phi_0) dx$$

**Equation 52: Loss of Thrust due to Profile Drag**

$$\Delta K_T = -2 \int_0^1 c_d \sigma \left(\frac{U_0}{V}\right)^2 \sin(\phi_0) dx$$

**Equation 53: Contribution of Profile Drag to the Thrust Coefficient**

$$\Delta K_Q = 2 \int_0^1 c_d \sigma \left(\frac{U_0}{V}\right)^2 \cos(\phi_0) x dx$$

**Equation 54: Contribution of Profile Drag to the Torque Coefficient**

$$\Delta K_P = \frac{\Delta K_Q}{\lambda}$$

**Equation 55: Contribution of Profile Drag on the Power Coefficient**

Finally the thrust and power coefficients for the propeller with ideal load distribution and taking profile drag effects into account are:

$$KT = \frac{KT_1}{\left(\frac{R}{R_1}\right)} + \Delta K_T$$

**Equation 56: Thrust Coefficient for a Propeller at MIL Conditions with Profile Drag**

$$KP = \frac{KP_1}{\left(\frac{R}{R_1}\right)} + \Delta K_P$$

**Equation 57: Torque Coefficient for a Propeller at MIL Conditions with Profile Drag**

And the efficiency of the propeller is

$$\eta = \frac{TV}{P} = \frac{K_T}{K_P}$$

**Equation 58: Efficiency for a Propeller at MIL Conditions with Profile Drag**

Initial values for B (number of blades),  $\lambda_1$  (advance ratio), and  $\bar{w}$  (relative displacement velocity) can be estimated using normal propeller requirements (thrust required, cruising velocity, diameter ranges, multiple cases changing the number of blades). Once initial values are selected, the computation follows an iterative process where some first estimates are made using the following assumptions:  $K_{T_1} = K_T$  and  $\lambda_2 = \lambda$ . The iterations continue until the advance ratio and thrust coefficient line up with the design requirements.

#### 2.4.6 – Propeller Performance Calculations

In order to solve for a given propeller that may not have an ideal load distribution or a propeller that is operating off of its intended design point, one must realize that the treatment presented by Wald for the design case does not directly apply. However, a solution for the case of a propeller operating at non-ideal conditions can be constructed if an approximation of the velocities at the blade elements is made.

The classical treatment of this case is called the combined blade element-momentum theory and was based on the assumption that each blade element is completely independent from the other

blade elements, which is only justified for the case of an infinitely bladed propeller (actuator disk). As was previously discussed, the trailing vortex system does not allow for independence of the individual blade elements. The trailing vorticity shed from each blade element contributes to the perturbation velocity at every other blade element. Therefore the combined blade element-momentum theory is not a good means for estimating the performance of a propeller operating at non-ideal conditions (unless Prandtl factor corrections are made for the blade elements near the tips).

Wald presents a computational solution to the loading of a given propeller employing vortex concepts. The basic problem statement is as follows: Given the advance ratio  $\lambda$  and the geometric description of the propeller ( $B$ ,  $\beta(x)$ ,  $c(x)$ , airfoil characteristics) it is required to solve for the thrust and torque of the propeller.

The general procedure is to find  $\bar{w}(x)$  at each radial station such that the induced velocity and consequent lift coefficient implied by local 2-D flow conditions at an element are consistent with the circulation that follows from the value of  $\bar{w}(x)$ . The solution will be found via an iterative procedure where the following 2 expressions for  $c_l$  must be solved simultaneously:

$$c_l = a_0(\beta - \phi_0 - \alpha_{L_0})$$

$$c_l = \frac{2\lambda\bar{w}(1 + \bar{w})G(x)}{\sigma(U_0/V)}$$

The thrust and torque coefficients and efficiency can be shown to be

$$K_T = 2 \int_0^1 (c_l \cos(\phi_0) - c_d \sin(\phi_0)) \sigma \left(\frac{U_0}{V}\right)^2 dx$$

**Equation 59: Thrust Coefficient of a Propeller Operating at non-MIL Conditions**

$$K_Q = 2 \int_0^1 (c_l \sin(\phi_0) + c_d \cos(\phi_0)) \sigma \left( \frac{U_0}{V} \right)^2 x dx$$

**Equation 60: Torque Coefficient of a Propeller Operating at non-MIL Conditions**

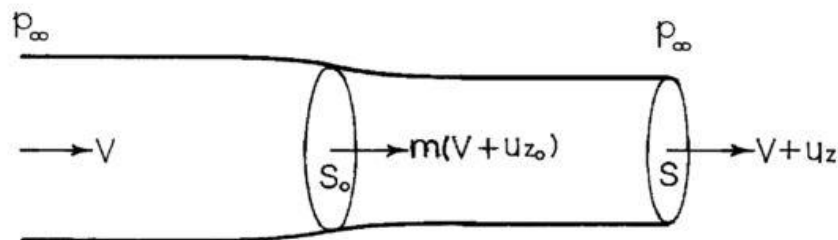
$$\eta = \frac{\lambda K_T}{K_Q}$$

**Equation 61: Propeller Efficiency of a Propeller Operating at non-MIL Conditions**

#### 2.4.7 – Other Contributions by Wald

Wald went on to provide a brief study on propeller interactions with bodies in general, specifically with nacelles directly behind the propeller in a tractor configuration, and propellers in a wake. His research on interactions with bodies is briefly presented here. This case and the other cases that Wald presented would be useful for future incorporation into propeller design and estimation tools.

Consider the case of an impulse disc operating in a velocity field locally modified by the presence of a large body. No viscous wake flows into the propeller and the body is assumed not to be subject to viscous effects. Figure 20 shows the modification of inserting a factor  $m$  into the velocity at the disc. Note that  $m=1$  in the absence of interference. Also notice that the disturbance of the flow through the propeller is local and leaves the final slipstream velocity  $V = u_z$  unaffected.



**Figure 20: Flow through a Propeller near a Body**



Using the momentum equation, the total force on the system is shown to be

$$T_{net} = \rho(V + u_z)u_z S$$

**Equation 62: Total Force on Actuator Disk System**

The increase of total pressure applied as an increase in static across the disk is

$$\Delta p = \rho u_z \left( V + \frac{u_z}{2} \right)$$

**Equation 63: Increase in Total Pressure**

The continuity equation gives

$$S(V + u_z) = S_0 m (V + u_{z_0})$$

**Equation 64: Continuity Equation for the Actuator Disk System near a Body**

Since half the final velocity is induced at the actuator disk ( $u_{z_0} = u_z/2$ ), the actual thrust of the disk is

$$T = \frac{\rho u_z (V + u_z) S}{m} = \frac{T_{net}}{m}$$

**Equation 65: Thrust of the Actuator Disk near a Body**

Therefore

$$m = \frac{T_{net}}{T}$$

This expression shows that the total thrust on the system (body and propeller) divided by the thrust of the propeller gives m, the ratio of total thrust to actual propeller thrust. If no body is present, then m=1. If the propeller operates in an area where the velocity is increased due to the presence of the body then m>1.

Additionally, the efficiency of the propeller is

$$\eta = \frac{2}{1 + \sqrt{1 + K_T/m}}$$

**Equation 66: Efficiency of the Actuator Disk near a Body**

Notice that if the propeller operates in an area of increased flow velocity due to the presence of a body ( $m > 1$ ), then the efficiency will increase.

As previously mentioned, Wald also developed further theory for the specific cases of a tractor configuration with a nacelle or fuselage as well as for propellers operating in a wake. These areas are important to consider and it would be very useful to integrate these specific cases into current propeller design and performance model software such as QPROP. However, this integration activity is outside of the scope of the current work.

## CHAPTER III

### QPROP AND QMIL

QPROP and QMIL were developed by Professor Mark Drela at the Massachusetts Institute of Technology (MIT). The programs are designed to analyze the performance of propeller and motor combinations and to generate propeller geometries for the minimum induced loss (MIL) condition, respectively. Combined, they provide a useful tool set for the propeller designer in the development of unique propeller geometries that provide better solutions for unique applications than those available on the commercial market. This chapter provides the formulation for QPROP and QMIL as presented by Professor Drela but modified for the author's interests described below. (Drela)

#### 3.1 – Scope of Use

As discussed briefly in the Introduction, the author focused the analysis of the QPROP and QMIL computer programs to specific conditions used to design and analyze propellers for small scale UAVs. These specific conditions are listed as follows:

1. Tractor Propeller Configuration
2. Single Propeller Propulsion System

3. For the Design Case (QMIL)
  - a. Inputs: Radius, Velocity, RPM, and Power Available
  - b. Outputs: Propeller Geometry
4. For the Analysis Case (QPROP)
  - a. Inputs: Propeller Geometry, Velocity, RPM
  - b. Primary Outputs: Thrust, Torque, Efficiency
5. Only interested in Propeller Results (Motor/Engine will be considered separately)

### 3.2 – QPROP and QMIL Formulation

QPROP and QMIL were designed to be used for multiple design and analysis cases including windmills, propeller-motor combinations, and design for load constraints. However the formulation provided below focuses on the specific conditions listed previously. This formulation will then be compared with Wald's formulation of the MIL propeller problem using the trailing vortex system.

Professor Mark Drela published his formulation of QPROP and QMIL on his website (Drela).

QPROP and QMIL use classical BET and Vortex theory developed by Betz, Goldstein, Theodorsen, and Larrabee with 4 extensions identified by Drela:

1. Radially-varying self-induction velocity which gives consistency with the heavily-loaded actuator disk limit
2. Perfect consistency of the analysis and design formulations.
3. Solution of the overall system by a global Newton method, which includes the self-induction effects and powerplant model.

4. Formulation and implementation of the Maximum Total Power (MTP) design condition for windmills.

### 3.2.1 – Flowfield Velocities

The axial and tangential components of the total relative velocity,  $W$ , are decomposed as follows:

$$W_a = V + u_a + v_a$$

**Equation 67: QPROP Axial Component of Velocity**

$$W_t = \Omega r - u_t - v_t$$

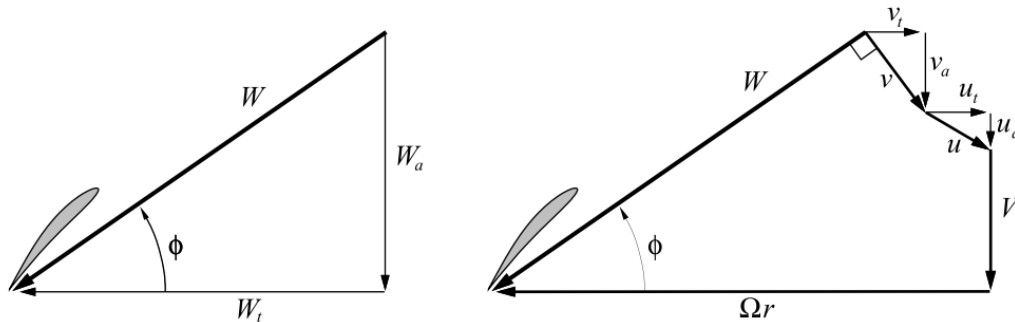
**Equation 68: QPROP Tangential Component of Velocity**

$$W = \sqrt{W_a^2 + W_t^2}$$

**Equation 69: QPROP Total Relative Velocity**

Where,  $u$  and  $v$  are the local externally-induced and rotor-induced velocities respectively and the subscripts a and t indicate axial and tangential velocities respectively. The local externally-induced velocities ( $u_t, u_a$ ) are shown in Figure 21 however, for the purpose of this work, the externally-induced velocities are assumed to be zero, i.e. no upstream propellers or counter-rotating propellers will be considered (recall assumptions 1 & 2 in Section 3.1). The rotor-induced velocities ( $v_t, v_a$ ) are those velocities caused by the propeller blade rotation and can be related to the circulation on the rotor blades via Helmholtz’s theorem.

These velocity vectors are shown in the figure below:

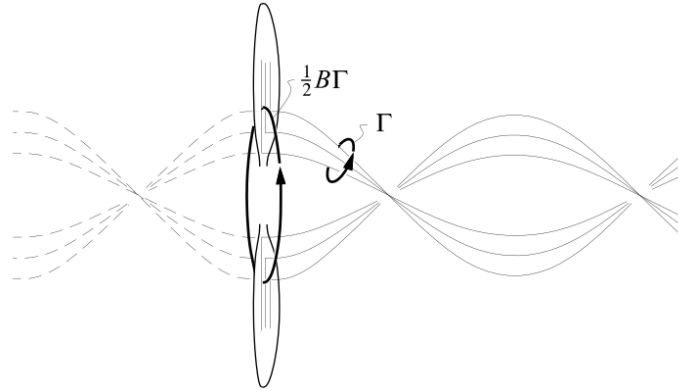


**Figure 21: Total Blade-Relative Velocity at a Radial Station (Drela)**

Using Helmholtz's Theorem and the below figure which shows the circulation from a propeller blade, one can find the following relations for the circumferentially averaged rotor-induced tangential velocity:

$$\bar{v}_t = \frac{B\Gamma}{4\pi r}$$

**Equation 70: QPROP Rotor-Induced Tangential Velocity**



**Figure 22: Circulation Circuits for Obtaining Circulation/Swirl Relation (Drela)**

Using Prandtl's Approximation for tip losses, the circumferential-averaged tangential velocity,  $\bar{v}_t$ , and the tangential velocity on the blade,  $v_t$ , are assumed to be related by:

$$\bar{v}_t = v_t F \sqrt{1 + \left(4\lambda_w R / \pi B r\right)^2}$$

**Equation 71: QPROP Assumed Relationships between Tangential Velocities**

The square root term becomes larger towards the axis and the modified Prandtl factor, F, becomes larger near the tips.

$$F = \frac{2}{\pi} \cos^{-1}(e^{-f})$$

**Equation 72: QPROP Modified Prandtl Factor**

$$f = \frac{B}{2} \left(1 - \frac{r}{R}\right) \frac{1}{\lambda_w}$$

**Equation 73: QPROP Modified Prandtl Factor Exponent**

$$\lambda_w = \frac{r}{R} \tan \phi = \frac{r W_a}{R W_t}$$

**Equation 74: QPROP Local Wake Advance Ratio**

In Drela's modified F, the normal overall advance ratio has been replaced with local wake advance ratio,  $\lambda_w$ . This is more realistic for heavy disk loadings where  $\lambda$  and  $\lambda_w$  vary greatly. The overall advance ratio,  $\lambda$ , does not vary with radius but the local wake advance ratio,  $\lambda_w$ , does vary with radius.

Equating the previous equations for the circumferential-averaged tangential velocity gives the following relationship for the local tangential induced velocity relative to the blade:

$$v_t = \frac{B\Gamma}{4\pi r} \frac{1}{F \sqrt{1 + \left(4\lambda_w R / \pi B r\right)^2}}$$

**Equation 75: QPROP Local Tangential Induced Velocity**

The axial induced velocity is then found by assuming that  $v$  is perpendicular to  $W$ .

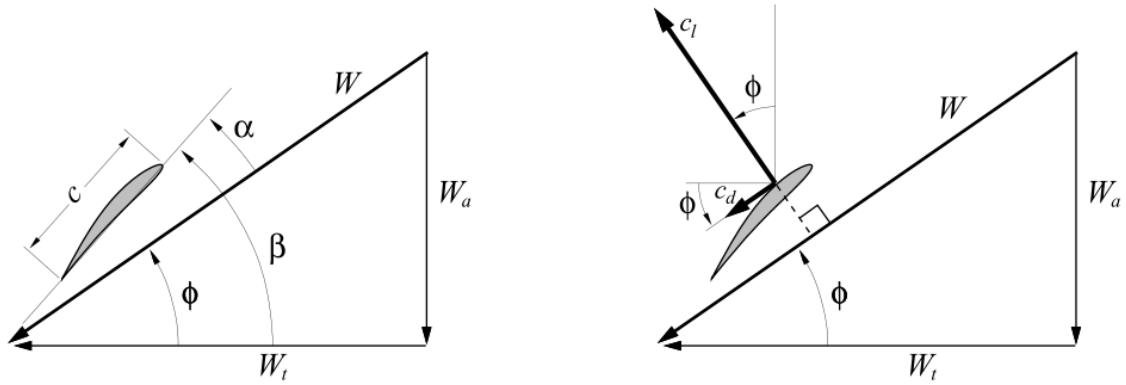
$$v_a = v_t \frac{W_t}{W_a}$$

**Equation 76: QPROP Axial Induced Velocity**

This assumption is valid for a non-contracting helical wake which has the same pitch at all radii, which Wald showed to be true regardless of the loading. Drela's method of using the Helmholtz theorem for the circulation together with the Prandtl Tip factor are a simplified estimation to avoid the Biot-Savart integration over the entire wake. Wald performed at least a partial Biot-Savart integration in order to relate the overall circulation distribution,  $\Gamma(r)$ , to the local rotor-induced velocities,  $v_t$  and  $v_a$ .

### 3.2.2 – Blade Geometry and Analysis Solution

The propeller geometry and local velocity triangle for one radial location are shown in the figure below.



**Figure 23: Blade Geometry and Velocity Triangle (Drela)**

The local angle of attack that blade section experiences is

$$\alpha(r) = \beta - \phi = \beta - \tan^{-1} \frac{W_a}{W_t}$$

**Equation 77: QPROP Local Angle of Attack**

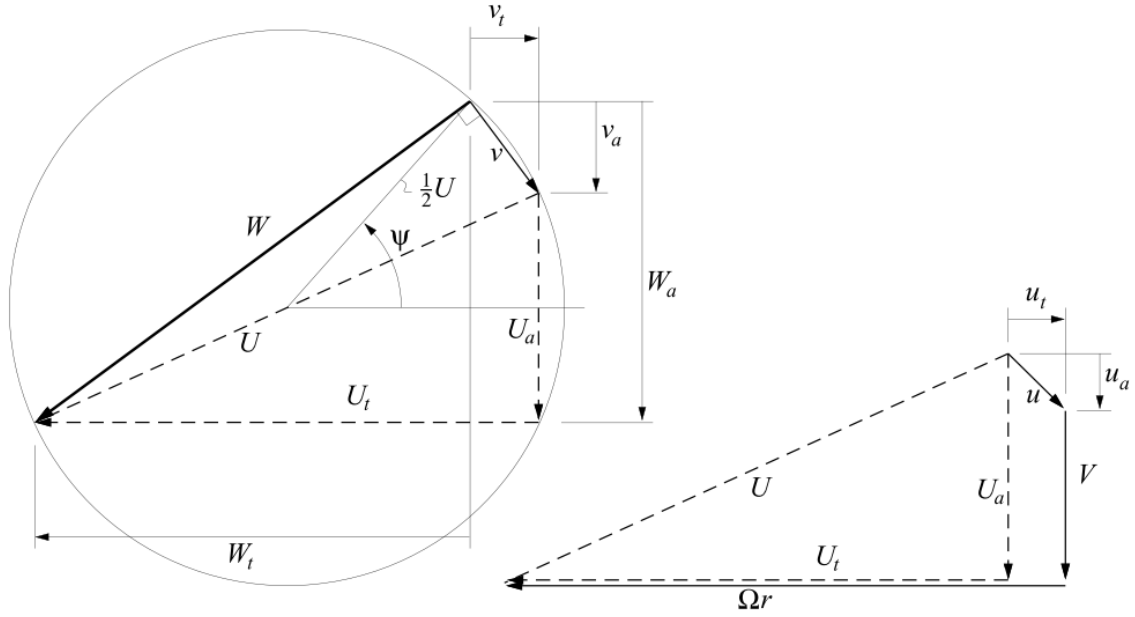
Given the local angle of attack, the local lift and drag coefficients can be determined based on the airfoil geometry and the air properties (Reynolds Number and Mach Number). Once the lift coefficient is determined, the corresponding local blade circulation is:

$$\Gamma = \frac{1}{2} W * c * c_l$$

**Equation 78: QPROP Local Blade Circulation**

The analysis proceeds as follows. For a given blade (where  $c(r)$ ,  $\beta(r)$ ,  $c_l$  and  $c_d$  are known) and given flight conditions (Cruising velocity,  $V$ , and RPM which can be converted to RPS or  $\Omega$ ), the circulation distribution along the radius,  $\Gamma(r)$ , can be calculated at each radial station. Drela provides the following equations that can be solved using the Newton method and iterating on a dummy variable,  $\Psi$ , in lieu of iterating on  $\Gamma$  directly.





**Figure 24: Velocity Parameterization by the Angle  $\Psi$  (Wald)**

It is convenient to define intermediate velocity components as the overall velocities without the propeller induced velocities  $v_a$  and  $v_t$ .

$$U_a = V + u_a$$

**Equation 79: QPROP Intermediate Axial Velocity**

$$U_t = \Omega r - u_t$$

**Equation 80: QPROP Intermediate Tangential Velocity**

$$U = \sqrt{U_a^2 + U_t^2}$$

**Equation 81: QPROP Intermediate Total Velocity**

Using  $\Psi$ , one can parameterize the remaining variables as shown below:

$$W_a(\psi) = \frac{1}{2}U_a + \frac{1}{2}U \sin \psi$$

**Equation 82: QPROP Axial Velocity as a Function of  $\Psi$  (Drela)**

$$W_t(\psi) = \frac{1}{2}U_t + \frac{1}{2}U \cos \psi$$

**Equation 83: QPROP Tangential Velocity as a Function of  $\Psi$  (Drela)**

$$v_a(\psi) = W_a - U_a$$

**Equation 84: QPROP Local Axial Velocity as a Function of  $\Psi$  (Drela)**

$$v_t(\psi) = U_t - W_t$$

**Equation 85: QPROP Local Tangential Velocity as a Function of  $\Psi$  (Drela)**

$$\alpha(\psi) = \beta - \tan^{-1}\left(\frac{W_a}{W_t}\right)$$

**Equation 86: QPROP Angle of Attack as a Function of  $\Psi$  (Drela)**

$$W(\psi) = \sqrt{W_a^2 + W_t^2}$$

**Equation 87: QPROP Total Velocity as a Function of  $\Psi$  (Drela)**

$$Re(\psi) = \frac{\rho W c}{\mu}$$

**Equation 88: QPROP Reynolds Number as a Function of  $\Psi$  (Drela)**

$$Ma(\psi) = \frac{W}{a}$$

**Equation 89: QPROP Mach Number as a Function of  $\Psi$  (Drela)**

Recall that this thesis is only interested in tractor configuration propellers, therefore the externally-induced velocity,  $u$ , is assumed to equal zero. This condition causes  $U_a = V$  and  $U_t = \Omega r$ , which can be seen to be true from the right side of Figure 24.

The circulation is then related to the tangential induced velocity using the Helmholtz relation as before (except that the parameterization is used this time):

$$\lambda_w(\psi) = \frac{r W_a}{R W_t}$$

**Equation 90: QPROP Local Wake Advance Ratio as a function of  $\Psi$  (Drela)**

$$f(\psi) = \frac{B}{2} \left(1 - \frac{r}{R}\right) \frac{1}{\lambda_w}$$

**Equation 91: QPROP Modified Prandtl Factor Exponent as a function of  $\Psi$  (Drela)**

$$F(\psi) = \frac{2}{\pi} \cos^{-1} e^{-f}$$

**Equation 92: QPROP Modified Prandtl Factor as a function of  $\Psi$  (Drela)**

$$\Gamma(\psi) = v_t \frac{4\pi r}{B} F \sqrt{1 + \left(\frac{4\lambda_w R}{\pi B r}\right)^2}$$

**Equation 93: QPROP Local Blade Circulation as a Function of  $\Psi$  (Drela)**

The Newton residual is then used as:

$$\mathcal{R}(\psi) = \Gamma - \frac{1}{2} W c c_l$$

**Equation 94: QPROP Newton Residual (Drela)**

$$\delta\psi = -\frac{\mathcal{R}}{d\mathcal{R}/d\psi}$$

**Equation 95: QPROP Newton  $\Psi$  Step (Drela)**

Each iteration will cause one Newton update ( $\psi = \psi + \delta\psi$ ) and will decrease the absolute value of the Newton residual until it reaches some pre-determined value for machine zero (e.g. 0.0000001).

### 3.2.3 – Thrust and Torque Relationships

Once the circulation distribution,  $\Gamma(\psi)$ , is found, the overall torque and thrust of the propeller can be found by resolving the thrust and torque components at each radial station and proceeding to integrate over the length of the blade. In other words, the forces acting on each blade station are determined using the airfoil properties at that station and then the forces are summed along the blade to determine the final values for lift and drag which are then related to the thrust and the torque of the propeller.

If a net flow angle,  $\phi$ , is introduced to represent the flow angle at the blade station, then the components of lift and drag can be resolved into the thrust and torque components as shown in Figure 25 below.

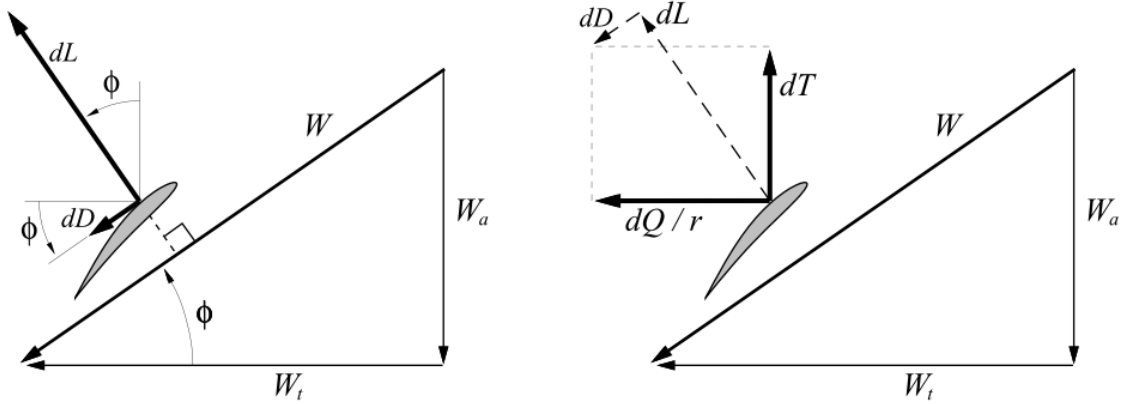


Figure 25: Propeller Blade Section Lift and Drag Resolved into Components of Thrust and Torque (Drela)

$$dL = B \frac{1}{2} \rho W^2 c_l c dr$$

Equation 96: QPROP Lift Produced by a Blade Section (Drela)

$$dD = B \frac{1}{2} \rho W^2 c_d c dr$$

Equation 97: QPROP Drag Induced by a Blade Section (Drela)

$$dT = dL \cos(\phi) - dD \sin(\phi) = B \frac{1}{2} \rho W^2 (c_l \cos(\phi) - c_d \sin(\phi)) c dr$$

Equation 98: QPROP Thrust of a Blade Section (Drela)

$$dQ = (dL \sin(\phi) + dD \cos(\phi)) r = B \frac{1}{2} \rho W^2 (c_l \sin(\phi) + c_d \cos(\phi)) c r dr$$

Equation 99: QPROP Torque of a Blade Section (Drela)

Note that:

$$W \cos \phi = W_t$$

$$W \sin \phi = W_a$$

Expressing the thrust and torque components in terms of the circulation and net velocity components gives:

$$dT = \rho B \Gamma (W_t - \epsilon W_a) dr$$

Equation 100: QPROP Thrust of a Blade Section (Drela)

$$dQ = \rho B \Gamma (W_a + \epsilon W_t) r dr$$

Equation 101: QPROP Torque of a Blade Section (Drela)

$$\epsilon = \frac{c_d}{c_l}$$

**Equation 102: QPROP Ratio of Drag to Lift Coefficients (Drela)**

Then the local efficiency is given by:

$$\eta = \frac{V dT}{\Omega dQ} = \frac{V c_l \cos \phi - c_d \sin \phi}{\Omega r c_l \sin \phi + c_d \cos \phi} = \frac{V W_t - \epsilon W_a}{\Omega r W_a + \epsilon W_t}$$

**Equation 103: QPROP Local Efficiency**

The local efficiency may be decomposed into induced and profile efficiencies as follows:

$$\eta = \eta_i \eta_p$$

**Equation 104: QPROP Local Efficiency in Terms of Induced and Profile Efficiencies**

$$\eta_i = \frac{1 - v_t/U_t}{1 + v_a/U_a}$$

**Equation 105: QPROP Local Induced Efficiency**

$$\eta_p = \frac{1 - \epsilon W_a/W_t}{1 + \epsilon W_t/W_a}$$

**Equation 106: QPROP Local Profile Efficiency**

If  $V/\Omega R \rightarrow 0$ , then  $\epsilon \rightarrow 0$ , and assuming no externally induced velocity (as we have), then the efficiency reduces to:

$$\eta \rightarrow \frac{1}{1 + v_a/V}$$

**Equation 107: QPROP Local Efficiency under Actuator Disk Limit Conditions (Drela)**

Which is exactly consistent with the actuator disk limit, even for very large disk loadings.

The loads on the propeller can be found simply by integrating the previous expressions for dT and dQ along the propeller blade in terms of circulation.

$$T = \rho B \int_0^R \Gamma (W_t - \epsilon W_a) dr \simeq \rho B \sum_r \Gamma (W_t - \epsilon W_a) \Delta r$$

**Equation 108: QPROP Total Propeller Thrust**

$$Q = \rho B \int_0^R \Gamma(W_a + \epsilon W_t) r dr \simeq \rho B \sum_r \Gamma(W_a - \epsilon W_t) r \Delta r$$

**Equation 109: QPROP Total Propeller Torque**

QPROP and QMIL use the simple midpoint rule for the above integral summations. The total efficiency using the total thrust, T, and total torque, Q, can be shown to be

$$\bar{\eta} = \frac{VT}{\Omega Q}$$

**Equation 110: QPROP Total Propeller Efficiency**

QPROP and QMIL perform the analysis problem and design problem respectively. QPROP is designed to perform multiple types of design problems, however the author has restricted its use to only the case where velocity, RPM, and pitch are treated as known values and thrust, torque and efficiency are the primary outputs. Similarly, QMIL is designed to be used for a few different design cases, however the author has restricted its use to only the case of designing a propeller for the minimum induced loss condition (MIL).

### 3.3 – QPROP Structure

QPROP performs the analysis problem by solving the equations given in Section 3.2.3 for some imposed operating conditions. The unknowns are  $\Gamma(r)$ , V,  $\Omega$ , and  $\Delta\beta$  and the constraints on  $\Gamma(r)$  are the Newton residuals at each radial station defined previously. V,  $\Omega$ , and  $\Delta\beta$  are then constrained using the following residuals:

$$\mathcal{R}_1(V, \Omega, \Delta\beta) = V - V_{specified}$$

**Equation 111: QPROP Newton Residual 1**

$$\mathcal{R}_2(V, \Omega, \Delta\beta) = \Omega - \Omega_{specified}$$

**Equation 112: QPROP Newton Residual 2**

$$\mathcal{R}_3(V, \Omega, \Delta\beta) = \Delta\beta - \Delta\beta_{specified}$$

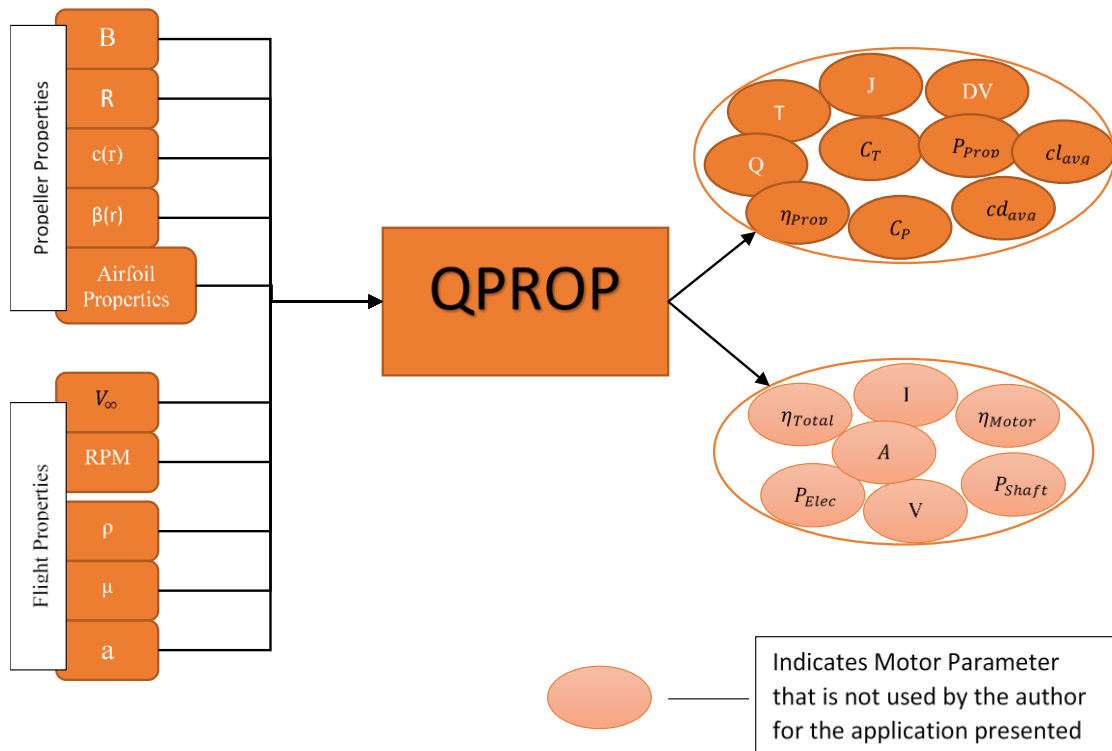
**Equation 113: QPROP Newton Residual 3**

These three residuals are then simultaneously driven to zero. In other words the values used in each iteration are getting closer to the specified values through the following multivariable Newton iteration.

$$\begin{Bmatrix} \delta V \\ \delta \Omega \\ \delta \Delta \beta \end{Bmatrix} = - \left[ \frac{\partial(\mathcal{R}_1, \mathcal{R}_2, \mathcal{R}_3)}{\partial(V, \Omega, \Delta \beta)} \right]^{-1} \begin{Bmatrix} \mathcal{R}_1 \\ \mathcal{R}_2 \\ \mathcal{R}_3 \end{Bmatrix}$$

**Equation 114: QPROP Multi-Variable Newton Iteration**

Figure 26 shows an overview of the necessary inputs required for QPROP as well as the outputs that QPROP produces in its analysis.



**Figure 26: QPROP Inputs and Outputs**

### 3.4 – QMIL Structure

QMIL provides the design solution by determining the geometry of a propeller that matches some specified parameters. For the purposes of this thesis, the specified parameters consist of  $R$ ,  $V$ ,  $\Omega$ ,  $Q$  (which is determined from the available power input), airfoil properties, number of blades ( $B$ ), and the fluid properties. The 2 unknowns at each blade radial station are the chord and the pitch

angle both as functions of the radius,  $c(r)$  and  $\beta(r)$ . The restraints used for the MIL condition are a specified local lift coefficient and a constant locally induced:

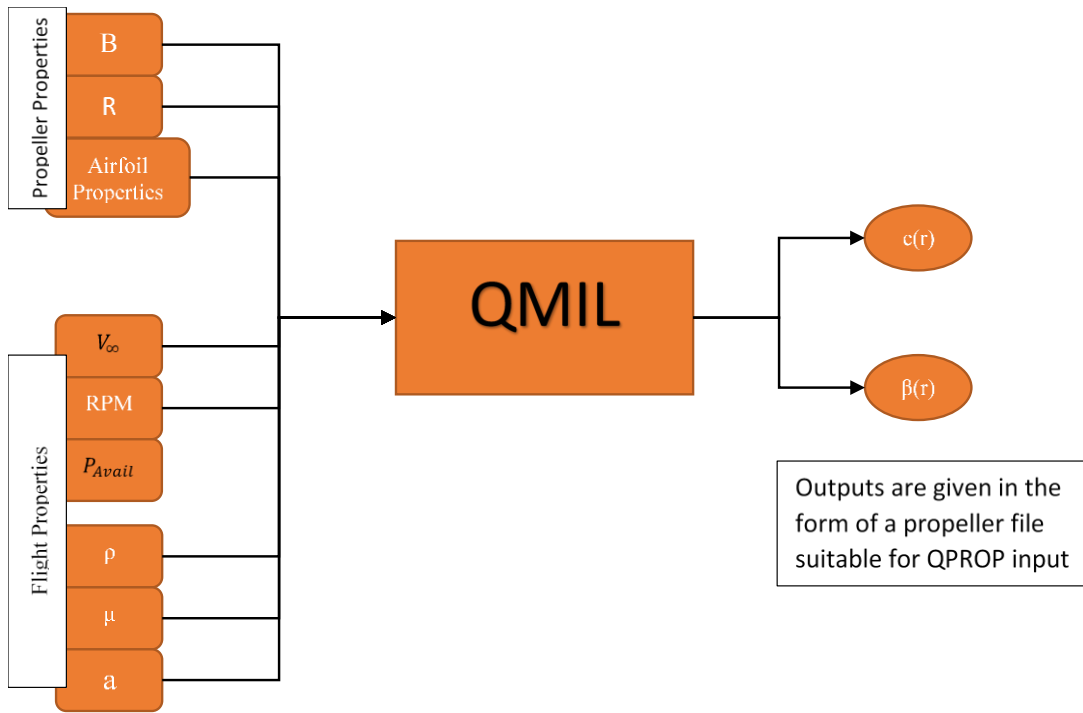
$$\mathcal{R}_{r1} = c_l - c_{l_{specified}}$$

**Equation 115: QMIL Restraint 1**

$$\mathcal{R}_{r2} = \bar{\eta}\Omega r W_a - V W_t$$

**Equation 116: QMIL Restraint 2**

Figure 27 shows an overview of the necessary inputs required for QMIL as well as the outputs that QMIL produces in solving the design problem.



**Figure 27: QMIL Inputs and Outputs**



## CHAPTER IV

### PROPDES

PROPDES (short for Propeller Designer) is a Microsoft Excel based, Visual Basic driven tool that was created to function as a shell wrapper to allow for quicker and easier operation of Professor Drela's QPROP and QMIL. The author originally developed PROPDES to assist in running multiple iterations of analysis (QPROP) cases in an attempt to validate QPROP's performance when compared to wind tunnel test data on commercially available propellers. At this time, PROPDES has been modified to allow for the following actions:

- Design Case - Running iterative design cases by using QMIL inside a loop such that the outputs from the previous QMIL calculation is used as input for the next design iteration in QMIL until the design converges (Details of why this was accomplished follow in Section 6.3 – PROPDES Validation (PV) Results)
- Analysis Case - Runs analysis on an existing propeller using QPROP within a user friendly graphical user interface (GUI)
- Joint Design/Analysis Case - Running a joint design-analysis case where QMIL develops the propeller geometry and QPROP uses the QMIL-developed propeller file for the analysis case

## 4.1 – Scope of Use

As discussed previously in the Introduction and in Section 4.1, the author developed PROPDES to easily perform analysis cases using QPROP and QMIL computer programs with specific conditions in mind for small scale UAVs. These specific conditions are listed as follows:

1. Tractor Propeller Configuration
2. Single Propeller Propulsion System
3. For the Design Case (QMIL)
  - a. Inputs: Radius, Velocity, RPM, and Power Available
  - b. Outputs: Propeller Geometry
4. For the Analysis Case (QPROP)
  - a. Inputs: Propeller Geometry, Velocity, RPM
  - b. Primary Outputs: Thrust, Torque, Efficiency
5. Only interested in Propeller Results (Motor/Engine will be considered separately)

## 4.2 – PROPDES Formulation

As previously discussed, PROPDES is a VBA driven software wrapper for QPROP and QMIL that runs within Microsoft Excel. The following figure shows the worksheets within the PROPDES.xlsm file which are grouped by color based on the function of the sheet. In addition to the sheets shown in Figure 28, there are a few hidden worksheets that contain information used by PROPDES during the design and analysis cases. These hidden sheets consist of:

1. An airfoil property sheet “Clark Y” which contains the CL and CD data for the Clark Y airfoil based on Reynolds Number and Angle of Attack.

2. An APC distribution sheet “APC Electric” that is only used in the case where QMIL fails to converge to a solution using the Clark Y airfoil.



Figure 28: Worksheets in PROPDES.xlsm

PROPDES performs the following functions (color coded per the worksheets in the figure above):

1. Initialization
2. Design Case - Creates a propeller file (QMIL)
3. Analysis Case - Analyzes an existing propeller file (QPROP)
4. Provides for configuration management of the software

These functions and their corresponding Excel worksheets within the PROPDES workbook are discussed below. Appendix B contains the visual basic modules that are used in PROPDES.xlsm.

#### 4.2.1 - Initialization



Figure 29: Worksheets in PROPDES.xlsm used for Initialization

	1	2
1	PROPDES Filename:	C:\PROPDES\[PROPDES(12-17).xlsm]Analyze Prop
2	PROPDES Filepath:	C:\PROPDES\
3		
4	<b>Analyze Prop Filepaths:</b>	
5	Prop File Folder:	C:\PROPDES\Propeller_Files\

Figure 30: PROPDES - Initial Setup Worksheet

The VBA modules used for the initialization case are shown below in Table 1.

**Table 1: PROPDES VBA Modules used for Initialization**

<b>Module</b>	<b>Function/Sub-routine</b>	<b>Purpose</b>	<b>Where it's Called</b>
Functions	UpdatePropFileNames	Update the list of propeller file names contained in the propeller folder	Workbook_Open Subroutine which automatically runs upon opening the Excel file

The Initial Setup worksheet simply defines the necessary folder locations and filename for the PROPDES.xlsm file. This is necessary due to PROPDES calling other scripts and programs (such as the batch file created by and ran by PROPDES as well as the QPROP.exe and QMIL.exe executables). By default, PROPDES attempts to read and write into the same directory as it is located therefore, there are no user inputs on this sheet. Each cell above is populated using Excel worksheet functions that determine the folder location of the current PROPDES.xlsm file and use that information to determine the default location of the propeller files (...PROPDES\Propeller\_Files\).

The QPROP.exe and QMIL.exe files must be located in the same folder as the PROPDES.xlsm file in order for the programs to run correctly. PROPDES allows for the cells in the Initial Setup worksheet to be easily changed by the user in order to specify different folder locations for the PROPDES files (QPROP.exe, QMIL.exe, qcon.def, Motor.txt, and PROPDES.xlsm) and the propeller files repository. However, the PROPDES files must be located in the directory shown above in Figure 30 due to a restriction in the FORTRAN code for QPROP that the author created.

The condition file (qcon.def) was not being utilized by QPROP. The author corrected this by editing one of the lines in the FORTRAN code to place the qcon.def file in a static location, namely C:\PROPDES\qcon.def. Therefore, the PROPDES files must be located in the C:\PROPDES\ directory. Additionally, the following files must be contained in the same folder (C:\PROPDES\):

- PROPDES.xlsm

- QPROP.exe (modified version as explained above for qcon.def file)
- QMIL.exe
- Qcon.def\*
- Motor.txt

\*Qcon.def may be absent if the user desires to perform calculations using standard sea level air properties

As shown in Figure 30, the propeller files necessary for program execution are defaulted to be stored in the same directory as the PROPDES.xlsm location but in a separate folder titled ‘Propeller\_Files’. This folder location may be manually input by deleting the formula currently stored in cell (5, 2) and replacing with text that identifies the desired folder location. However, once this change is made the file will need to be saved, closed, and re-opened to allow the initialization code to call the UpdatePropFileNames() sub-routine in order to populate the dropdown menus used to select the propeller file on the ‘Analyze Prop’ worksheet.

The Motor.txt file is required for QPROP and QMIL, however the author is not currently using any of the outputs that are derived based on the motor file so it is not necessary for the user to update the motor file to properly use PROPDES.

#### 4.2.2 – Design Case: QMIL



**Figure 31: Worksheets in PROPDES.xlsm used for the Design Case (QMIL)**

The VBA modules, sub-routines, and functions are used for the design case<sup>+</sup> as follows:

**Table 2: PROPDES VBA Modules used for the Design Case**

<b><u>Module</u></b>	<b><u>Function/Sub-routine</u></b>	<b><u>Purpose</u></b>	<b><u>Where it is Called</u></b>
Main	Program()	Defines variables, performs conversions and creates files necessary to run QMIL and QPROP iteratively	'Create Prop' button on the "Create Prop Inputs" worksheet
Main	DesignCL()	Determines the lowest drag point on the drag polar and finds $CL(\alpha)$ at that point. Outputs to 'Create Prop Inputs' worksheet for each iteration	Main.Program()*
QMILsubs	QMIL()	Runs sub-routines to create necessary input files, run QMIL, and retrieve the outputs	Main.Program()*
QMILsubs	CreateQMILinput()	Reads in data from 'Create Prop Inputs' worksheet and formats as required by QMIL. Creates QMIL input text file.	QMILsubs.QMIL()**
QMILsubs	QMILreader()	Takes QMIL default output (text file) and reads it into the 'Create Prop Inputs' worksheet for each iteration	QMILsubs.QMIL()**
Functions	Titles()	Formats titles for each iteration posted to the 'Create Prop Inputs' worksheet	QMILsubs.QMILreader()**
Main	ReyNum()	Calculates the Reynolds number at each radial station for current iteration and outputs to 'Create Prop Inputs' worksheet	Main.Program()*
Main	checkConv()	Compares changes in chord and beta between each iteration and exits loop if convergence is successful.	Main.Program()*

<b>Module</b>	<b>Function/Sub-routine</b>	<b>Purpose</b>	<b>Where it is Called</b>
QPROPsubs	QPROP()	Runs sub-routines to create necessary input files, run QPROP, and retrieve the outputs	Main.Program()
QPROPsubs	CreateQPROPrun()	Uses variables read in from 'Create Prop Inputs' worksheet and formats as required by QPROP. Creates QPROP input text file.	QPROPsubs.QPROP()
QPROPsubs	QPROPreader()	Takes QPROP default output (text file) and reads it into the 'Create Prop Output' worksheet	QPROPsubs.QPROP()
Main	Charts()	Produces and formats charts created and placed on 'Output Charts' worksheet	Main.Program()

\*Inside main loop of the program (iteration of QMIL)

\*\*Subroutine/function within a subroutine that is in the main loop of the program (iteration of QMIL)

+Table does not include Modules, sub-routines, or functions called as part of the UseAPC() or CreatePropellerFile() sub-routines described later in Paragraph 4.2.2.2.

The design case is handled by 3 worksheets: Create Prop Inputs, Output Charts and Create Prop Output. The Create Prop Inputs worksheet is designed to allow user inputs in each of the light blue shaded cells. Some of these inputs are read in directly during the VBA subroutine called when the 'Create Prop' button is pressed, other inputs are used for calculations on the sheet that could be informational to the user or could be read in by the VBA subroutine.

The 'Create Prop' subroutine will read in all of the necessary variables from this worksheet and the Initial Setup worksheet. The program will then create a batch file and use the batch file to run QMIL for the given conditions. The results from each iteration of QMIL are stored on the Create Prop Inputs worksheet; Figure 32 shows a screenshot of the Create Prop Inputs worksheet and includes the first and second iteration results. The 'Clear' button is provided to run a VBA subroutine which simply clears the data fields that are generated upon running the 'Create Prop' subroutine.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1	Diameter:	18	Inches			Vinf:	30	KIAS	@3/4	Radius:	CLD:	0.3856	CD0:	0.00724	Reref:	578257	Re=rho*v*/mu
2	RPM:	2000					50.61	fps		CL_a:	5.7868	CD2L:	0.0125	Reexp:	-0.5		
3	Rho:	0.00237	slugs/ft^3			n:	33.33333333	1/s		Ctmin:	-0.3	CDL:	0.0125	QMIL Input File Name:	PROPDES_Input.txt		
4	Mu:	0.00000362	lbf-s/ft^2			Power Avail:	1	HP		Ctmax:	1.1253	CLCD:	0.485	QMIL Output File Name:	PROPDES_Output.txt		
5	Blades:	2				Hub Radius:	2	Inches						QPROP Output File Name:	QPROP_Output.txt		
6						J:	1.0122			Tip Mach:	0.141						
7	Create Prop	Radius Sta:	0	1	2	3	4	5	6	7	8	9	10	11	12		
8	Clear	X:	0.2222	0.2481	0.2741	0.3000	0.3259	0.3519	0.3778	0.4037	0.4296	0.4556	0.4815	0.5074	0.5333		
9		r (inches):	2.00	2.23	2.47	2.70	2.93	3.17	3.40	3.63	3.87	4.10	4.33	4.57	4.80		
10		Velocity (fps):	34.9	39.0	43.1	47.1	51.2	55.3	59.3	63.4	67.5	71.6	75.6	79.7	83.8		
11		Chord (inches):	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0		
12		Reynolds:	380,887	425,324	469,760	514,197	558,634	603,071	647,508	691,944	736,381	780,818	825,255	869,691	914,128		
13		Xides:	0.222	0.248	0.274	0.300	0.326	0.352	0.378	0.404	0.430	0.456	0.481	0.507	0.533		
14		CLdes:	0.474	0.470	0.471	0.471	0.354	0.352	0.378	0.404	0.430	0.456	0.481	0.507	0.533		
15																	
16		Radius:	2.117	2.350	2.583	2.817	3.050	3.283	3.517	3.750	3.983	4.217	4.450	4.683	4.917		
17		Chord:	17.124	17.448	18.762	17.476	16.354	17.000	17.115	17.258	17.192	17.351	16.118	14.960	14.962		
18		Beta:	66.794	64.677	62.337	60.719	59.165	57.094	55.245	53.438	51.748	50.041	48.835	47.703	46.182		
19	Iteration 1	Reynolds:	472,824	481,760	518,047	482,543	451,550	469,400	472,585	476,520	474,694	479,097	445,049	413,078	413,122		
20		Xides:	0.235	0.261	0.287	0.313	0.339	0.365	0.391	0.417	0.443	0.469	0.494	0.520	0.546		
21		CLdes:	0.627	0.626	0.624	0.626	0.628	0.627	0.627	0.627	0.627	0.626	0.629	0.631	0.631		
22																	
23		Radius:	2.117	2.350	2.583	2.817	3.050	3.283	3.517	3.750	3.983	4.217	4.450	4.683	4.917		
24		Chord:	12.339	13.256	13.920	14.339	14.638	14.901	15.035	15.076	15.022	14.903	14.654	14.350	14.048		
25		Beta:	68.375	66.192	63.958	61.861	59.850	57.893	56.032	54.256	52.565	50.949	49.436	47.994	46.599		
26		Reynolds:	340,701	366,019	384,347	395,913	404,175	411,448	415,155	416,285	414,796	411,502	404,610	396,240	387,880		
27		Xides:	0.23518	0.26111	0.28704	0.31296	0.33889	0.36482	0.39074	0.41667	0.44261	0.46850	0.49444	0.52038	0.54628		
28		CLdes:	0.63081	0.63132	0.63169	0.63192	0.63171	0.63120	0.63094	0.63086	0.63096	0.63120	0.63168	0.63193	0.63176		

Figure 32: PROPDES - Create Prop Inputs Worksheet Screenshot

Module Main sub-routine Program() defines the numerical value and module Main sub-routine Checkconv determines if the convergence conditions are met prior to PROPDES exiting the iteration loop containing the call QMIL command. The convergence conditions are set to check whether the sum of the changes of the chord values across all 30 radial stations has changed less than 1.0 or if the sum of the changes of the beta values across all 30 radial stations has changed less than 1.0. In other words,

$$\sum_0^{30} \Delta C < 1.0 \text{ or } \sum_0^{30} \Delta \beta < 1.0$$

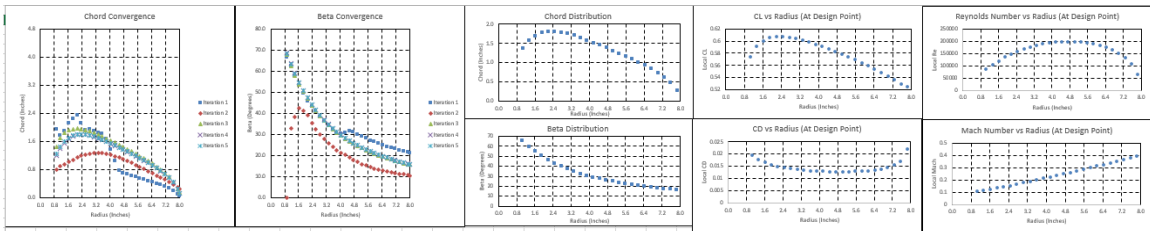
Equation 117: PROPDES Convergence Conditions

Once the main program has met the convergence conditions, the Output Charts worksheet is updated with the latest data. Figure 33 shows a screenshot of the Output Charts worksheet which contains the updated charts.

The Chord Convergence and Beta Convergence charts are updated to show the incremental differences of the chord and beta distributions with respect to the radius. These distributions are useful in checking whether or not the convergence conditions have been appropriately set. If the chord and beta values are still changing drastically, then more iterations would be required to ensure the solution has fully converged. The user can vary the number of iterations by simply updating the convergence condition which is defined in the VBA module Main sub-routine Program() as the variable 'ConvergenceFactor'.



The remaining charts show several variables with respect to the radius for the last iteration performed. The chord and beta charts are the physical descriptions of the designed propeller blades. The remaining charts are indicating values as they are estimated by QMIL at the design conditions only. This fact is important to note since one cannot simply use these charts to determine the range of these values that the propeller may be subjected to. For example, the maximum tip mach number is very important to propeller designers but the chart shown on the Output Charts worksheet below only shows the tip mach number at the design point and does not provide a reference for tip mach numbers while operating at off-design conditions (e.g. higher RPM or higher forward velocity than the design point).



**Figure 33: PROPDES - Output Charts Worksheet Screenshot**

Finally, the Create Prop Output worksheet contains all of the raw data from the QMIL output file. This worksheet is provided for information purposes so that the user can verify the inputs were taken correctly from the Create Prop Inputs worksheet. Additionally, the blue highlighted area seen in Figure 34 is provided as a quick conversion calculator to further verify that the results correspond to the design conditions intended.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
#	QPROP Version 1.22						m/s to knots:	1.943844		V(m/s)	15.426		RPM:	2000						
#							Newtons to pounds:	0.224808943		T(N)	28.51		Vinf:	29.98574 knots						
#	Blades: 2	Radius: 9. inches	RPM: 2000				N-m to lbf-ft:	0.737562149		Q(N-m)	3.55		Thrust:	6.409303 pounds						
#							Watts to HP:	0.001341022		Pshaft(W)	743.5		Torque:	2.618346 lbf-ft						
#	Speed: 400 3321 (6V) direct drive									adv:	0.32219		Shaft Power:	0.99705 HP						
#	0.31000 motor parameter 1, R (Ohms)									CT:	0.1237		J:	0.32219						
#	0.77000 motor parameter 2, Io (Amps)									CP:	0.06737		CT:	0.479435						
#	2760.0 motor parameter 3, Kv (rpm/Vo)									effprop:	0.5915		CP:	0.130556						
#													Propeller Eff:	0.5915						
#	rho = 1.2250 kg/m^3																			
#	mu = 0.17811E-04 kg/m-s																			
#	a = 340.00 m/s																			
#																				
#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
#																				
#	V(m/s)	rpm	Dbeta	T(N)	Q(N-m)	Pshaft(W)	Volts	Amps	effmot	effprop	adv	CT	CP	DV(m/s)	eff	Pelec	Pprop	cl_avg	cd_avg	
#	15.426	2000	0	28.51	3.55	743.5	319.05	1026.857422	0.0023	0.5915	0.32219	0.1237	0.067369998	7.4098	0.0013	327600	439.8	0.6316	0.007428	
#																				
#	radius	chord	beta	Cl	Cd	Re	Mach	effi	effp	Wa(m/s)	Aswirl	adv_wake								
#	2.259901	12.87005	67.172	0.6311	0.00881	428650	0.056	0.606599987	0.9641	17.25	1.26E+01	0.5311								
#	2.531491	13.62202	64.536	0.6315	0.00838	474249	0.059	0.606599987	0.9681	17.61	1.32E+01	0.5311								
#	2.803144	14.19289	62.021	0.6318	0.00802	517062	0.061	0.606599987	0.9711	17.99	1.36E+01	0.5311								
#	3.078734	14.59446	59.627	0.6318	0.00773	556961	0.064	0.606599987	0.9733	18.36	1.39E+01	0.5311								
#	3.354324	14.8543	57.349	0.6313	0.00749	593805	0.067	0.606599987	0.975	18.73	1.41E+01	0.5311								
#	3.629914	14.96454	55.194	0.6311	0.00729	626600	0.07	0.606599987	0.9762	19.09	1.42E+01	0.5311								
#	3.905504	14.94485	53.159	0.6311	0.00713	655187	0.074	0.606599987	0.9772	19.43	1.42E+01	0.5311								
#	4.181094	14.81099	51.234	0.6313	0.007	679392	0.077	0.606599987	0.9778	19.76	1.41E+01	0.5311								

Figure 34: PROPDES - Create Prop Output Worksheet Screenshot

#### 4.2.2.1 – PROPDES Structure for Design Case: QMIL

As previously stated, the design case worksheets in PROPDES act as a shell for easier operation of QMIL. Therefore, it follows that the inputs and outputs for the PROPDES design case worksheets are extremely similar to those previously shown for QMIL in Figure 27.

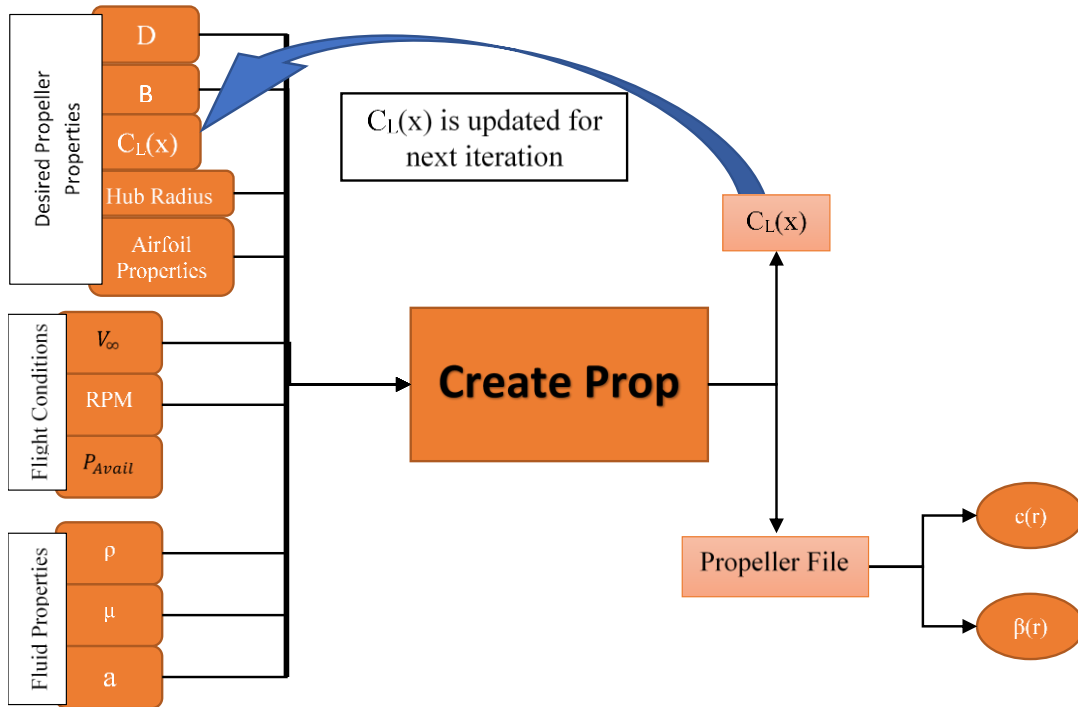
PROPDES requires 3 major sets of data to be input:

1. Desired Propeller Properties
2. Flight Conditions
3. Fluid Properties

This data is used to create the various input files to support the operation of QMIL per the batch file created and executed by PROPDES. The  $C_L(x)$  data is read in from the Create Prop Inputs worksheet and is calculated on the worksheet based on the user input for the chord distribution on row 11. QMIL provides 2 outputs within the PROPDES program:

1. Coefficient of Lift as a function of the radius station,  $C_L(x)$
2. Propeller file consisting of chord and beta as a function of the radius

The  $C_L(x)$  output is fed back into the Desired Propeller Properties input for each subsequent iteration as shown by the blue arrow in Figure 35. This feedback loop allows for a more accurate output from QMIL for each subsequent iteration. Once the QMIL solution converges, the propeller file is produced and saved in the folder specified on the Initial Setup worksheet with the filename as specified on the Create Prop Inputs worksheet.

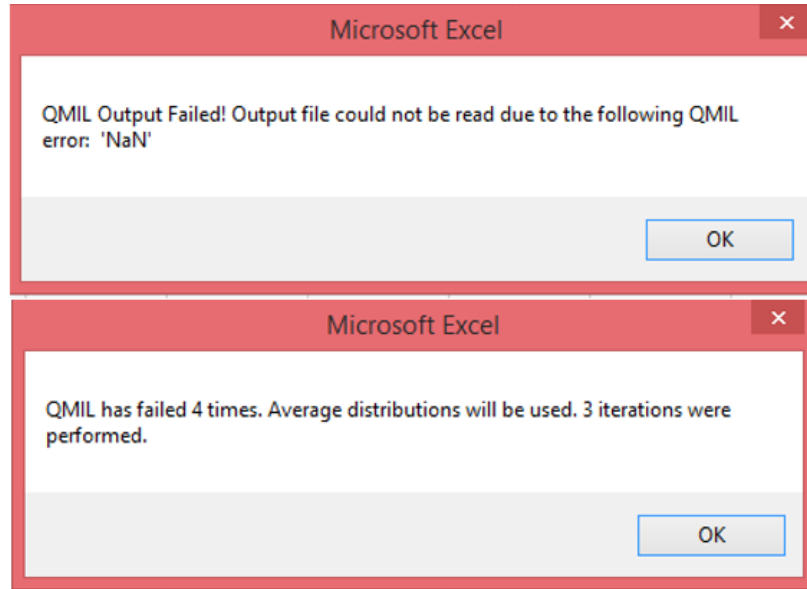


**Figure 35: PROPDES - Create Prop Inputs and Outputs**

#### 4.2.2.2 – Use of APC Geometry

Early in the design and testing of PROPDES, it became apparent that QMIL is sensitive to the initial conditions propeller file that must be provided as an input (See Figure 35 above). Due to this sensitivity, the author developed a few subroutines (UseAPC() and CreatePropellerFile()) that are utilized in the case that QMIL fails to produce a useable propeller file. The UseAPC() subroutines uses the standard 2 bladed APC chord and beta distribution as measured on an APC 19x12 propeller (Brandt, 2005) to produce a propeller file for input into the next iteration of QMIL. The CreatePropellerFile() subroutine is ran if the UseAPC() is called multiple times and it uses the average distributions from the last 3 runs to define a propeller file that can then be

analyzed by QPROP. In either case the user is notified by a pop-up message similar to the ones shown below in Figure 36.



**Figure 36: Message Box Examples Showing APC Distributions will be Used (Top) and Average Distributions will be Used (Bottom)**

#### 4.2.3 – Analysis Case: QPROP



**Figure 37: Worksheets in PROPDES used for Analysis Case (QPROP)**

The VBA modules used for the analysis case are as follows in Table 3.

**Table 3: PROPDES VBA Modules used for the Analysis Case**

<u>Module</u>	<u>Function/Sub-routine</u>	<u>Purpose</u>	<u>Where it is Called</u>
AnalyzePropeller	AnalyzeProp()	Reads in variables from ‘Analyze Prop’ worksheet and formats as required by QPROP. Calls routines required to create inputs, run QPROP, and read in outputs.	‘Analyze Prop Using QPROP’ button on the ‘Analyze Prop’ worksheet
AnalyzePropeller	A_CreateQcon()	Creates air conditions file for QPROP input	AnalyzePropeller.A analyzeProp()
AnalyzePropeller	A_CreateQPROPrun()	Creates QPROP input text file.	AnalyzePropeller.A analyzeProp()

<b><u>Module</u></b>	<b><u>Function/Sub-routine</u></b>	<b><u>Purpose</u></b>	<b><u>Where it is Called</u></b>
AnalyzePropeller	A_runQPROP()	Calls ShellandWait() to run QPROP.exe and create output file	AnalyzePropeller.A nalyzeProp()
AnalyzePropeller	AnalyzeQPROPreader()	Takes QPROP default output (text file) and reads it into the 'Analyze Prop' worksheet	AnalyzePropeller.A nalyzeProp()
AnalyzePropeller	A_Chart	Produces and formats charts created and placed on 'Analyze Prop' worksheet	AnalyzePropeller.A nalyzeProp()

The design case is handled on the Analyze Prop worksheet in the PRODES.xlsm file. The Analyze Prop worksheet is designed to allow user inputs in each of the light blue shaded cells similarly to the analysis case worksheets. Some of these inputs are read in directly during the VBA subroutine called when the 'Analyze Prop' button is pressed, other inputs are used for calculations on the sheet that could be informational to the user or could be read in by the VBA subroutine.

The 'Analyze Prop' subroutine will read in all of the necessary variables from this worksheet and the Initial Setup worksheet. For convenience, a drop down menu of available propeller files is provided on the Analyze Prop worksheet and is updated each time the PRODES.xlsm file is opened or a new propeller is created using the 'Create Prop' subroutine. This provides the user with a simple tool to use in selecting the propeller of interest for an analysis case.

When a user presses the 'Analyze Prop' soft button on the Analyze Prop worksheet, PRODES will create a batch file and use the batch file to run QPROP for the given conditions. The results from QPROP consist of analysis performed for the entire RPM and forward velocity ranges as specified on the Analyze Prop worksheet. These results are stored on the Analyze Prop worksheet; Figure 37 shows a screenshot of the worksheet and includes 2 of the 3 charts that are

integrated into the worksheet to provide a more concise result. The 3 charts that are integrated into the Analyze Prop worksheet are updated each time the ‘Analyze Prop’ subroutine is performed and consist of the following:

1. Coefficient of thrust as a function of the advance ratio,  $C_T(J)$
2. Coefficient of power as a function of the advance ratio,  $C_P(J)$
3. Propeller efficiency as a function of the advance ratio,  $\eta(J)$

The ‘Clear’ button is provided to run a VBA subroutine which simply clears the data fields that are generated upon running the ‘Analyze Prop’ subroutine.

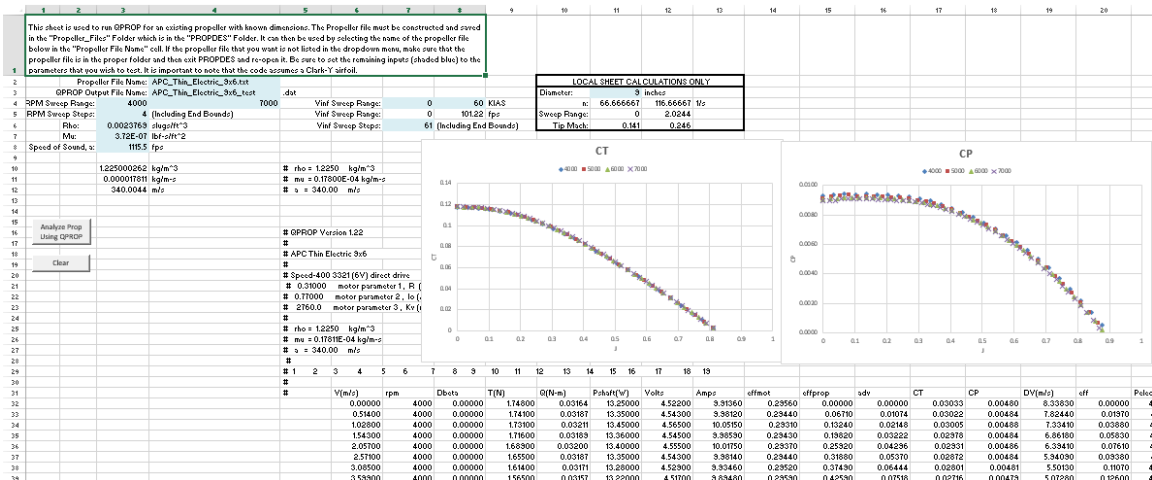


Figure 38: PROPDES - Analyze Prop Worksheet Screenshot

#### 4.2.3.1 – PROPDES Structure for Analysis Case: QPROP

As previously stated, the analysis case worksheets in PROPDES act as a shell for easier operation of QPROP. Therefore, it follows that the inputs and outputs for the PROPDES analysis case worksheet are extremely similar to those previously shown for QPROP in Figure 26.

Similarly to the design case, PROPDES requires 3 major sets of data to be input to support the analysis case:

1. Propeller Properties

2. Flight Conditions

3. Fluid Properties

This data is used to create the various input files to support the operation of QPROP per the batch file created and executed by PROPDES. The ‘Analyze Prop’ subroutine provides several outputs via QPROP within the PROPDES program:

1. Specifically solves for various propeller values at the flight conditions specified

- a. Thrust,  $T$
- b. Torque,  $Q$
- c. Advance Ratio,  $J$
- d. Coefficient of Thrust,  $C_T$
- e. Coefficient of Power,  $C_P$
- f. Efficiency of the Propeller,  $\eta_{Prop}$
- g. Slipstream Velocity Increment,  $DV$
- h. Power-weighted Average of Local Lift Coefficient,  $c_{l_{avg}}$
- i. Power-weighted Average of Local Drag Coefficient,  $c_{d_{avg}}$

2. Charts outputs over the range of RPM and forward velocity specified

- a. Coefficient of thrust as a function of the advance ratio,  $C_T(J)$
- b. Coefficient of power as a function of the advance ratio,  $C_P(J)$
- c. Propeller efficiency as a function of the advance ratio,  $\eta(J)$

Once the ‘Analyze Prop’ subroutine is ran, the QPROP output file is produced and saved in the folder specified on the Initial Setup worksheet with the filename as specified on the Analyze Prop worksheet. The charts output by the ‘Analyze Prop’ subroutine are of great interest to the propeller designer. These three simple charts can provide a great deal of information on the characteristics and performance of a given propeller.

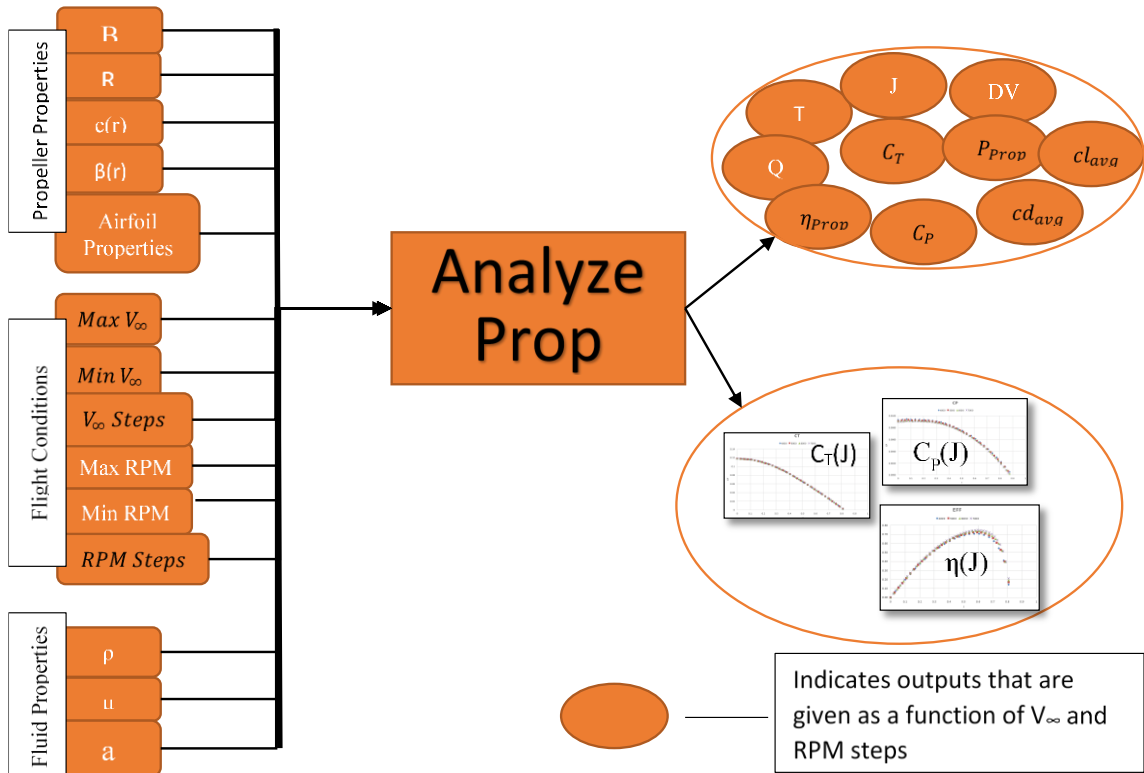


Figure 39: PROPDES - Analyze Prop Inputs and Outputs

#### 4.2.4 – Software Configuration Management

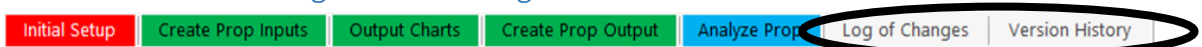


Figure 40: Worksheets in PROPDES used for Software Configuration Management

There are no VBA Modules utilized for the configuration management of PROPDES.

Configuration management is critical for any software and PROPDES is no exception. The author has built in 2 worksheets to aid in keeping the configuration of the software under control as other users make changes, updates, or develop more functionality into the software. The Log of Changes worksheet is a fairly straightforward log that allows the developer to document all



changes, issues, errors, and comments that relate to the operation of the PROPDES.xlsm program and track these changes through to completion by using a standard stoplight color scheme. The screenshot below shows a segment of the log worksheet where issues were identified and have since been corrected (shown in green). Yellow text signifies items that were identified as issues and are not able to be corrected (work-arounds may have been implemented) and red indicates a known issue that has not yet been solved/corrected.

1	
1	<p><b>5/14/2013</b></p> <p>PROPDES is still in development. Currently it is running QPROP and QMIL in a loop using results from one iteration as input for the next iteration. NEED TO CREATE AN EASY WAY TO OUTPUT PROPELLER CHARTS (EFF, Q, T) IN ORDER TO COMPARE WITH KNOWN RESULTS.</p> <p><b>STATUS: NEED A WAY TO OUTPUT STANDARD PROP CHARTS FOR ANALYZE PROP CODE AND THE PROPDES CODE.</b></p>
2	<p><b>Completed on 10/9/2014. Output charts (CT, CP and Eff vs J) are being updated each time Analyze Prop is ran.</b></p>
3	<p><b>5/15/2013</b></p> <p>Fixed issue with error 'File not found' referring to QPROP_Output.dat. Discovered that I had a space in my file path so QPROP was not running at all! Corrected the file path to have _ instead of spaces...</p> <p>Also, corrected error in program that lead to wrong sheets being used for CL, CD, and APC Geometry interpolations. I need to find a way to submit a sheet name instead of a sheet number so that the sheet order does not change the code. I added an additional sheet "Initial Setup" and this caused "CL vs Alpha" to become sheet 4 instead of sheet 3 and so on. I believe that interp() is the only function still using sheet numbers. Be sure to check this if you change order or add sheets to the workbook. [9/16/13 - I updated code so that the Sheet variable is defined as a string and therefore the program now passes the sheet name to the interp function. I believe this corrected the issue. Marked the code that I updated as Changed 9/16/13.]</p>

**Figure 41: PROPDES - Log of Changes Worksheet Screenshot**

The Version History worksheet is intended to show changes at a much higher level than the Log of Changes worksheet. The Version History worksheet simply shows when version numbers are rolled and the author recommends using a very simple version numbering system of <major>.<minor> where major changes consist in a functional change and minor changes consist of cleaning up code or minor housekeeping errors.

1	A change that results in a functional change should be documented as a new version as								
2	opposed to a increment change.								
3									
4		<b>Version</b>	<b>Date</b>	<b>POC</b>	<b>Comments</b>				
5		1.0	TBD	Trevor Lowe trevor.lowe@okstate.edu	Thesis Submittal				
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									

Figure 42: PROPDES - Version History Worksheet Screenshot

The Log of Changes and Version History worksheets do not have any macro capabilities and therefore do not use any of the VBA Modules.

#### 4.2.5 – Clark Y Performance Data and APC Distributions (Hidden Worksheets)

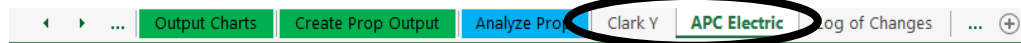


Figure 43: Hidden Worksheets containing Clark Y Performance Data and APC Distributions

The Clark Y and APC Electric worksheets do not have any macro capabilities and therefore do not use any of the VBA Modules. However, these data sets are used by other macros as discussed in the previous sections. These worksheets are hidden by default but a user may unhide them as needed to change the data sets or to adjust the values as desired.



Figure 44: XFOIL Logo (Drela)

The Clark Y data set was imported directly from XFOIL. XFOIL is another product by Drela and it provides an interactive program for analyzing subsonic airfoils.

(<http://web.mit.edu/drela/Public/web/xfoil/>)

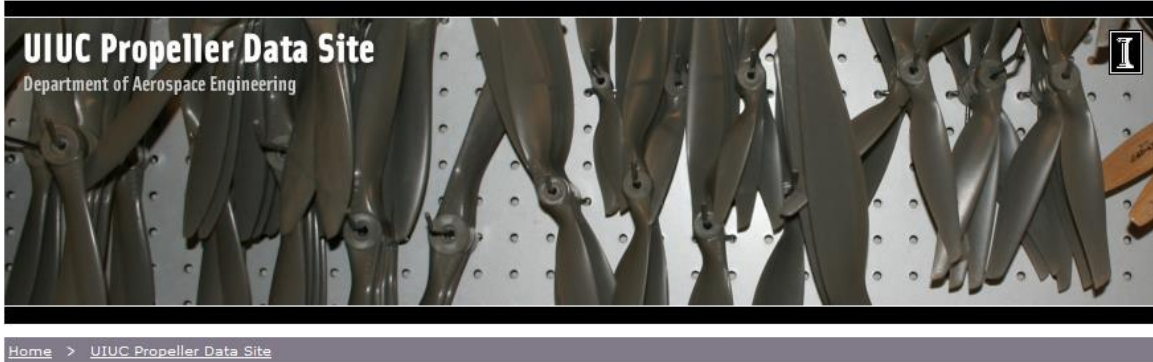


Figure 45: UIUC Propeller Data Site Homepage

The APC distributions were input directly from the UIUC propeller database for an APC19x12. If desired, these distributions could be easily changed for another propeller by editing the hidden worksheet. (<http://m-selig.ae.illinois.edu/props/propDB.html>)

## 4.3 – Limitations

As with any analytical program, the output is only as good as the input and the restrictions and limitations of the program must be well understood by the user in order for PROPDES to produce useful and accurate results.

### 4.3.1 – Number of Radial Stations

PROPDES currently uses thirty radial stations when running QMIL to develop a propeller design. Thirty stations provide enough fidelity when designing propellers that have relatively small radii however this presents problems when designing propellers with a larger radius desired. Consider a 12 inch radius propeller with 30 radial stations:

$$\Delta r = \frac{R}{\# \text{ of Sta}} = \frac{12''}{30} = 0.4''$$

Contrast that result with the following 36 inch radius propeller:

$$\Delta r = \frac{R}{\# \text{ of Sta}} = \frac{36''}{30} = 1.2''$$

Obviously, the larger the radius the less fidelity PROPDES will provide which may cause a reduction in accuracy with very large propellers.

#### 4.3.2 – Airfoil Selection

PROPDES is currently limited to a single airfoil, the Clark Y. This airfoil was selected due to its fairly common use among propeller designers which made for easier comparison for validation purposes. The airfoil was also due to the fact that the APC propeller website describes the airfoil that their propellers utilize as a “modified Clark Y”. It would be fairly straightforward to include additional airfoils by adding two new sheets to the Excel file (one for CL vs Alpha and one for CD vs Alpha for the new airfoil) and using XFOIL or a similar method to add the necessary data points for the lift and drag coefficients across the range of angle of attacks.

The currently stored airfoil worksheets are titled “CL vs Alpha” and “CD vs Alpha” and these sheets are currently hidden, however there is no password lock on the PROPDES workbook so a user could simply unhide them in order to copy and paste the format for another airfoil.

Obviously the code would need to be updated as well to include a method to select which airfoil the user would like to use for a given calculation. This improvement will be necessary to improve the accuracy of PROPDES for airfoils other than the Clark Y.

#### 4.3.3 – No Consideration for Manufacturability

Currently, PROPDES does not provide a method for the user to input manufacturing limitations, e.g. chord length limits or thickness limitations due to materials used. This feature would be extremely useful for a propeller designer; however, it is outside the scope of the goal of the current work which is to attempt to validate QPROP and QMIL using wind tunnel and other reported data points.

#### 4.3.4 – Lack of Motor Analysis

This limitation is briefly mentioned in Section 4.1, Item 5. QPROP and QMIL are designed to be capable of taking motor inputs and analyzing motor/propeller combinations to give the propulsion

designer a more overall analysis. For the purposes of this paper, the author has restricted the use of QPROP and QMIL such that PROPDES currently does not analyze the motor and all outputs that rely on the motor file are therefore suspect. These results rely on a default motor file that will not be realistic for most of the propellers analyzed. An analysis was completed to trace the variables through the QPROP and QMIL FORTRAN code and the following output variables listed in the ‘Analyze Prop’ worksheet were identified as being impacted by the motor file and therefore should NOT be relied on:

- $P_{\text{shaft}}$  – Shaft Power
- V – Volts
- A – Amps
- $\eta_{\text{motor}}$  – Motor Efficiency
- $\eta$  – Total Efficiency
- $P_{\text{elec}}$  – Electric Power

These parameters are also identified in Chapter III, Figure 26.

#### 4.3.5 – QPROP and QMIL Limitations

Since PROPDES acts as a simple file wrapper to run specified cases using QPROP and QMIL, it is obvious that any limitations on QPROP and QMIL are limitations for PROPDES. These QPROP/QMIL limitations are listed below:

1. Estimation of Drag for Low Reynolds Number Flow. Drela does not provide details in any of the files delivered with QPROP/QMIL except to say that “the profile drag characteristic is a quadratic  $CD(CL)$  function, with an approximate

stall drag increase, and a power-law scaling with Reynolds number.”

(qprop\_user\_guide.pdf)

2. QMIL only designs for the given conditions. There is currently not an automated method that would optimize for one flight condition (e.g. cruise) and ensure that the design meets the needs of another flight condition (e.g. takeoff, sprint, loiter, etc) without running ‘Analyze Prop’ separately for each flight condition.

## 4.4 – Ideas for Future Development of PROPDES

Ideas for future work:

1. Take inputs from user regarding desired performance and create a loop to run QMIL and QPROP to perform design-analysis-design-analysis-etc until all analysis conditions are optimized
2. Take inputs from user regarding manufacturing capability limitations (minimum thickness, chord limits, hub limits, etc) and subjecting the QMIL design to these limitations.
3. Take inputs from user regarding the motor file and have PROPDES create Motor.txt and output charts that would be useful for the end user. Currently, the motor file is provided based on necessity and the outputs that rely on the contents of the motor file are to be ignored.
4. Allow other airfoils to be selected (similar to the way propellers can be selected).
5. Develop an XFOIL VBA module that would allow automatic creation of a hidden worksheet for any airfoils supported by XFOIL which could then be selected for use in the design or analysis portion of PROPDES.

6. Allow the use of multiple airfoils on a single blade (e.g. Clark Y for first 25% of the blade and then change to NACA airfoil for the remaining 75%). QPROP currently allows for that utility but PROPDES does not have a way to create the advanced propeller file required for that option.

## CHAPTER V

### VERIFICATION AND VALIDATION OF QPROP USING PROPDES

The primary purpose of this thesis is to determine if QPROP provides accurate results, specifically for low Reynolds number flow regimes. Several sources have performed rudimentary verifications by way of simply choosing a single point to analyze and independently verifying that QPROP uses the correct equations/methodology as presented by Drela. (Turan, 2009; Hrad, 2010; Pederson, 2011) A more thorough verification is presented here where QPROP's results for a range of propellers and flight properties are compared to wind tunnel test results from two different sources. This approach provides a more rigorous study to determine the estimated accuracy of the QPROP results based on the ranges of the various inputs.

The secondary purpose of this thesis is to develop a software suite that is more user friendly and quicker to set up than the native QPROP/QMIL FORTRAN codes. Validation procedures were developed and are discussed below. These procedures ensure that PROPDES meets the requirements of running QPROP and QMIL independently for various ranges of propeller sizes, RPMs and velocities.



## 5.1 – QPROP Verification (QV) Procedures

PROPDES was described extensively in the previous chapter and will be used exclusively for the verification efforts. PROPDES provides an easy to use wrapper for QPROP that can be manipulated to create multiple runs for a given propeller. These runs will focus on QPROP’s accuracy when compared to experimental wind tunnel data.

Several sources of data exist for propellers that have been tested in wind tunnels. The 2 data sets selected for inclusion in this work are a propeller test performed in the Oklahoma State University wind tunnel (Gamble, 2009) and propellers tested at UIUC provided on the UIUC Propeller Database. (J.B. Brandt, R.W. Deters, G.K. Ananda, and M.S. Selig, 2015)

A review of the literature showed that adequate data exists for the following propellers and these propellers provide a decent range of diameter and pitch used on small UAVs of particular interest to the author and OSU. Additionally, APC thin electric propellers were chosen to maintain consistency in airfoil properties. The RPMs were selected based on the experimental data available. The max velocity was determined from the maximum advance ratio and the maximum RPM given in experimental data as shown here:

$$J = \frac{V}{nD} \Rightarrow V_{max} = (J_{max})(n_{max})(D)$$

**Equation 118: Determining Velocity Range for Test Cases**

Therefore, the following propeller cases were selected to be analyzed using QPROP and the results will be compared to the wind tunnel results:

**Table 4: QPROP Verification Test Cases**

Run #	Make/Model	Blades	Diameter (Inches)	Pitch (Inches)	RPM Cases	Velocity Range (KIAS)	Wind Tunnel Data Source
QV1	APC Thin Electric	2	9	4.5	4002, 5008, 6018, 6917	0-40	UIUC Database
QV2	APC Thin Electric	2	11	5.5	3010, 3994, 4999, 6002	0-35	UIUC Database

Run #	Make/Model	Blades	Diameter (Inches)	Pitch (Inches)	RPM Cases	Velocity Range (KIAS)	Wind Tunnel Data Source
QV3	APC Thin Electric	2	11	7	3003, 3998, 4997, 5988, 6003	0-45	UIUC Database
QV4	APC Thin Electric	2	11	8	3016, 3997, 4999, 6000	0-50	UIUC Database
QV5	APC Thin Electric	2	11	8.5	3005, 3998, 5000, 5999	0-50	UIUC Database
QV6	APC Thin Electric	2	11	10	3014, 3996, 4998, 5501	0-55	UIUC Database
QV7	APC Thin Electric	2	14	12	1997, 2498, 3005, 3507	0-40	UIUC Database
QV8	APC Thin Electric	2	17	12	2000, 2506, 3008, 3407	0-45	UIUC Database
QV9	APC Thin Electric	2	18	12	1666, 2398, 3570, 4555	0-55	Gamble
QV10	APC Thin Electric	2	19	12	1500, 2096, 2508, 3007	0-50	UIUC Database

Each of the above runs will be performed using the PROPDES “Analyze Propeller” worksheet.

The output files will be collected and compared to the published wind tunnel data. Additionally, CP, CT, and Efficiency charts will be compared with experimental results. These results will be discussed in Chapter VI and the full test tables/charts for each run are attached in Appendix D.

## 5.2 – PROPDES Validation (PV) Procedures

For the validation effort, only the first iteration of PROPDES (hence a single iteration of QMIL) and the results will be compared to those obtained by running QMIL by itself. These tests should show that PROPDES, in its current format, does not adjust the calculations used by QMIL.

Additionally, the improved PROPDES (runs iterations of QMIL using the previous QMIL output as the new input for QMIL) will be ran for the same cases and the results will be captured and discussed.

A few design points will be chosen similar to those used in the QPROP verification, however the propeller geometries will vary since QMIL will now be used to design the chord and beta

distributions for the individual propeller blades. The design points chosen to correlate with the QPROP verification points are as follows:

**Table 5: PROPDES Validation Test Cases**

<b>Run #</b>	<b>Blades</b>	<b>Diameter (Inches)</b>	<b>RPM</b>	<b>Velocity (KIAS)</b>	<b>Power (HP)</b>
PV1	2	9	6000	40	1
PV2	2	11	4000	15	1
PV3	2	11	4000	25	1
PV4	2	11	4000	50	1
PV5	2	18	4500	45	1
PV6	2	19	3000	40	1

Each of the above points will be ran in PROPDES and in QMIL's native FORTRAN format. The PROPDES results will then be compared with the QPROP verification analysis to see if any of these cases provide a propeller design that is superior to that of the APC propeller distributions at these specific design points. The results will be discussed in Chapter VI and the raw output files are given in Appendix E.

### 5.3 – Further Testing

The goal of testing PROPDES further is to conduct a more diverse sensitivity analysis in an effort to further determine the limitations on PROPDES. Limitations captured here will be due to the inability of PROPDES to complete a run and will not determine the accuracy of the PROPDES results. In order to obtain accuracy data, each PROPDES result would need to be manufactured and tested in a wind tunnel so that experimental data would then be available for comparison.

Several design points will be used to better understand any sensitivities and limitations that exist for the number of blades, diameter, velocity, and RPM inputs (Chord and Beta are not chosen here since QMIL will be used to establish the propeller geometry for the MIL condition at each design point.) The ranges for each variable were selected as follows:

**Table 6: Variable Ranges for Further Test Cases**

	<b>Blades</b>	<b>Velocity (KIAS)</b>	<b>Diameter (Inches)</b>	<b>RPM</b>
<b>Ranges:</b>	2-6	20 - 60	8 – 24	2000 - 6000
<b>Points:</b>	2, 4, 6	20, 40, 60	8, 16, 24	2000, 4000, 6000

The assumptions used for performing the Further Testing portion are as follows:

- Hub Diameter = 10% Propeller Diameter
- Power Available = 1 Horsepower
- Air Properties were constant and equal to standard atmosphere (Rho, Mu, a)
- Clark Y Airfoil Used

The design points chosen are shown in the following table:

**Table 7: Further Test Case Design Points**

<b>Design Cases</b>	<b>Blades</b>	<b>Velocity (KIAS)</b>	<b>Diameter (Inches)</b>	<b>RPM</b>	<b>Advance Ratio (J)</b>
1	2	20	8	2000	1.5183
2	2	20	8	4000	0.75915
3	2	20	8	6000	0.5061
4	2	20	16	2000	0.75915
5	2	20	16	4000	0.379575
6	2	20	16	6000	0.25305
7	2	20	24	2000	0.5061
8	2	20	24	4000	0.25305
9	2	20	24	6000	0.1687
10	2	40	8	2000	3.0366
11	2	40	8	4000	1.5183
12	2	40	8	6000	1.0122
13	2	40	16	2000	1.5183
14	2	40	16	4000	0.75915
15	2	40	16	6000	0.5061
16	2	40	24	2000	1.0122
17	2	40	24	4000	0.5061
18	2	40	24	6000	0.3374
19	2	60	8	2000	4.5549
20	2	60	8	4000	2.27745
21	2	60	8	6000	1.5183
22	2	60	16	2000	2.27745
23	2	60	16	4000	1.138725

Design Cases	Blades	Velocity (KIAS)	Diameter (Inches)	RPM	Advance Ratio (J)
24	2	60	16	6000	0.75915
25	2	60	24	2000	1.5183
26	2	60	24	4000	0.75915
27	2	60	24	6000	0.5061
28	4	20	8	2000	1.5183
29	4	20	8	4000	0.75915
30	4	20	8	6000	0.5061
31	4	20	16	2000	0.75915
32	4	20	16	4000	0.379575
33	4	20	16	6000	0.25305
34	4	20	24	2000	0.5061
35	4	20	24	4000	0.25305
36	4	20	24	6000	0.1687
37	4	40	8	2000	3.0366
38	4	40	8	4000	1.5183
39	4	40	8	6000	1.0122
40	4	40	16	2000	1.5183
41	4	40	16	4000	0.75915
42	4	40	16	6000	0.5061
43	4	40	24	2000	1.0122
44	4	40	24	4000	0.5061
45	4	40	24	6000	0.3374
46	4	60	8	2000	4.5549
47	4	60	8	4000	2.27745
48	4	60	8	6000	1.5183
49	4	60	16	2000	2.27745
50	4	60	16	4000	1.138725
51	4	60	16	6000	0.75915
52	4	60	24	2000	1.5183
53	4	60	24	4000	0.75915
54	4	60	24	6000	0.5061
55	6	20	8	2000	1.5183
56	6	20	8	4000	0.75915
57	6	20	8	6000	0.5061
58	6	20	16	2000	0.75915
59	6	20	16	4000	0.379575
60	6	20	16	6000	0.25305
61	6	20	24	2000	0.5061
62	6	20	24	4000	0.25305
63	6	20	24	6000	0.1687
64	6	40	8	2000	3.0366
65	6	40	8	4000	1.5183
66	6	40	8	6000	1.0122
67	6	40	16	2000	1.5183
68	6	40	16	4000	0.75915
69	6	40	16	6000	0.5061
70	6	40	24	2000	1.0122

<b>Design Cases</b>	<b>Blades</b>	<b>Velocity (KIAS)</b>	<b>Diameter (Inches)</b>	<b>RPM</b>	<b>Advance Ratio (J)</b>
71	6	40	24	4000	0.5061
72	6	40	24	6000	0.3374
73	6	60	8	2000	4.5549
74	6	60	8	4000	2.27745
75	6	60	8	6000	1.5183
76	6	60	16	2000	2.27745
77	6	60	16	4000	1.138725
78	6	60	16	6000	0.75915
79	6	60	24	2000	1.5183
80	6	60	24	4000	0.75915
81	6	60	24	6000	0.5061

These results of these test cases will be captured in a test data sheet and will be discussed in Chapter VI.

## CHAPTER VI

### RESULTS AND CONCLUSIONS

#### 6.1 – General Findings

The test cases were ran using PROPDES per the discussion in Chapter V. Overall, the QPROP predictions appear to be fairly reasonable when limited to the first half of the propeller efficiency curve from  $J = 0$  to  $J$  at maximum efficiency. The propellers tested with the smallest Pitch:Diameter ratio show the greatest percent differences for the CT, CP and Efficiency predictions compared to wind tunnel test data.

When limiting the data to the first half of the efficiency curve, the worst estimations for the thrust and power coefficients were within 22% with the majority within 10%. Additionally, the worst efficiency estimate was 8.11% with most around 5%. Further investigation is needed to determine if a relationship exists between any of the propeller variables and QPROP's prediction accuracy.

An additional finding was made regarding the CT, CP, and Advance Ratio definitions used by QPROP/QMIL and the differences in those equations used by OSU and UIUC in published wind tunnel results. This finding is discussed in detail in the following sections.

Overall, PROPDES does provide a decent estimation tool for UAV propellers, however more research is needed to improve the estimations for the ranges of variables tested in the current work.

### 6.1.1 – QPROPs use of Non-Standard Coefficients

During initial testing and review of PROPDES, it became evident that there were issues when directly comparing the QPROP outputs with wind tunnel data. Upon further investigation, it was found that QPROP uses slightly different defining equations than UIUC and OSU for the coefficients of Thrust and Power as well as the advance ratio. These equations used by QPROP are given by Drela in the qprop\_doc.txt file delivered in the QPROP folder when downloaded from Drela’s QPROP website.

[\(http://web.mit.edu/drela/Public/web/qprop/\)](http://web.mit.edu/drela/Public/web/qprop/)

In each of the subsections, CT, CP, and J are broken down and defined in terms of how QPROP outputs these values versus how literature (particularly the UIUC propeller database since that was the primary source of wind tunnel data used in the QPROP verification testing) defines these terms. The final equations in each of these subsections has been incorporated into the PROPDES worksheets so that the charts and test data were all reported using the UIUC definitions. A “cheat sheet” or quick reference card was developed to show the relationship between these values as well as to identify the QPROP outputs that were a function of motor parameters and therefore were not applicable to PROPDES (since PROPDES utilizes a standard motor file). This cheat sheet is attached as Appendix A.

Table 8 below shows the conversions necessary for CT, CP, and the advance ratio:

**Table 8: Conversions Required to Compare Wind Tunnel Data to QPROP Outputs**

Variable	QPROP	Multiply QPROP by:	UIUC
Thrust Coeff, CT	$\frac{T}{\frac{1}{2}\rho(\omega R)^2\pi R^2}$	$\frac{\pi^3}{8}$	$\frac{T}{\rho n^2 D^4}$
Power Coeff, CP	$\frac{Q}{\frac{1}{2}\rho(\omega R)^2\pi R^3}$	$\frac{\pi^4}{8}$	$\frac{2\pi Q}{\rho n^2 D^5}$
Prop Efficiency, Eta	$\frac{TV}{Q\Omega}$	1	$\frac{TV}{P}$
Advance Ratio, J	$\frac{V}{\omega R}$	$\pi$	$\frac{V}{nD}$



6.1.1.1 – Coefficient of Thrust

QPROP

$$CT_Q = \frac{T}{\frac{1}{2}\rho(\omega R)^2\pi R^2}$$

$$= \frac{T}{\frac{1}{2}\rho\omega^2\pi R^4}$$

$$R = \frac{1}{2}D, R^4 = \left(\frac{1}{2}D\right)^4 = \frac{1}{16}D^4$$

$$CT_Q = \frac{T}{\frac{1}{32}\rho\omega^2\pi D^4}$$

Divide both sides by  $CT_Q$ :

$$1 = \frac{32\frac{1}{CT_Q}T}{\rho\omega^2\pi D^4}$$

Set these equations equal to each other and solve for  $CT_U$ :

$$\frac{32\frac{1}{CT_Q}T}{\rho\omega^2\pi D^4} = \frac{4\frac{1}{CT_U}\pi^2 T}{\rho\omega^2 D^4}$$

$$\frac{32\frac{1}{CT_Q}}{\pi} = 4\frac{1}{CT_U}\pi^2$$

$$\frac{1}{CT_Q} = \frac{\pi^3}{8CT_U}$$

Multiply both sides by  $CT_Q CT_U$ :

$$CT_U = \frac{\pi^3}{8}CT_Q$$

UIUC

$$CT_U = \frac{T}{\rho n^2 D^4}$$

$$n = \frac{\omega}{2\pi}, n^2 = \frac{\omega^2}{4\pi^2}$$

$$CT_U = \frac{T}{\rho\omega^2/4\pi^2 D^4}$$

$$CT_U = \frac{4\pi^2 T}{\rho\omega^2 D^4}$$

Divide both sides by  $CT_U$ :

$$1 = \frac{4\frac{1}{CT_U}\pi^2 T}{\rho\omega^2 D^4}$$

Therefore QPROP's definition of CT must be multiplied by a factor of  $\frac{\pi^3}{8}$  in order to compare the QPROP CT with the UIUC database. This factor was added to the PROPDES output worksheets.

#### 6.1.1.2 – Coefficient of Power

##### QPROP

$$CP_Q = \frac{Q}{1/2\rho(\omega R)^2\pi R^3}$$

$$CP_Q = \frac{Q}{1/2\rho\omega^2\pi R^5}$$

$$R = 1/2 D, R^5 = (1/2 D)^5 = 1/32 D^5$$

$$CP_Q = \frac{Q}{1/64\rho\omega^2\pi D^4}$$

Divide both sides by  $CP_Q$ :

$$1 = \frac{64\frac{1}{CP_Q}Q}{\rho\omega^2\pi D^5}$$

Set these equations equal to each other and solve for  $CT_U$ :

$$\frac{8\frac{1}{CP_Q}}{\pi} = \frac{1}{CP_U}\pi^3$$

$$\frac{1}{CP_Q} = \frac{1}{CP_U} \frac{\pi^4}{8}$$

Multiply both sides by  $CP_Q CP_U$ :

$$\boxed{CP_U = \frac{\pi^4}{8} CP_Q}$$

Therefore QPROP's definition of CP must be multiplied by a factor of  $\frac{\pi^4}{8}$  in order to compare the QPROP CP with the UIUC database. This factor was added to the PROPDES output worksheets.

##### UIUC

$$CP_U = \frac{2\pi Q}{\rho n^2 D^5}$$

$$n = \frac{\omega}{2\pi}, n^2 = \frac{\omega^2}{4\pi^2}$$

$$CP_U = \frac{2\pi Q}{\rho\omega^2/4\pi^2 D^5}$$

$$CP_U = \frac{8\pi^3 Q}{\rho\omega^2 D^5}$$

Divide both sides by  $CP_U$ :

$$1 = \frac{8\frac{1}{CP_U}\pi^3 Q}{\rho\omega^2 D^5}$$

### 6.1.1.3 – Advance Ratio

#### QPROP

$$J_Q = \frac{V}{\omega R}$$

$$R = \frac{1}{2} D$$

$$J_Q = \frac{V}{\omega(\frac{1}{2}D)}$$

$$J_Q = \frac{2V}{\omega D}$$

Divide both sides by  $J_Q$ :

$$1 = \frac{2\frac{1}{2}V}{\omega D}$$

Set these equations equal to each other and solve for  $CT_U$ :

$$\frac{2\frac{1}{2}V}{\omega D} = \frac{2\pi\frac{1}{2}V}{\omega D}$$

$$\frac{1}{J_Q} = \pi \frac{1}{J_U}$$

Multiply both sides by  $J_Q J_U$ :

$$J_U = \pi J_Q$$

Therefore QPROP's definition of the advance ratio must be multiplied by a factor of  $\pi$  in order to compare the QPROP  $J$  with the UIUC database. This factor was added to the PROPDES output worksheets.

## 6.2 – QPROP Verification (QV) Results

Each of the test cases listed in Table 4 on page 81 were performed and the results are presented in this paragraph.

### 6.2.1 – Static QPROP Verification Results

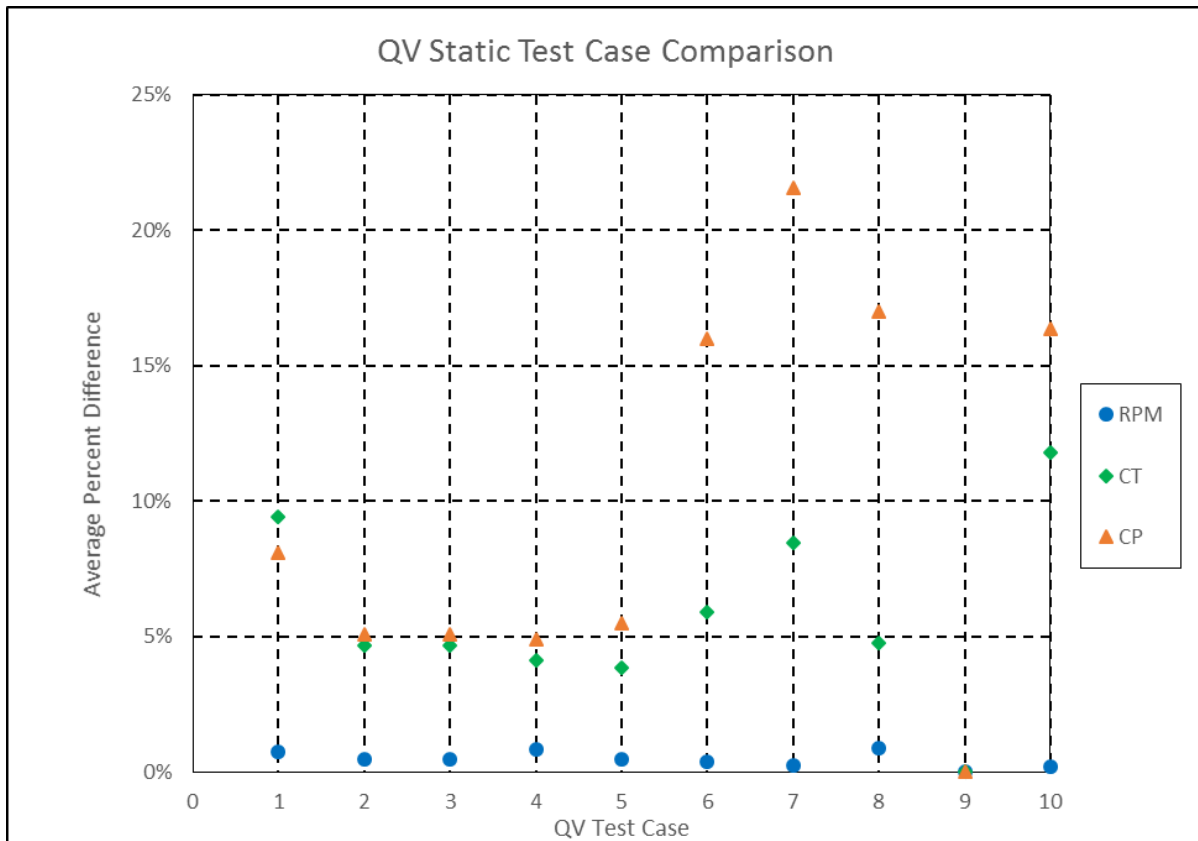
The QPROP static predictions were compared with the experimental results published by Brandt on the UIUC propeller database site.  $CT$  and  $CP$  at each RPM data point given in the experimental data was

compared to the corresponding QPROP CT and CP predictions for that respective RPM. The summary is given below as well as an example of the test data sheet for the static QV runs. The complete static QV test sheets can be found in Appendix D.

**Table 9: QV Static Test Case Comparison**

QV Static Test Case Comparison			
Run	RPM	CT	CP
QV1	0.76%	9.43%	8.12%
QV2	0.48%	4.68%	5.08%
QV3	0.48%	4.68%	5.08%
QV4	0.85%	4.11%	4.91%
QV5	0.47%	3.87%	5.49%
QV6	0.39%	5.90%	16.00%
QV7	0.27%	8.47%	21.55%
QV8	0.87%	4.77%	17.01%
QV9*	N/A	N/A	N/A
QV10	0.18%	11.80%	16.38%

\*Gamble did not present static data so no comparison is made for QV9



**Figure 46: QV Static Test Case Comparison**

Figure 46 shows that the static cases for QV2 – QV5 were predicted very well by QPROP (within approximately 5%). These test cases correspond to the APC11x5.5 – APC11x8.5 propellers. Here is a slightly higher disagreement with QV1 (APC9x4.5). CT values are predicted within roughly 10% for all cases however the CP predictions were under-predicted by an average of more than 15% for QV7-10. It is not apparent from the above data that the QPROP results are under-predictions of the experimental data but that can be observed by looking at each QV static test data sheet. The QV7 static test data sheet is given below as an example:

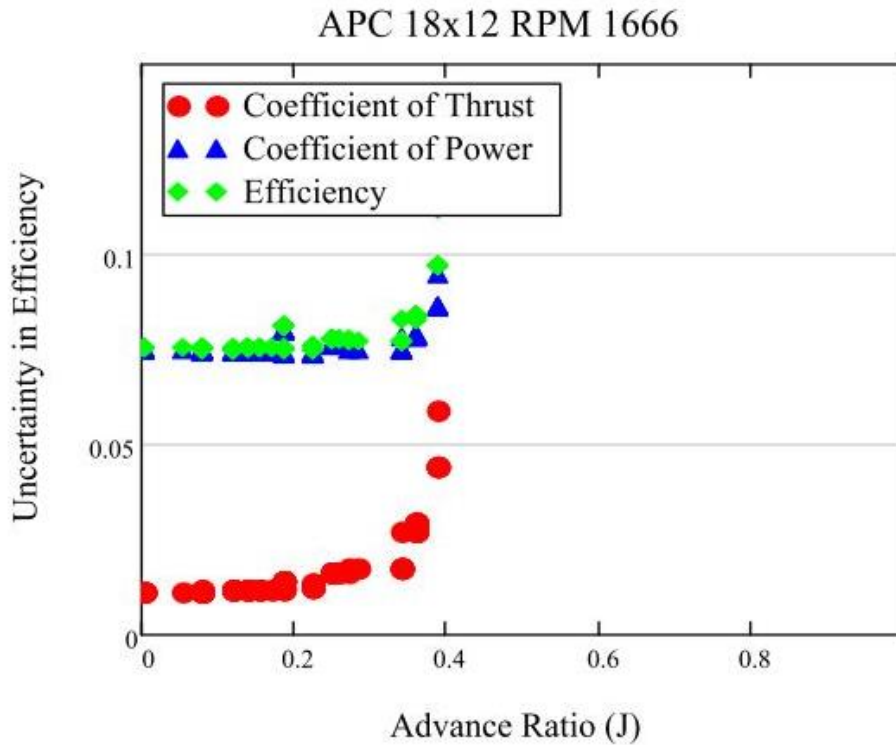
**Table 10: QV7 Static Run Test Data Sheet**

Static Run QV7 - APC - Diameter: 14" - Pitch: 12" - Blades: 2 - UIUC											
Experimental Data			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
1496	0.0868	0.0623	1496	0.08186	0.05133	0	0.00494	0.01097	0.00%	5.70%	17.60%
1636	0.0866	0.0618	1630	0.08186	0.05090	6	0.00474	0.01090	0.37%	5.48%	17.64%
1741	0.0877	0.0628	1764	0.08190	0.05052	23	0.00580	0.01228	1.32%	6.62%	19.56%
1904	0.0881	0.0624	1898	0.08193	0.05018	6	0.00617	0.01222	0.32%	7.00%	19.59%
2036	0.0881	0.0622	2032	0.08193	0.04987	4	0.00617	0.01233	0.20%	7.00%	19.82%
2172	0.0892	0.0623	2166	0.08197	0.04961	6	0.00723	0.01269	0.28%	8.10%	20.38%
2302	0.0892	0.0626	2300	0.08197	0.04935	2	0.00723	0.01325	0.09%	8.10%	21.17%
2444	0.0895	0.0625	2434	0.08197	0.04912	10	0.00753	0.01338	0.41%	8.41%	21.41%
2574	0.0898	0.0626	2568	0.08201	0.04891	6	0.00779	0.01369	0.23%	8.67%	21.87%
2706	0.0901	0.0627	2702	0.08201	0.04872	4	0.00809	0.01398	0.15%	8.98%	22.30%
2842	0.0902	0.0626	2836	0.08205	0.04853	6	0.00815	0.01407	0.21%	9.04%	22.47%
2972	0.0909	0.0631	2970	0.08205	0.04836	2	0.00885	0.01474	0.07%	9.74%	23.35%
3115	0.0912	0.0633	3104	0.08205	0.04821	11	0.00915	0.01509	0.35%	10.03%	23.85%
3244	0.0916	0.0635	3238	0.08209	0.04806	6	0.00951	0.01544	0.18%	10.38%	24.32%
3376	0.0919	0.0634	3372	0.08209	0.04793	4	0.00981	0.01547	0.12%	10.68%	24.41%
3506	0.0929	0.0638	3506	0.08209	0.04779	0	0.01081	0.01601	0.00%	11.64%	25.09%
<b>Max:</b>									1.32%	11.64%	25.09%
<b>Average:</b>									0.27%	8.47%	21.55%

### 6.2.2 – Dynamic QPROP Verification Results

The QPROP dynamic predictions were compared with the experimental results published by Brandt and Gamble. CT, CP, and efficiency at each advance ratio data point given in the experimental data were

compared to the corresponding QPROP CT, CP and efficiency prediction for that respective advance ratio. When making these comparisons, it is important to note that Brandt reported a maximum variation in an individual calibration slope of 2% in any given test series however Gamble showed that the uncertainty in the OSU wind tunnel increases with an increase in the advance ratio as shown below.



**Figure 47: Reported Uncertainty for APC 18x12 at 1666 RPM - QV9 (Gamble)**

Figure 47 shows a sharp increase in uncertainty at  $J = 0.4$  which could correspond to the difference in experimental efficiency to PROPDES predicted efficiency for the QV9 test case shown in Figure 48 below.

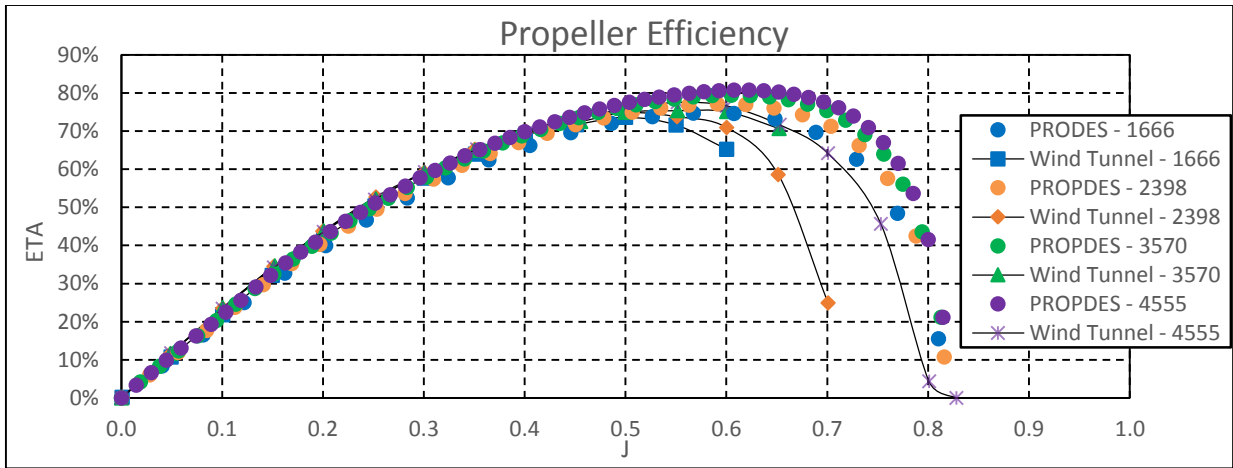


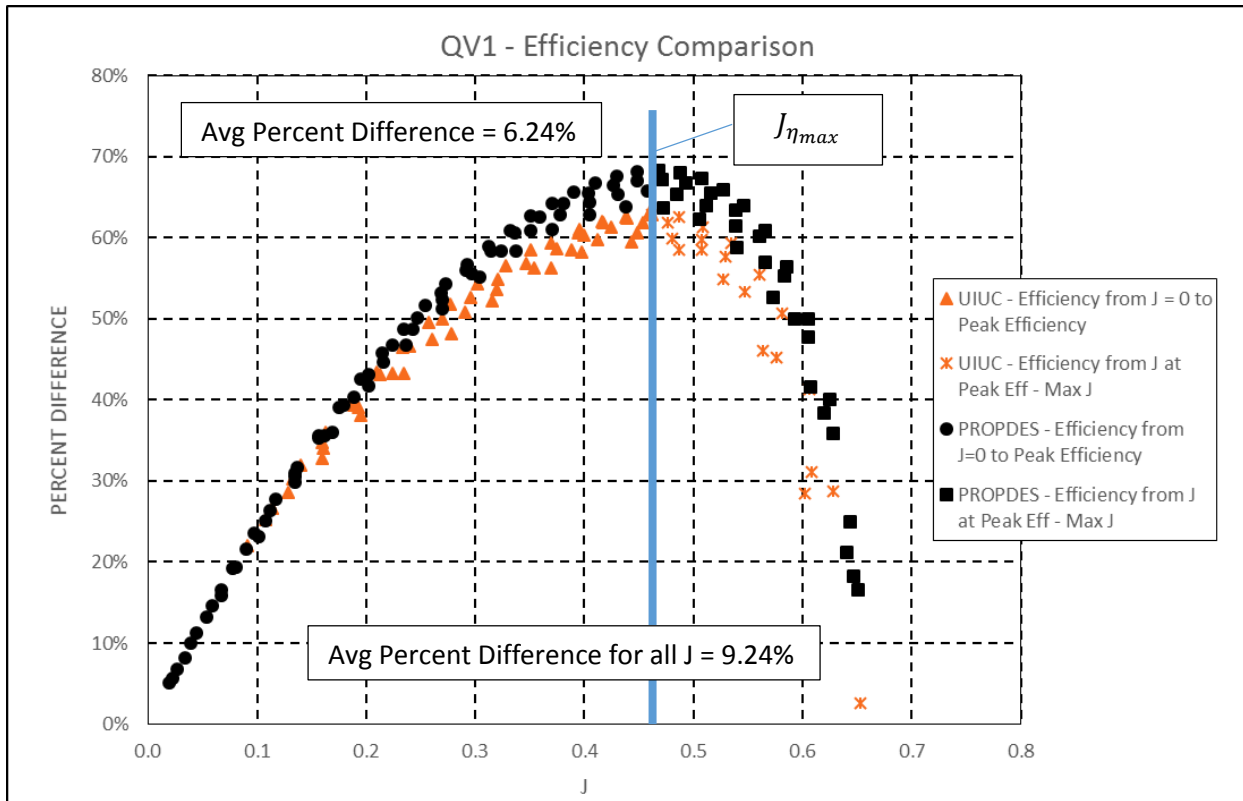
Figure 48: QV9 Efficiency Results

A summary of the dynamic QV test cases is given below as well as an example of the test data sheet for these runs. The complete dynamic QV test sheets can be found in Appendix D.

#### 6.2.2.1 – Comparing the Advance Ratio at Maximum Efficiency

One of the first observations captured during testing was that the predictions provided by QPROP worsen greatly after the advance ratio corresponding to the point of maximum efficiency. This observation is due to QPROP over-predicting the efficiency of the propeller and is compounded by the advance ratio at maximum efficiency  $J_{\eta_{max}}$  to also be over-predicted by QPROP. The slight shift in both the efficiency and the advance ratio causes the second half of the efficiency curve to be over-predicted.

Figure 49 shows an example of the efficiency curve comparison between the QPROP predicted values and the wind tunnel values with the  $J_{\eta_{max}}$  being equal for both cases but the peak efficiency is over-predicted by QPROP by approximately 8%.



**Figure 49: Example of Accuracy Difference based on Advance Ratio Curve (QV1)**

The shift in  $J_{\eta_{max}}$  is better shown in Figure 50. Notice that  $J_{\eta_{max}}$  for the experimental data is approximately 0.59 and the  $J_{\eta_{max}}$  for the QPROP predicted data is 0.77 for a difference of 0.18. This shift in the curve greatly impacts the accuracy of the QPROP predictions after  $J_{\eta_{max}} = 0.59$ .



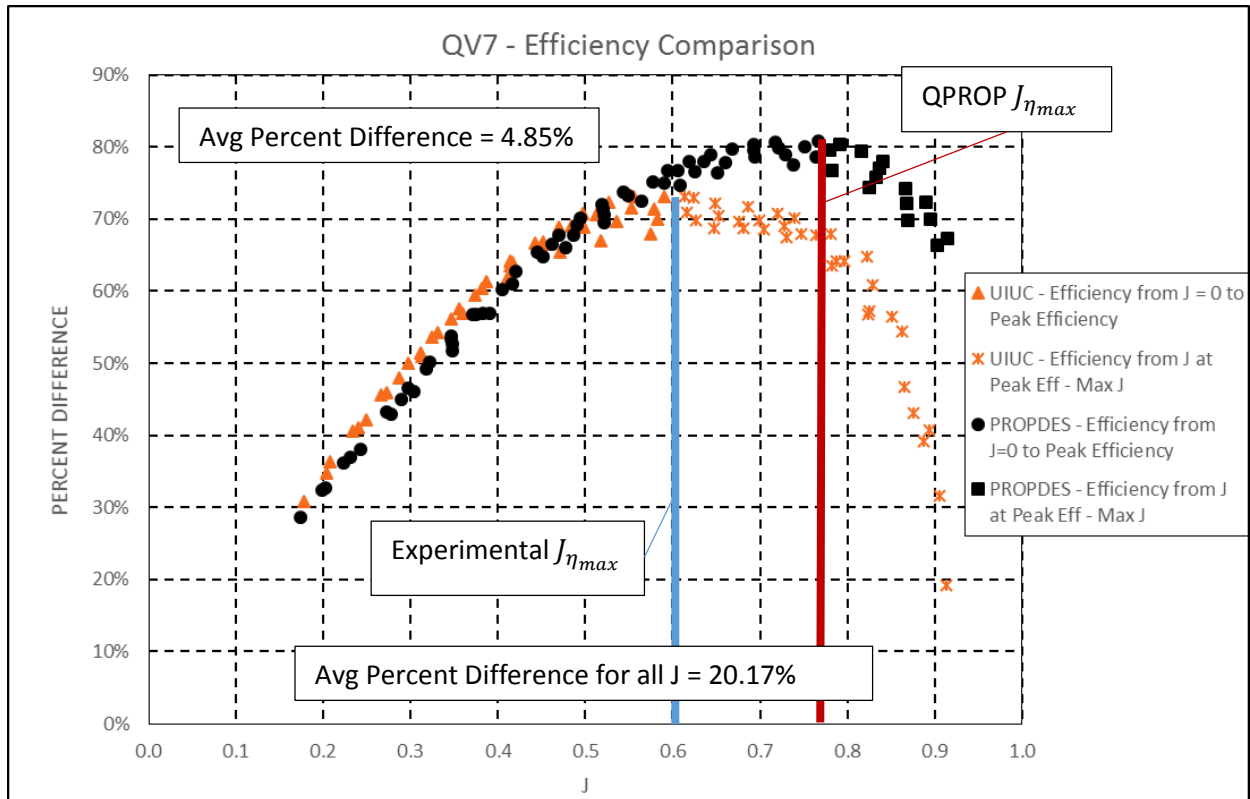


Figure 50: Example of Accuracy Difference based on Difference in  $J_{\eta_{max}}$  (QV7)

All of the QV results were examined for difference in accuracies based on the  $J_{\eta_{max}}$  values for the experimental data as well as the QPROP predictions. The following tables show how the average percent differences increase if only the data from  $J = 0$  to  $J$  at QPROP  $J_{\eta_{max}}$ . An additional improvement is seen by limiting the advance ratio further to  $J = 0$  to  $J$  at Experimental  $J_{\eta_{max}}$ .

Table 11: QV - Average Percent Differences (All J)

Averages with all J				
	J	CT	CP	Eta
QV1	2.06%	39.17%	11.56%	20.76%
QV2	1.97%	46.60%	16.06%	22.88%
QV3	1.73%	44.96%	17.01%	21.10%
QV4	1.78%	25.60%	11.91%	11.75%
QV5	1.62%	56.52%	11.21%	30.97%
QV6	1.56%	42.47%	16.07%	21.38%
QV7	1.58%	37.97%	12.51%	20.17%
QV8	1.49%	68.14%	10.40%	44.97%
QV9	3.94%	31.17%	14.61%	26.59%

<b>Averages with all J</b>				
	<b>J</b>	<b>CT</b>	<b>CP</b>	<b>Eta</b>
<b>QV10</b>	<b>1.56%</b>	<b>19.05%</b>	<b>21.74%</b>	<b>7.62%</b>

**Table 12: QV - Average Percent Differences (J=0 to J at QPROP Peak Efficiency)**

<b>Averages with J =0 to J at PROPDES Peak Eta</b>				
	<b>J</b>	<b>CT</b>	<b>CP</b>	<b>Eta</b>
<b>QV1</b>	<b>2.33%</b>	<b>13.73%</b>	<b>7.64%</b>	<b>6.24%</b>
<b>QV2</b>	<b>2.12%</b>	<b>17.19%</b>	<b>9.79%</b>	<b>8.11%</b>
<b>QV3</b>	<b>1.98%</b>	<b>10.98%</b>	<b>9.43%</b>	<b>4.97%</b>
<b>QV4</b>	<b>1.98%</b>	<b>7.78%</b>	<b>5.81%</b>	<b>4.57%</b>
<b>QV5</b>	<b>1.85%</b>	<b>7.79%</b>	<b>5.74%</b>	<b>4.69%</b>
<b>QV6</b>	<b>1.77%</b>	<b>8.47%</b>	<b>8.67%</b>	<b>6.69%</b>
<b>QV7</b>	<b>1.82%</b>	<b>13.73%</b>	<b>6.92%</b>	<b>7.20%</b>
<b>QV8</b>	<b>1.69%</b>	<b>8.07%</b>	<b>6.15%</b>	<b>3.97%</b>
<b>QV9</b>	<b>4.44%</b>	<b>15.23%</b>	<b>12.01%</b>	<b>6.18%</b>
<b>QV10</b>	<b>1.78%</b>	<b>18.59%</b>	<b>22.05%</b>	<b>4.30%</b>

**Table 13: QV - Average Percent Differences (J=0 to J at Experimental Peak Efficiency)**

<b>Averages with J =0 to J at Wind Tunnel Peak Eta</b>				
	<b>J</b>	<b>CT</b>	<b>CP</b>	<b>Eta</b>
<b>QV1</b>	<b>2.33%</b>	<b>13.73%</b>	<b>7.64%</b>	<b>6.24%</b>
<b>QV2</b>	<b>2.12%</b>	<b>17.19%</b>	<b>9.79%</b>	<b>8.11%</b>
<b>QV3</b>	<b>2.10%</b>	<b>9.45%</b>	<b>8.59%</b>	<b>4.73%</b>
<b>QV4</b>	<b>2.02%</b>	<b>6.56%</b>	<b>5.08%</b>	<b>4.46%</b>
<b>QV5</b>	<b>1.98%</b>	<b>5.16%</b>	<b>4.42%</b>	<b>3.84%</b>
<b>QV6</b>	<b>2.03%</b>	<b>4.17%</b>	<b>6.70%</b>	<b>6.43%</b>
<b>QV7</b>	<b>2.05%</b>	<b>7.84%</b>	<b>4.33%</b>	<b>4.85%</b>
<b>QV8</b>	<b>1.75%</b>	<b>6.83%</b>	<b>5.71%</b>	<b>3.04%</b>
<b>QV9</b>	<b>5.03%</b>	<b>14.43%</b>	<b>10.96%</b>	<b>6.20%</b>
<b>QV10</b>	<b>1.78%</b>	<b>18.59%</b>	<b>22.05%</b>	<b>4.30%</b>

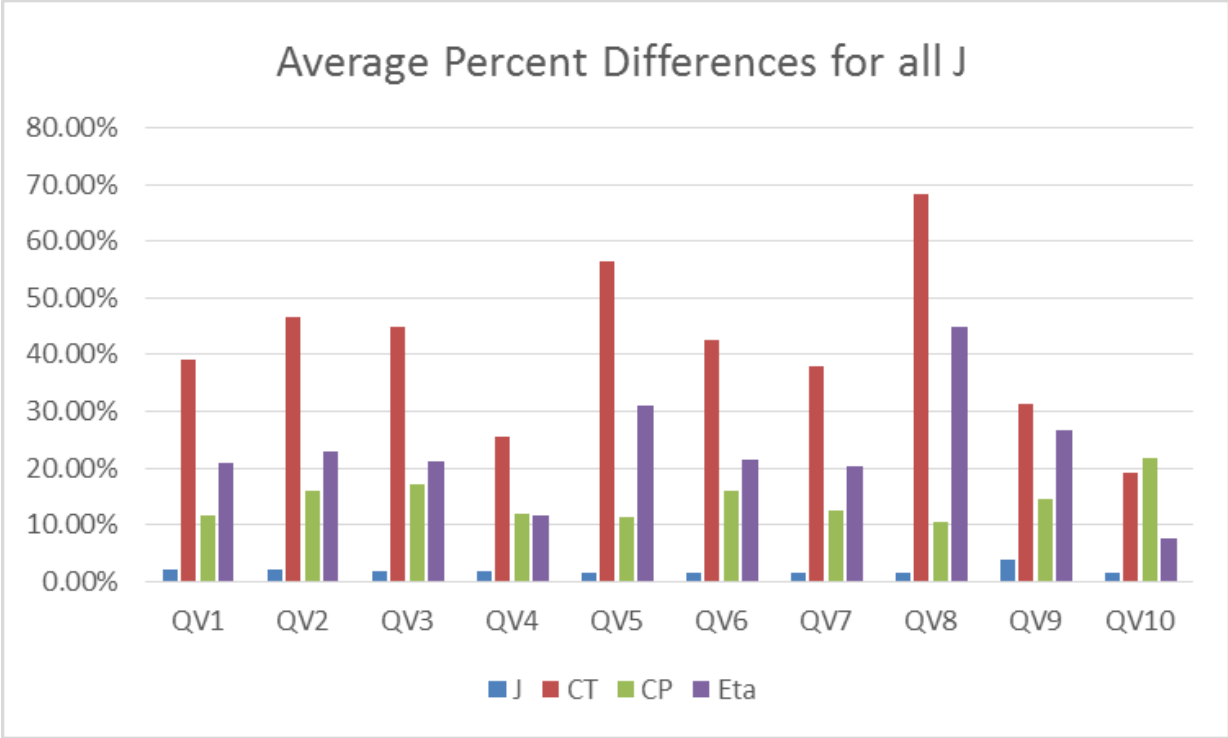


Figure 51: QV - Average Percent Differences for all J

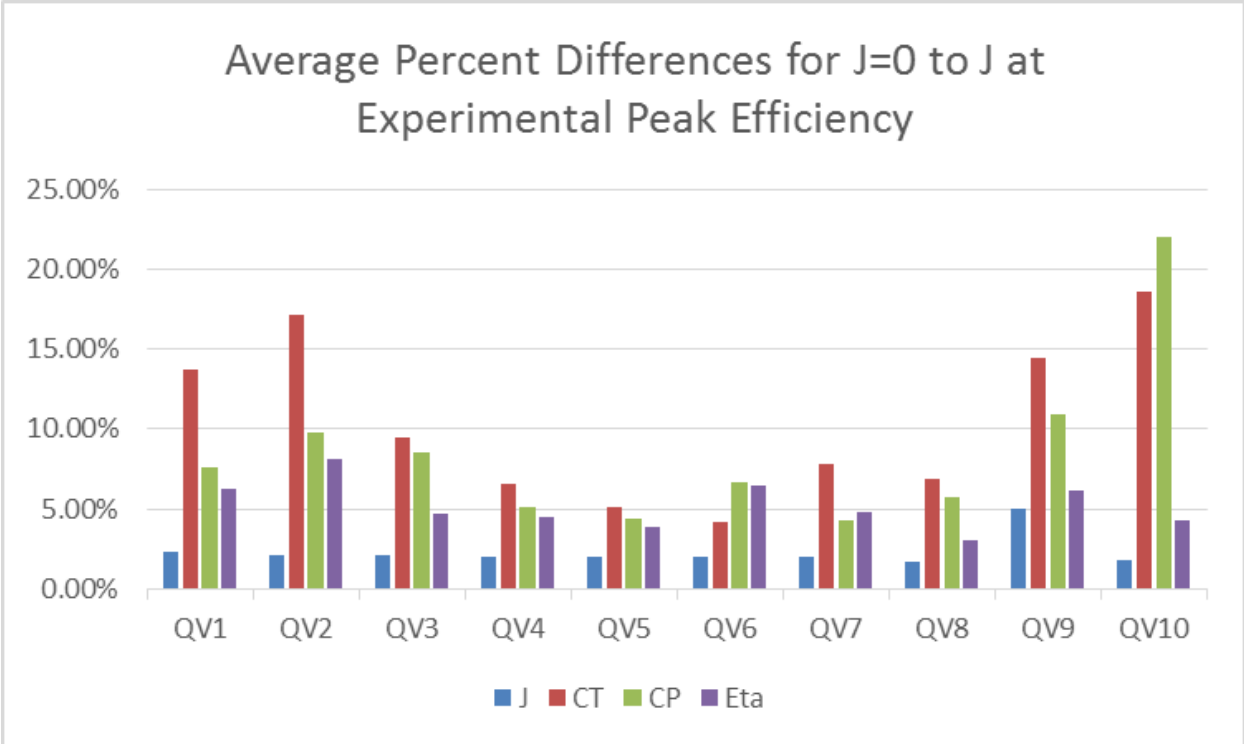


Figure 52: QV - Average Percent Difference for J = 0 to J at Experimental Peak Efficiency

Figure 52 shows that the QPROP estimated efficiency is very reasonable (within 8%) for each of the test cases when only concerned with the first portion of the efficiency curve. However, CT and CP predictions vary as much as 22% even in this limited range of data.

#### 6.2.2.2 – Effects of P/D on the QPROP/PROPDES Predictions

When examining Figure 52 it is interesting to note that QV1 and QV2 consisted of very low pitch values (4.5 and 5.5 respectively) and the accuracy of the CT predictions suffered. Additionally, QV9 and QV10 showed greater disparity between the predicted CT and CP values and the experimental data. These runs had the same pitch as QV7 and QV8 (12” pitch) however the diameter grew to 18” and 19” respectively. This change in diameter would result in a change to the Pitch to Diameter ratio (P/D). The P/D’s for each run are compared to the percent differences for CT, CP, and Efficiency in the following table:

**Table 14: QV P/D Compared to Average Percent Difference**

Run	Diameter	Pitch	P/D	CT Average Percent Difference	CP Average Percent Difference	Eta Average Percent Difference
QV1	9	4.5	0.5	13.73%	7.64%	6.24%
QV2	11	5.5	0.5	17.19%	9.79%	8.11%
QV3	11	7	0.636364	9.45%	8.59%	4.73%
QV4	11	8	0.727273	6.56%	5.08%	4.46%
QV5	11	8.5	0.772727	5.16%	4.42%	3.84%
QV6	11	10	0.909091	4.17%	6.70%	6.43%
QV7	14	12	0.857143	7.84%	4.33%	4.85%
QV8	17	12	0.705882	6.83%	5.71%	3.04%
QV9	18	12	0.666667	14.43%	10.96%	6.20%
QV10	19	12	0.631579	18.59%	22.05%	4.30%

Table 14 shows that there may be a correlation to P/D and the error in the QPROP estimated CT. When P/D falls below 0.7, the average percent difference grows to 9% or more. Other factors play a role as well since the percent errors are vastly different for QV3 and QV10 despite having very similar P/D values. However, this data does seem to indicate a trend with regard to P/D. By examining QV2-QV6, which all have the same diameter but pitch increases with each test case, one will find that the percent difference

for the CT estimate gets better as the pitch increases for that specific diameter. Likewise, if one examines QV7-QV10, which all have the same pitch but the diameter increases, one will find that the percent difference increases as the diameter increases for that particular pitch (with the exception of QV8).

Figure 53 below shows the relationship between the average percent differences of each of the PROPDES estimated propeller coefficients and the Pitch:Diameter ratio. It is very evident that the P/D of 0.7 or above are much more accurate.

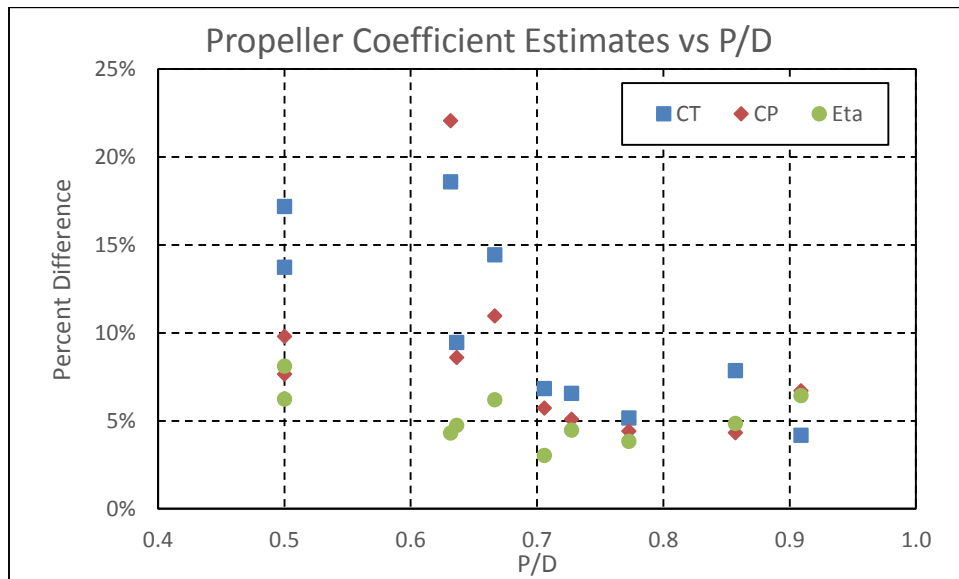


Figure 53: PROPDES Estimates vs Pitch/Diameter

Nothing further has been done to quantify the relationship between P/D and the percent differences of the QPROP estimations but it is an interesting finding that should be researched further to determine more precisely what kind of relationship exists and what the effects of even higher P/D propellers would be to the accuracy of the QPROP model.

### 6.2.2.3 – Comparing QPROP/PROPDES Results with Experimental Results

Returning to the concepts outlined in Figure 50, instead of simply looking at the first half of the efficiency curve (as discussed in Section 6.2.2.1), a comparison can also be made by highlighting the maximum efficiency values for each case and comparing the predicted values to the experimental values.

**Table 15: QV Maximum Efficiency Percent Difference**

Test Run	PROPDES		Wind Tunnel		Percent Difference	
	Max Eff	J	Max Eff	J	Max Eff	J
QV1	68.30%	0.468	62.80%	0.462	8.76%	1.30%
QV2	70.43%	0.460	69.00%	0.464	2.07%	0.86%
QV3	76.90%	0.608	71.60%	0.566	7.40%	7.42%
QV4	78.58%	0.644	75.20%	0.593	4.49%	8.62%
QV5	79.69%	0.699	73.90%	0.615	7.83%	13.72%
QV6	82.07%	0.823	76.20%	0.668	7.70%	23.20%
QV7	80.76%	0.767	73.20%	0.590	10.33%	29.98%
QV8	80.10%	0.671	75.70%	0.597	5.81%	12.41%
QV9	80.74%	0.607	77.55%	0.552	4.11%	10.04%
QV10	77.00%	0.532	73.50%	0.552	4.76%	3.71%

Table 15 shows the result of comparing the QPROP/PROPDES estimated maximum efficiency with the maximum efficiency of the wind tunnel experimental data. While the maximum efficiency is only off by approximately 10%, it is important to note the difference in the advance ratio at the maximum efficiency ( $J_{\eta_{max}}$ ) of nearly 30% in one case and over 10% in 5 of the test cases.

One additional comparison can be made by examining the  $J_{\eta_{max}}$  of the experimental value and retrieving the efficiency value for that advance ratio from the PROPDES/QPROP results. Performing this comparison results in very good agreement between experimental data and the QPROP/PROPDES results, which further bolsters the case for only comparing the front half of the efficiency curve. These results are provided in the following table:

**Table 16: Comparing QPROP/PROPDES Efficiency Estimations at the Experimental  $J_{\eta_{max}}$**

Test Run	PROPDES		Wind Tunnel		Percent Difference	
	Eff @ $J_{\eta_{max}}$	J	Eff @ $J_{\eta_{max}}$	J	Eff @ $J_{\eta_{max}}$	J
QV1	67.16%	0.471	62.80%	0.462	6.94%	1.95%
QV2	68.99%	0.464	69.00%	0.464	0.01%	0.00%
QV3	75.56%	0.575	71.60%	0.566	5.53%	1.59%
QV4	76.76%	0.596	75.20%	0.593	2.07%	0.51%
QV5	77.46%	0.618	73.90%	0.615	4.82%	0.49%
QV6	76.63%	0.663	76.20%	0.668	0.56%	0.75%
QV7	74.97%	0.590	73.20%	0.590	2.42%	0.00%

<b>QV8</b>	<b>77.69%</b>	<b>0.599</b>	<b>75.70%</b>	<b>0.597</b>	<b>2.63%</b>	<b>0.34%</b>
<b>QV9</b>	<b>79.48%</b>	<b>0.548</b>	<b>77.55%</b>	<b>0.552</b>	<b>2.49%</b>	<b>0.72%</b>
<b>QV10</b>	<b>76.98%</b>	<b>0.553</b>	<b>73.50%</b>	<b>0.552</b>	<b>4.73%</b>	<b>0.13%</b>

Table 16 shows the results for the first half of the experimental efficiency curves. While this is important, it is not as useful when using PROPDES since the user will not know exactly where the experimental efficiency curve will peak. In order to address this issue, Table 17 has been created below to show the percent differences for the PROPDES predicted peak efficiency compared to the experimental efficiency value at the corresponding advance ratio. PROPDES still does a decent job of predicting the max efficiency, however a degradation can be seen with the worst test case (QV7) being over-predicted by PROPDES by 18.76%.

**Table 17: Comparing QPROP/PROPDES Efficiency Estimations at the PROPDES-Predicted  $J_{\eta_{max}}$**

<b>Test Run</b>	<b>PROPDES</b>		<b>Wind Tunnel</b>		<b>Percent Difference</b>	
	<b>Eff @ <math>J_{\eta_{max}}</math></b>	<b>J</b>	<b>Eff @ <math>J_{\eta_{max}}</math></b>	<b>J</b>	<b>Eff @ <math>J_{\eta_{max}}</math></b>	<b>J</b>
<b>QV1</b>	<b>68.27%</b>	<b>0.468</b>	<b>62.80%</b>	<b>0.462</b>	<b>8.71%</b>	<b>1.36%</b>
<b>QV2</b>	<b>70.43%</b>	<b>0.460</b>	<b>68.99%</b>	<b>0.464</b>	<b>2.09%</b>	<b>0.85%</b>
<b>QV3</b>	<b>76.94%</b>	<b>0.609</b>	<b>71.50%</b>	<b>0.608</b>	<b>7.61%</b>	<b>0.09%</b>
<b>QV4</b>	<b>78.58%</b>	<b>0.644</b>	<b>74.60%</b>	<b>0.636</b>	<b>5.34%</b>	<b>1.28%</b>
<b>QV5</b>	<b>79.69%</b>	<b>0.699</b>	<b>71.20%</b>	<b>0.701</b>	<b>11.92%</b>	<b>0.22%</b>
<b>QV6</b>	<b>82.07%</b>	<b>0.823</b>	<b>71.20%</b>	<b>0.827</b>	<b>15.27%</b>	<b>0.48%</b>
<b>QV7</b>	<b>80.76%</b>	<b>0.767</b>	<b>68.00%</b>	<b>0.764</b>	<b>18.76%</b>	<b>0.38%</b>
<b>QV8</b>	<b>80.10%</b>	<b>0.671</b>	<b>69.50%</b>	<b>0.671</b>	<b>15.25%</b>	<b>0.01%</b>
<b>QV9</b>	<b>80.74%</b>	<b>0.607</b>	<b>76.62%</b>	<b>0.600</b>	<b>5.38%</b>	<b>1.18%</b>
<b>QV10</b>	<b>77.00%</b>	<b>0.531</b>	<b>73.50%</b>	<b>0.552</b>	<b>4.76%</b>	<b>3.71%</b>

Additionally, Table 18 shows the percent difference of the peak efficiency advance ratio values when comparing PROPDES to the experimental data. This data explicitly shows the shift in advance ratio that is seen in the PROPDES predictions compared to the experimental data. QV7 was again the worst performer since the advance ratio at peak efficiency was over-predicted by nearly 30%.

Table 18: Comparing PROPDES-Predicted  $J_{\eta_{max}}$  to the Experimental  $J_{\eta_{max}}$

Test Run	PROPDES	Wind Tunnel	Percent Difference
QV1	0.468	0.471	0.58%
QV2	0.460	0.464	0.88%
QV3	0.609	0.575	5.83%
QV4	0.644	0.596	8.07%
QV5	0.699	0.618	13.18%
QV6	0.823	0.663	24.13%
QV7	0.767	0.590	29.99%
QV8	0.671	0.599	12.03%
QV9	0.607	0.548	10.84%
QV10	0.531	0.553	3.84%

The following figure shows the differences in the data given in Table 16, Table 17, and Table 18.

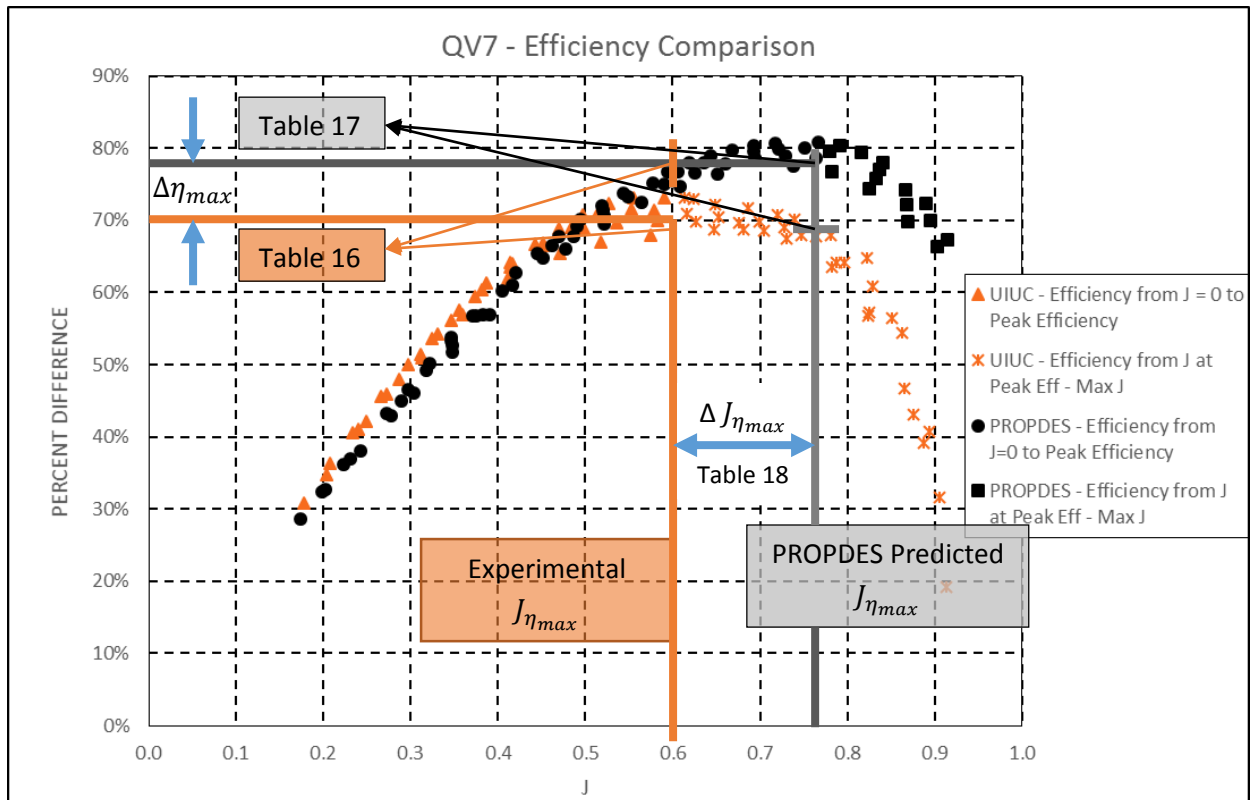


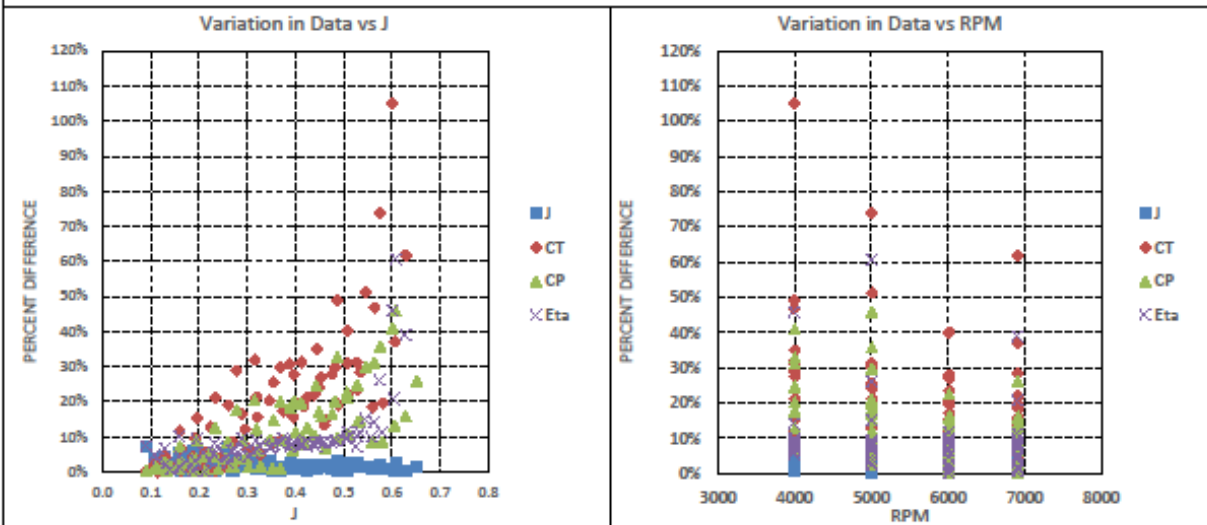
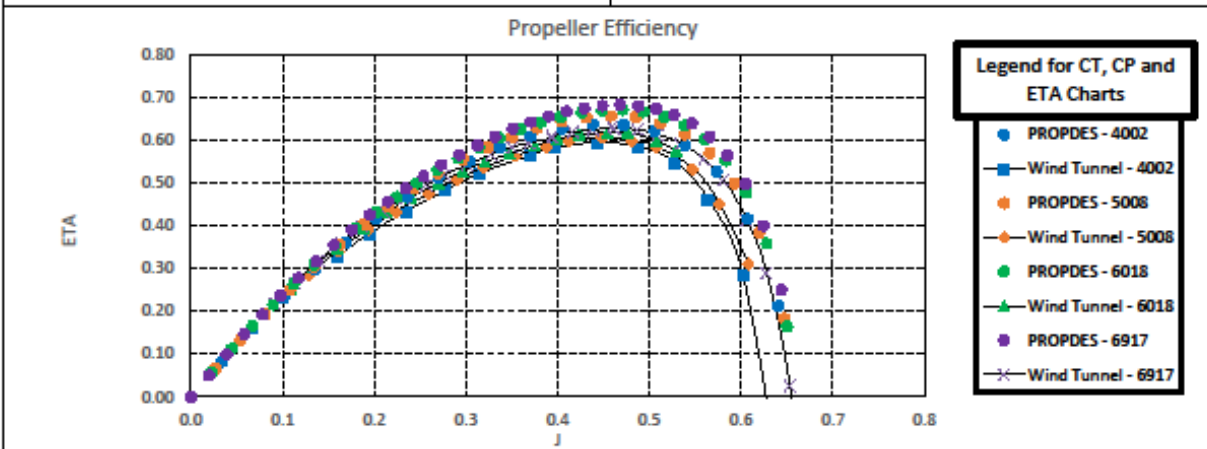
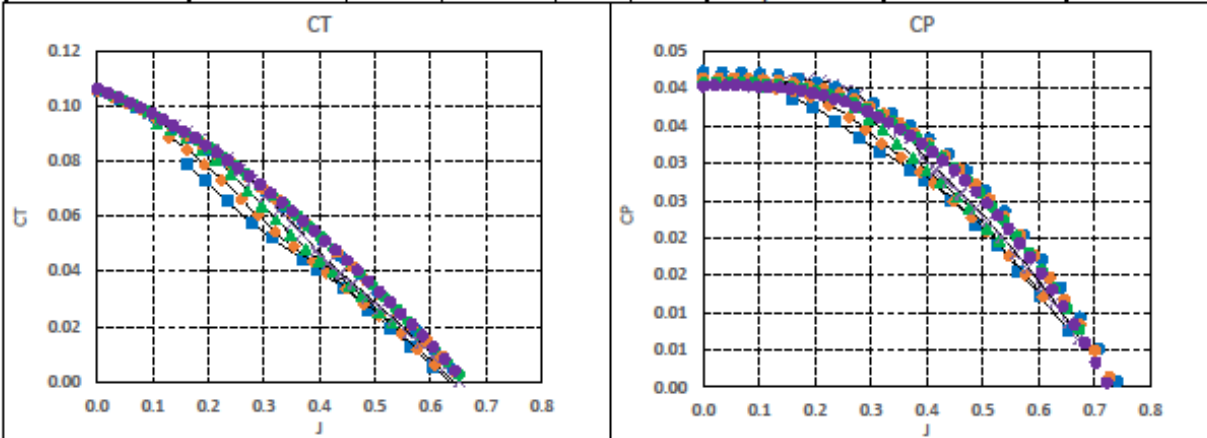
Figure 54: Example Efficiency Chart Showing the Differences in Experimental  $J_{\eta_{max}}$  and Predicted  $J_{\eta_{max}}$



6.2.2.4 – Example QV Test Data Sheet

## QV1 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	9	4.5	0.5	5002, 5008, 6018, 6917	0-40	UIUC



### 6.3 – PROPDES Validation (PV) Results

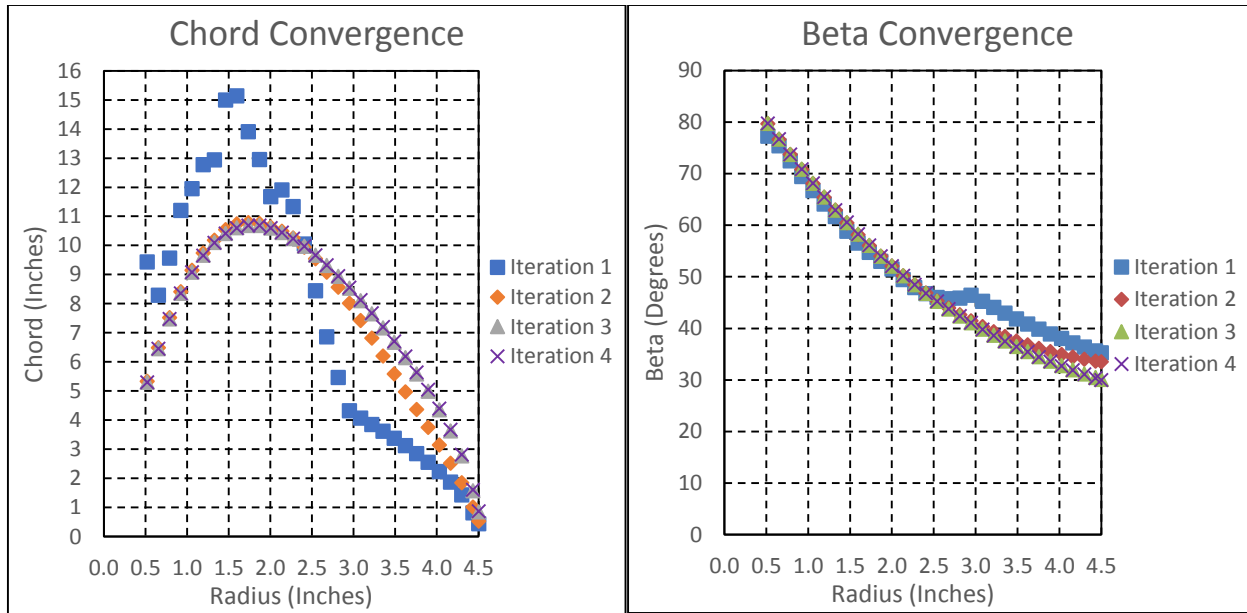
Each of the test points identified in Table 5 in section 5.2 were ran in PROPDES and in QMIL’s native FORTRAN format. The PROPDES results are compared with the QPROP verification analysis in Table 19 below and the results show that PROPDES does not change the QPROP results significantly. A few very slight changes are seen but these differences are attributed to machine rounding differences.

**Table 19: PROPDES Validation Single Iteration Comparison Results**

Run and Design Parameters				Max Differences		Max Percent Differences	
Run #	Diameter (Inches)	RPM	Velocity (KIAS)	Chord	Beta	Chord	Beta
PV1	9	6000	40	0.0000	0.0135	0.0000%	0.0383%
PV2	11	4000	15	0.0004	0.0794	0.0010%	0.2055%
PV3	11	4000	25	0.0000	0.0000	0.0000%	0.0000%
PV4	11	4000	50	0.0000	0.0000	0.0000%	0.0000%
PV5	18	4500	45	0.0000	0.0000	0.0000%	0.0000%
PV6	19	3000	40	0.0000	0.0000	0.0000%	0.0000%

The complete test data sheets for the PV single iteration comparison test cases are included in Appendix E.

Additionally, each of the PV test cases were allowed to complete iterations as described in Chapter 3 until the exit criteria was satisfied. Each iteration was captured and the results can be compared to see that performing a single iteration of QMIL on its own does not always provide a smooth chord or beta distribution. An example of the convergence charts are shown below in Figure 55 and the remaining cases are given in Appendix F.



**Figure 55: PV1 Convergence of Chord and Beta during PROPDES Iterations**

Finally, the PV test cases were used to run the ‘Create Propeller’/QMIL portion of PROPDES to determine if any of these designed propellers provide superior performance to that of the APC propeller distributions at these specific design points.

**Table 20: PROPDES Validation QMIL Designed Propellers Chord Sizing**

<b>Run #</b>	<b>Diameter (Inches)</b>	<b>Max Chord (Inches)</b>	<b>Max Chord as a Percent of Radius</b>
PV1	9	10.69	238%
PV2	11	28.16	512%
PV3	11	19.64	357%
PV4	11	10.06	183%
PV5	18	3.02	34%
PV6	19	5.42	57%

The author estimates that if the max chord as a percent of radius exceeds 100%, then the propeller would be difficult if not impossible to manufacture and at the very least would cause the hub thickness to be such that the propeller geometry would be impractical. Therefore any design solutions that suggest a max chord of greater than the propeller radius are considered to be unrealistic. With this condition in mind, only PV5 and PV6 resulted in QMIL/PROPDES designed propellers that seem reasonable. These

PROPDES designed propellers were compared with APC propellers at the PV design case parameters and the following pages show the results of this comparison.

Table 21 shows the propeller design parameters used in PROPDES for the PV5 test case.

**Table 21: PV5 PROPDES Propeller Design Parameters**

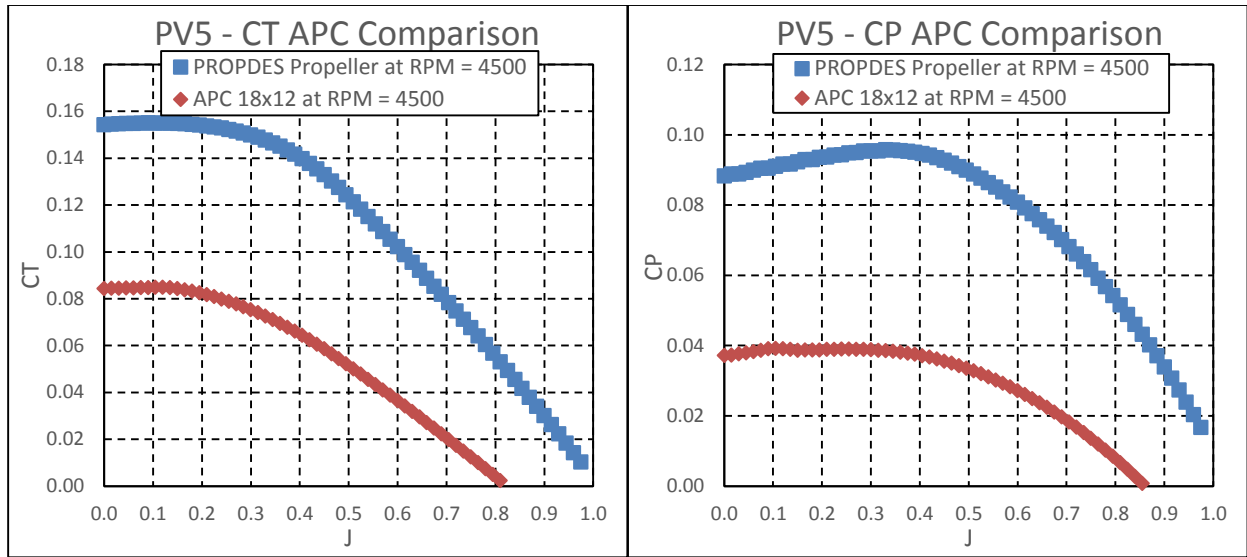
<b>Run:</b>	<b>PV5</b>
<b>Diameter(in/m):</b>	18
<b>RPM:</b>	4500
<b>Velocity (KIAS)</b>	45
<b>Blades:</b>	2
<b>J:</b>	0.676
<b>Power Available (HP):</b>	1

The performance of the PROPDES designed propeller was compared with the APC 18x12 propeller at the design conditions listed above.

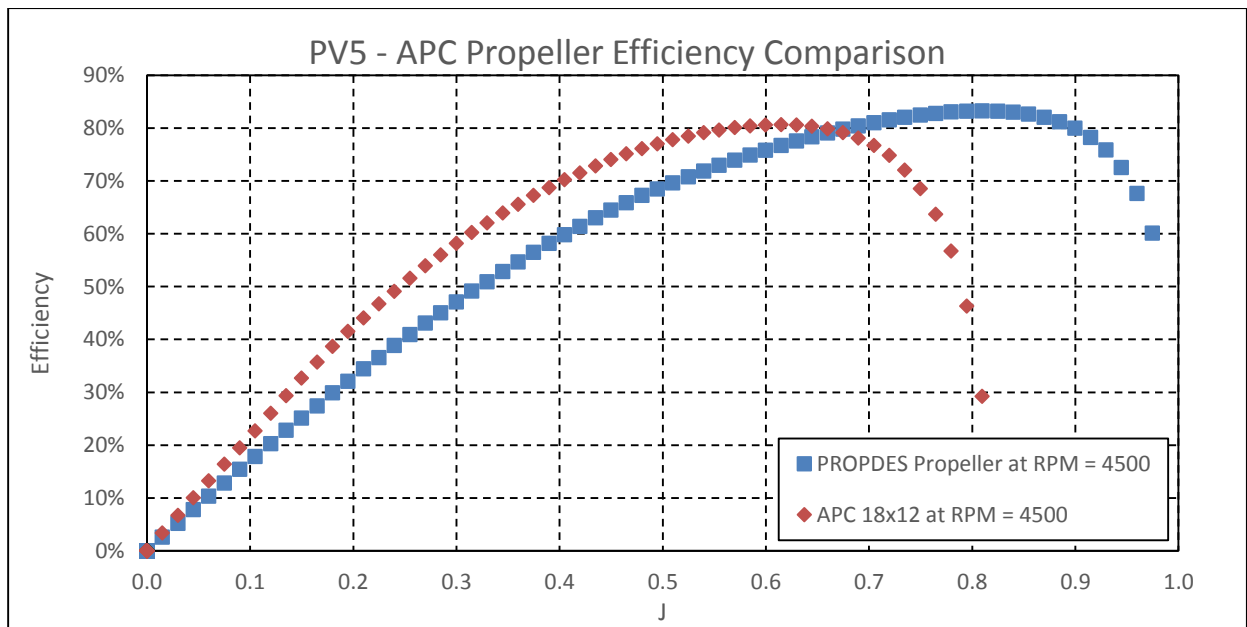
**Table 22: PV5 Prediction of PROPDES Propeller Performance at the Design Point Compared to APC 18x12**

	<b>V(fps)</b>	<b>RPM</b>	<b>T(lbf)</b>	<b>Q(ft-lbf)</b>	<b>Efficiency</b>	<b>J</b>	<b>CT</b>	<b>CP</b>
<b>QMIL Propeller</b>	910.98	4500	5.775	14.20569	79.80%	0.6748	0.0853	0.0722
<b>APC 19x12</b>	910.98	4500	1.676	4.153884	79.17%	0.6748	0.0248	0.0211

The following charts compare the CT, CP, and propeller efficiency curves for each of these propellers under the same conditions.



**Figure 56: PV5 PROPDES Designed Propeller Compared to APC 18x12 (CT & CP)**



**Figure 57: PV5 PROPDES Designed Propeller Compared to APC 18x12 (Efficiency)**

From the CT and CP curves above, one can see that the CT and CP of the PROPDES designed propeller is much greater than (approximately 2 times) that of the APC 18x12 propeller at the design/test case conditions. The efficiency curve shows a distinct shift to the right for the PROPDES designed propeller. For the PV5 case, the efficiencies at the test case ( $J = 0.676$ ) are within 3%, however the predicted thrust for the PROPDES designed propeller is approximately 3.5 times that of the APC propeller. This data

shows that the PROPDES designed propeller provides a superior solution for the given design constraints assuming that manufacturability is not an issue.

The following figures show the chord and beta distributions of the PROPDES designed propeller and the APC 18x12 propeller.

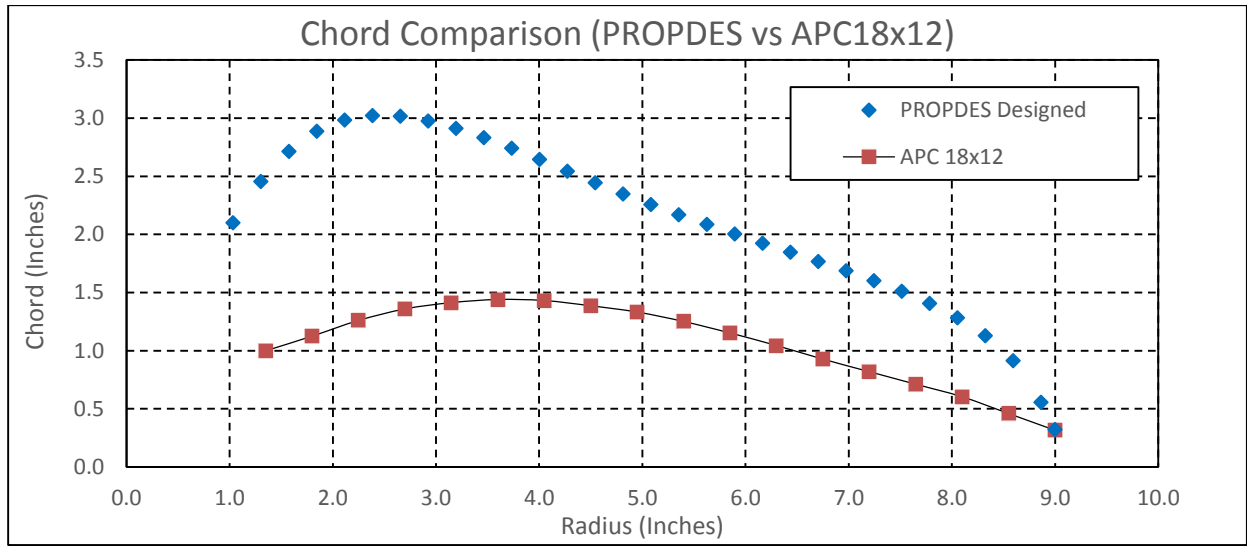


Figure 58: PV5 PROPDES Designed Propeller Compared to APC 18x12 (Chord)

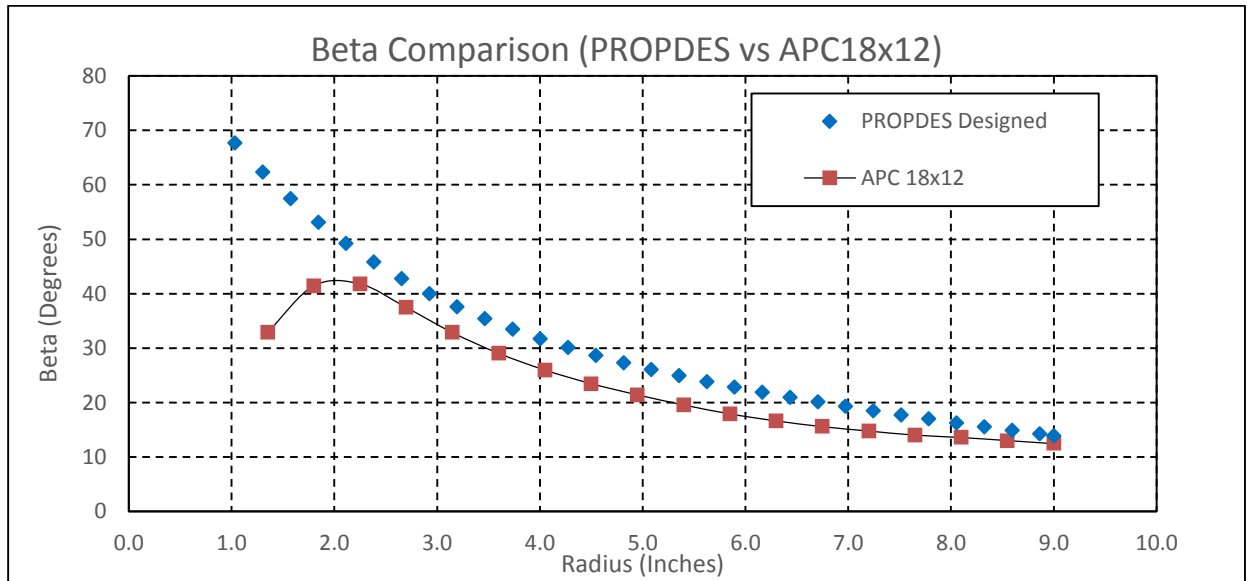


Figure 59: PV5 PROPDES Designed Propeller Compared to APC 18x12 (Beta)

Similar to the PV5 case discussed above, Table 23 shows the propeller design parameters used in PROPDES for the PV6 test case.

**Table 23: PV6 PROPDES Propeller Design Parameters**

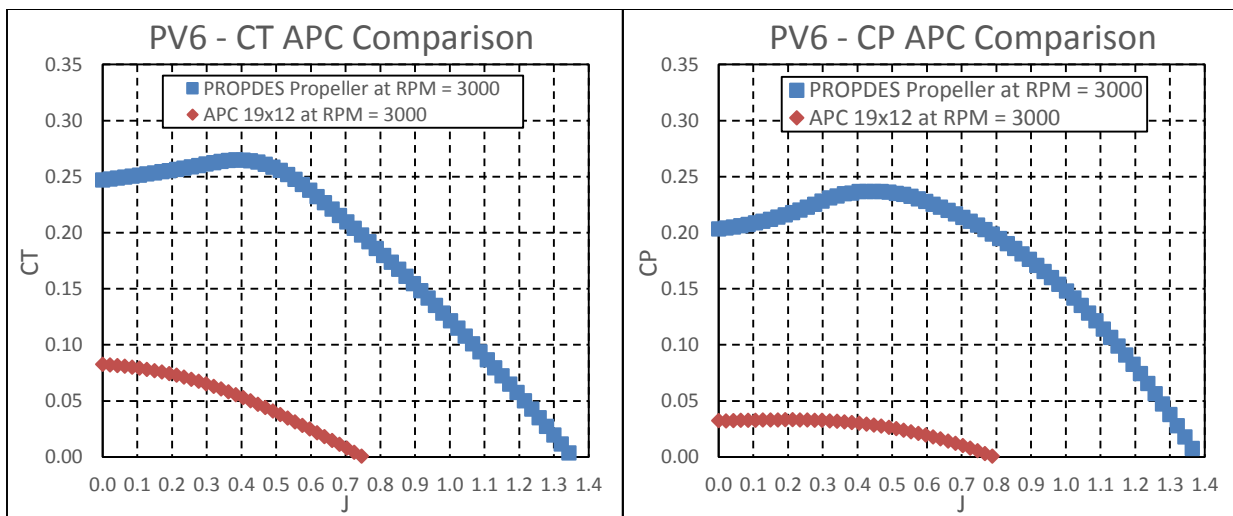
<b>Run:</b>	<b>PV6</b>
<b>Diameter(in/m):</b>	19
<b>RPM:</b>	3000
<b>Velocity (KIAS)</b>	40
<b>Blades:</b>	2
<b>J:</b>	0.852
<b>Power Available (HP):</b>	1

The performance of the PROPDES designed propeller was compared with the APC 19x12 propeller at the design conditions listed above.

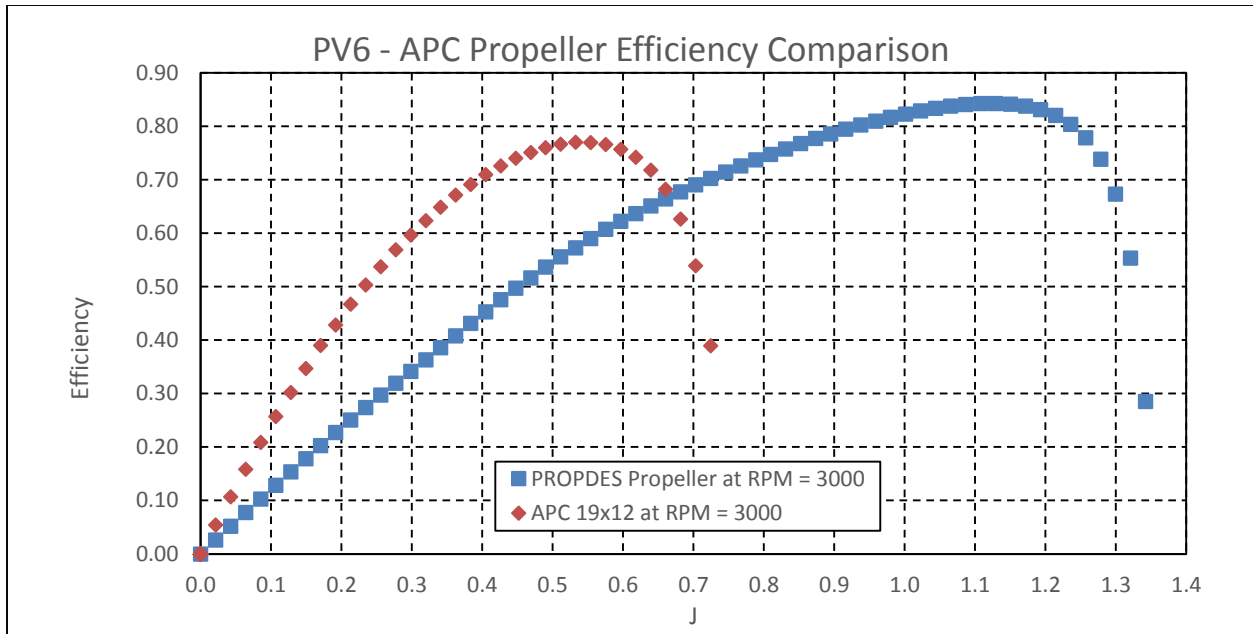
**Table 24: PV6 Prediction of PROPDES Propeller Performance at the Design Point Compared to APC 19x12**

	V(fps)	RPM	T(lbf)	Q(ft-lbf)	Efficiency	J	CT	CP
<b>PROPDES Propeller</b>	809.76	3000	6.252	21.31303	76.77%	0.8524	0.1674	0.1859
<b>APC 19x12</b>	809.76	3000	-0.658	-0.87507	#N/A	0.8524	#N/A	#N/A

The following charts compare the CT, CP, and propeller efficiency curves for each of these propellers under the same conditions.



**Figure 60: PV6 PROPDES Designed Propeller Compared to APC 19x12 (CT & CP)**



**Figure 61: PV6 PROPDES Designed Propeller Compared to APC 19x12 (Efficiency)**

From the CT and CP curves above, one can see that the CT and CP of the PROPDES designed propeller is much greater than that of the APC 19x12 propeller at the design/test case conditions. This difference is even more distinct than that of the PV5 case.

The efficiency curve again shows a distinct shift to the right for the PROPDES designed propeller. For the PV6 case, the efficiencies at the test case ( $J = 0.852$ ) vary drastically since the APC propeller is windmilling at this design point (to the right of the entire efficiency curve). Similarly to the PV5 case, this data shows that the PROPDES designed propeller provides a superior solution for the given design constraints assuming that manufacturability is not an issue.

The following figures show the chord and beta distributions of the PROPDES designed propeller and the APC 19x12 propeller.



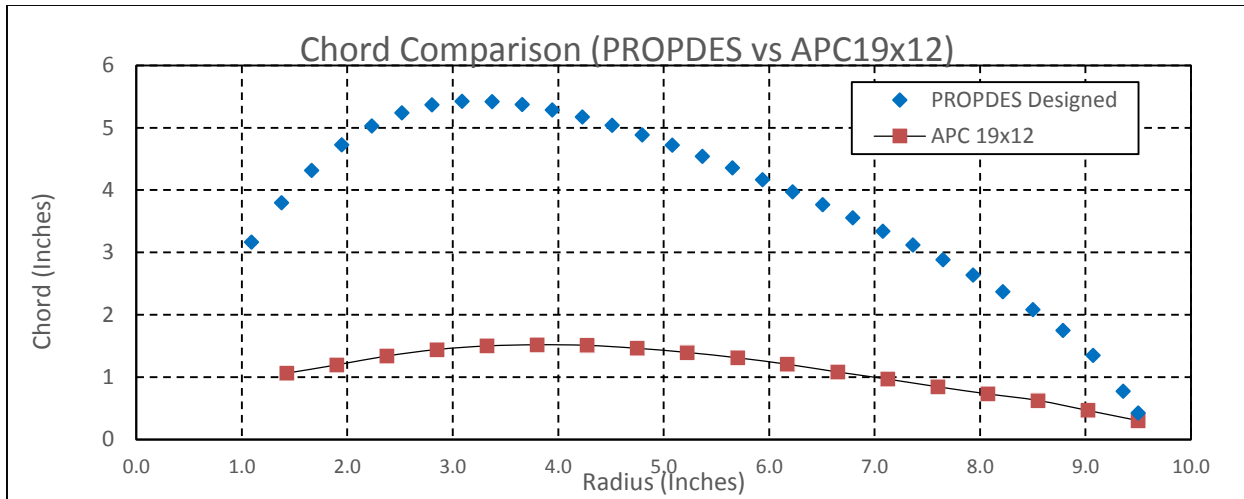


Figure 62: PV6 PROPDES Designed Propeller Compared to APC 19x12 (Chord)

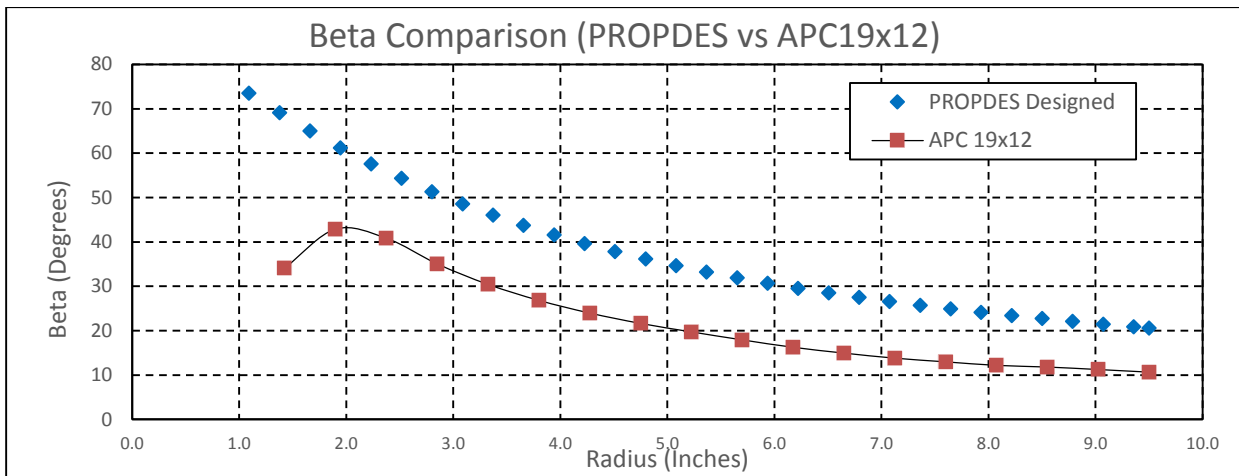


Figure 63: PV6 PROPDES Designed Propeller Compared to APC 19x12 (Beta)

## 6.4 – Further Testing Results

A test sheet was developed for tracking performance of each of the test points corresponding to Table 7.

Recall that the “Further Testing” was intended to design many propellers using PROPDES at multiple design points to determine how well PROPDES does at producing usable results across a variety of variables.

Most of the columns are relatively straightforward, however the column titled “Success?” deserves some explanation. For these test sheets, success was defined as the outcome only when PROPDES ran all iterations successfully until the convergence criterion was met, it did not end on the use of an APC

distribution, and the max chord was less than or equal to the propeller radius. The completed test sheets are given below:

**Table 25: Further Test Cases - Test Data Sheets**

Folder Location for Results: C:\PROPDES\Further Testing\ File Names: PROPDES\_Blades\_Dia\_RPM\_Vinf  
 Assumptions: Hub Diameter = 10% Prop Diameter Power Avail = 1 HP Air Properties Constant, Clark Y airfoil used  
 - = Negative Value  
 N/A = PROPDES failed to produce that output

Design Cases	Blades	Velocity (KIAS)	Diameter (Inches)	RPM	Advance Ratio (J)	Converged?	Date Ran:	Were APC Distributions Used?	Number of Iterations Performed	Success?	T (lbf)	Efficiency	Comments:
1	2	20	8	2000	1.5183	N	9/17/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
2	2	20	8	4000	0.75915	N	9/17/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
3	2	20	8	6000	0.5061	Y	9/17/2015	N	3	N	3.9	24%	Converged, max chord =30", R=4", not reasonable
4	2	20	16	2000	0.75915	Y	9/17/2015	N	4	N	6.2	38%	Converged, max chord = 32", R=8", not reasonable
5	2	20	16	4000	0.37957	N	9/17/2015	Y	4	N	1.8	68%	QMIL never ran successfully, APC distribution given.
6	2	20	16	6000	0.25305	N	9/17/2015	Y	12	N	9.0	48%	Average Distros used, Max C = 6", R=8" seems ok.
7	2	20	24	2000	0.5061	N	9/17/2015	Y	4	N	1.6	76%	QMIL never ran successfully, APC distribution given.
8	2	20	24	4000	0.25305	Y	9/17/2015	N	7	Y	9.6	59%	Converged, max chord = 5", R=12" seems ok.
9	2	20	24	6000	0.1687	N	9/17/2015	Y	7	N	12.5	53%	Average Distros used, Max C = 3", R=12" seems ok.
10	2	40	8	2000	3.0366	N	9/17/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
11	2	40	8	4000	1.5183	N	9/17/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
12	2	40	8	6000	1.0122	Y	9/17/2015	N	4	N	3.5	43%	Converged, Max Chord = 14", Radius = 4" not reasonable
13	2	40	16	2000	1.5183	Y	9/17/2015	N	5	N	4.9	61%	Converged, Max Chord = 16", Radius = 8", not reasonable
14	2	40	16	4000	0.75915	Y	9/17/2015	Y	5	Y	5.9	73%	Converged Max Chord = 5.4", Radius = 8" seems ok
15	2	40	16	6000	0.5061	Y	9/11/2015	Y	9	Y	6.0	73%	Good Example of Convergence.
16	2	40	24	2000	1.0122	Y	9/14/2015	Y	3	Y	6.5	80%	Converged, max chord = 6", R=12" seems reasonable.

Folder Location for Results:

C:\PROPDES\Further Testing\

File Names:

PROPDES\_Blades\_Dia\_RPM\_Vinf

- = Negative Value  
N/A = PROPDES failed to produce that output

Assumptions:

Hub Diameter = 10% Prop Diameter

Power Avail = 1 HP

Air Properties Constant, Clark Y airfoil used

Design Cases	Blades	Velocity (KIAS)	Diameter (Inches)	RPM	Advance Ratio (J)	Converged?	Date Ran:	Were APC Distributions Used?	Number of Iterations Performed	Success?	T (lbf)	Efficiency	Comments:
17	2	40	24	4000	0.5061	N	9/14/2015	Y	3	N	N/A	N/A	Conv but QPROP failed
18	2	40	24	6000	0.3374	N	9/14/2015	Y	2	N	N/A	N/A	Conv but QPROP failed
19	2	60	8	2000	4.5549	N	9/14/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
20	2	60	8	4000	2.27745	N	9/14/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
21	2	60	8	6000	1.5183	Y	9/14/2015	N	4	N	-	-	Converged, C = 9", R = 4", Not reasonable.
22	2	60	16	2000	2.27745	Y	9/14/2015	Y	5	N	N/A	N/A	Conv but QPROP failed
23	2	60	16	4000	1.13872	Y	9/14/2015	Y	3	Y	4.5	83%	Converged, C = 3.5", R = 8", seems reasonable
24	2	60	16	6000	0.75915	Y	9/14/2015	Y	6	Y	4.5	84%	Good Example of Convergence.
25	2	60	24	2000	1.5183	Y	9/14/2015	Y	3	Y	4.7	88%	Conv, C=3.5", R=12", seems reasonable
26	2	60	24	4000	0.75915	Y	9/14/2015	Y	6	Y	4.7	87%	Conv, chord smaller than APC but seems ok
27	2	60	24	6000	0.5061	N	9/14/2015	Y	2	N	3.6	67%	Avg Distros seems ok - Chord may be too small.
28	4	20	8	2000	1.5183	N	9/14/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
29	4	20	8	4000	0.75915	N	9/14/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
30	4	20	8	6000	0.5061	Y	9/14/2015	Y	4	N	4.3	26%	C=11", R=4", not reasonable
31	4	20	16	2000	0.75915	Y	9/14/2015	N	2	N	6.6	40%	C=13", R=8", not reasonable [Example of bad conv conditions]
32	4	20	16	4000	0.37957	N	9/14/2015	Y	4	N	3.0	62%	QMIL never ran successfully, APC distribution given.
33	4	20	16	6000	0.25305	Y	9/14/2015	Y	14	Y	8.0	49%	Good Example of convergence. C=3, R=8, Seems reasonable.

Folder Location for Results:

C:\PROPDES\Further Testing\

File Names:

PROPDES\_Blades\_Dia\_RPM\_Vinf

- = Negative Value  
N/A = PROPDES failed to produce that output

Assumptions:

Hub Diameter = 10% Prop Diameter

Power Avail = 1 HP

Air Properties Constant, Clark Y airfoil used

Design Cases	Blades	Velocity (KIAS)	Diameter (Inches)	RPM	Advance Ratio (J)	Converged?	Date Ran:	Were APC Distributions Used?	Number of Iterations Performed	Success?	T (lbf)	Efficiency	Comments:
34	4	20	24	2000	0.5061	N	9/14/2015	Y	4	N	2.6	71%	QMIL never ran successfully, APC distribution given.
35	4	20	24	4000	0.25305	N	9/14/2015	Y	2	N	8.0	49%	Converged, C=2.4", R=12", seems ok
36	4	20	24	6000	0.1687	N	9/14/2015	Y	16	N	20.0	48%	Avg Distros seems ok
37	4	40	8	2000	3.0366	N	9/14/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
38	4	40	8	4000	1.5183	N	9/14/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
39	4	40	8	6000	1.0122	Y	9/14/2015	Y	4	N	3.2	46%	C=7.2", R=4", Not reasonable.
40	4	40	16	2000	1.5183	Y	9/14/2015	Y	4	Y	5.0		C=7.2", R = 8" - Chord seems large.
41	4	40	16	4000	0.75915	Y	9/14/2015	Y	7	Y	6.0	73%	C=2.4", R = 8". Seems reasonable but QPROP Failed
42	4	40	16	6000	0.5061	Y	9/14/2015	Y	6	Y	6.0	72%	C=1.3", R=8". Seems reasonable.
43	4	40	24	2000	1.0122	Y	9/14/2015	Y	5	Y	6.6	81%	C=2.5", R=12". Seems reasonable.
44	4	40	24	4000	0.5061	Y	9/14/2015	Y	12	Y	6.2	75%	C=1", R=12", chord seems small.
45	4	40	24	6000	0.3374	N	9/14/2015	Y	30	N	8.1	66%	Average Distro seems ok
46	4	60	8	2000	4.5549	N	9/15/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
47	4	60	8	4000	2.27745	N	9/15/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
48	4	60	8	6000	1.5183	Y	9/15/2015	N	4	N	3.2	59%	C=4.8, R=4, Not reasonable.
49	4	60	16	2000	2.27745	Y	9/15/2015	N	4	Y	4.0	74%	C=4.5", R=8", seems reasonable
50	4	60	16	4000	1.13872	Y	9/15/2015	Y	5	Y	4.5	83%	C=1.6", R=8", seems reasonable
51	4	60	16	6000	0.75915	Y	9/15/2015	Y	7	Y	4.4	81%	C=0.9, R=8", may be getting too small near hub.
52	4	60	24	2000	1.5183	Y	9/15/2015	Y	5	Y	4.7	87%	C=0.75 @ hub, R=12, likely too small near hub

Folder Location for Results:

C:\PROPDES\Further Testing\

File Names:

PROPDES\_Blades\_Dia\_RPM\_Vinf

- = Negative Value  
N/A = PROPDES failed to produce that output

Assumptions:

Hub Diameter = 10% Prop Diameter

Power Avail = 1 HP

Air Properties Constant, Clark Y airfoil used

Design Cases	Blades	Velocity (KIAS)	Diameter (Inches)	RPM	Advance Ratio (J)	Converged?	Date Ran:	Were APC Distributions Used?	Number of Iterations Performed	Success?	T (lbf)	Efficiency	Comments:
53	4	60	24	4000	0.75915	N	9/15/2015	Y	47	N	4.6	81%	Avg Distros not reasonable - chord too small
54	4	60	24	6000	0.5061	N	9/15/2015	Y	24	N	6.9	75%	Avg Distros not reasonable - chord too small
55	6	20	8	2000	1.5183	N	9/15/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
56	6	20	8	4000	0.75915	N	9/15/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
57	6	20	8	6000	0.5061	Y	9/15/2015	N	4	N	4.5	28%	C=7", R=4", Not reasonable.
58	6	20	16	2000	0.75915	N	9/15/2015	Y	5	N	-	-	QMIL never ran successfully, APC distribution given.
59	6	20	16	4000	0.37957	N	9/15/2015	Y	4	N	4.0	58%	QMIL never ran successfully, APC distribution given.
60	6	20	16	6000	0.25305	N	9/15/2015	Y	17	N	9.4	45%	Average Distro seems ok
61	6	20	24	2000	0.5061	N	9/16/2015	Y	4	N	3.4	67%	Average Distro seems ok
62	6	20	24	4000	0.25305	N	9/16/2015	Y	73	N	10.0	51%	Average Distro seems ok
63	6	20	24	6000	0.1687	N	9/16/2015	N	101	N	5.0	31%	3/4 of the radial stations converged but hub area did not
64	6	40	8	2000	3.0366	N	9/16/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
65	6	40	8	4000	1.5183	N	9/16/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
66	6	40	8	6000	1.0122	Y	9/16/2015	N	4	N	3.9	48%	Converged - Chord = 4.4", R=4", not reasonable
67	6	40	16	2000	1.5183	Y	9/16/2015	Y	6	Y	5.3	65%	Converged - Chord = 4.8", R=8", seems ok
68	6	40	16	4000	0.75915	Y	9/16/2015	Y	7	Y	5.9	73%	Converged - Chord = 1.6", R=8", seems ok
69	6	40	16	6000	0.5061	Y	9/17/2015	Y	10	Y	5.7	69%	Converged - Chord = 1", R=8", seems ok
70	6	40	24	2000	1.0122	Y	9/17/2015	Y	5	Y	6.6	80%	Converged - Chord = 1.5", R=12" seems ok

Folder Location for Results:

C:\PROPDES\Further Testing\

File Names:

PROPDES\_Blades\_Dia\_RPM\_Vinf

- = Negative Value  
 N/A = PROPDES failed to produce that output

Assumptions:

Hub Diameter = 10% Prop Diameter

Power Avail = 1 HP

Air Properties Constant, Clark Y airfoil used

Design Cases	Blades	Velocity (KIAS)	Diameter (Inches)	RPM	Advance Ratio (J)	Converged?	Date Ran:	Were APC Distributions Used?	Number of Iterations Performed	Success?	T (lbf)	Efficiency	Comments:
71	6	40	24	4000	0.5061	N	9/17/2015	Y	28	N	7.9	70%	Average Distro used, Chord is too small
72	6	40	24	6000	0.3374	N	9/17/2015	Y	16	N	15.3	67%	Average Distro used, Chord is too small
73	6	60	8	2000	4.5549	N	9/17/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
74	6	60	8	4000	2.27745	N	9/17/2015	Y	4	N	-	-	QMIL never ran successfully, APC distribution given.
75	6	60	8	6000	1.5183	Y	9/17/2015	N	4	Y	3.3	61%	Conv, C=3.2", R=4", Seems ok
76	6	60	16	2000	2.27745	Y	9/17/2015	N	5	Y	4.0	75%	Conv, C=3", R=8", Seems ok
77	6	60	16	4000	1.13872	N	9/17/2015	Y	19	N	2.8	81%	Average Distro seems ok
78	6	60	16	6000	0.75915	N	9/17/2015	Y	14	N	4.0	75%	Average Distro seems ok
79	6	60	24	2000	1.5183	N	9/17/2015	Y	101	N	4.7	86%	3/4 of the radial stations converged but hub area did not
80	6	60	24	4000	0.75915	N	9/17/2015	Y	24	N	5.2	76%	Average Distro seems ok (May be too small chord)
81	6	60	24	6000	0.5061	N	9/17/2015	Y	28	N	7.2	70%	Average Distro chord too small (c=0.5")

A more condensed version of the above test data sheet is provided below. The condensed version contains only those cases determined to be successful and several of the less important columns have been excluded. Of the 81 total test cases, only 24 were determined to be successful. Additionally, Table 26 is sorted by the advance ratio.

**Table 26: Further Testing Results (Successful Runs Only)**

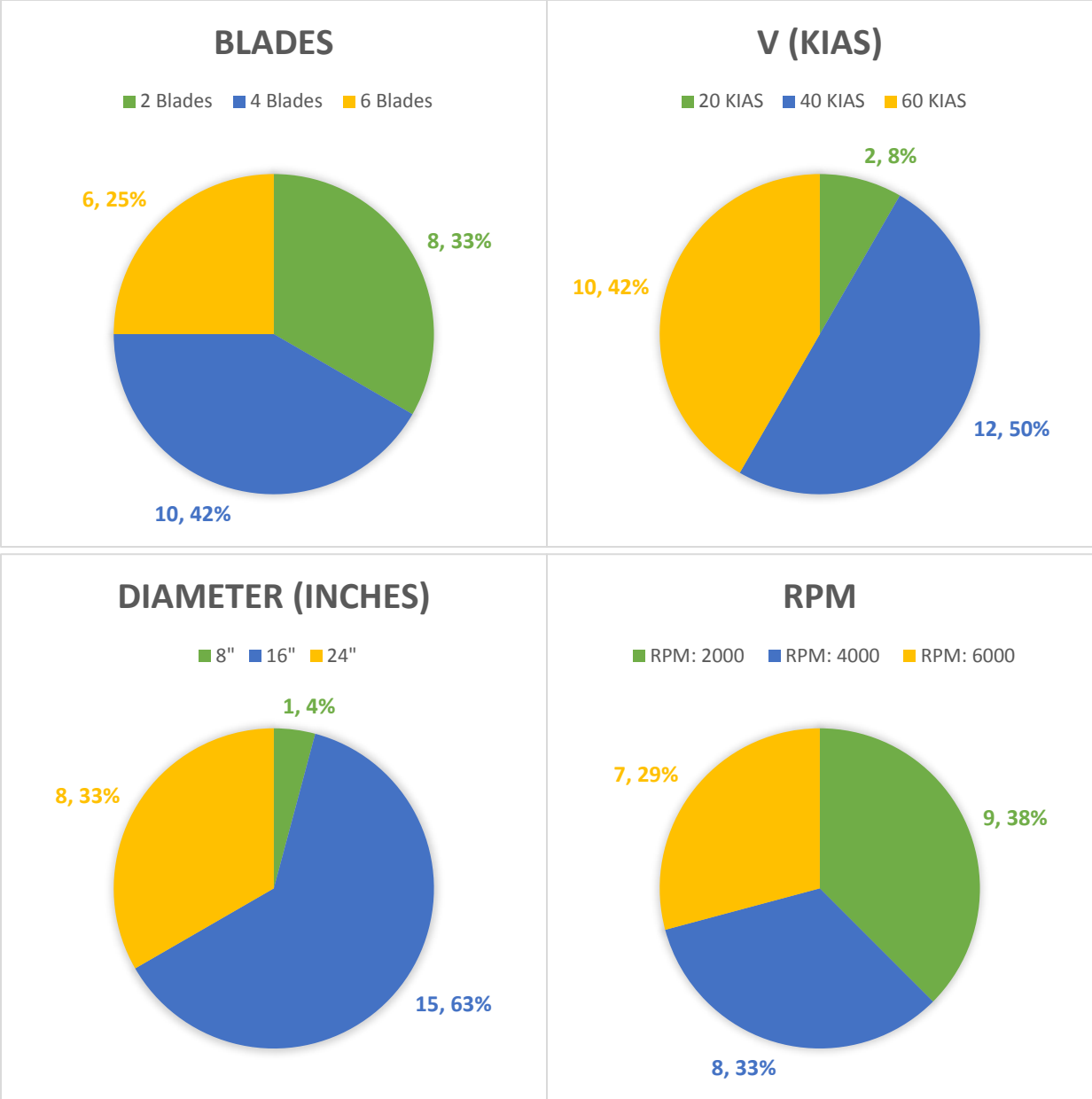
Design Case #	Blades	Velocity (KIAS)	Diameter (Inches)	RPM	Advance Ratio (J)	Were APC Distributions Used?	Number of Iterations Performed	T (lbf)	Max Eta
8	2	20	24	4000	0.25305	N	7	9.6	59%
14	4	20	16	6000	0.25305	Y	14	8.0	49%
15	4	40	24	4000	0.5061	Y	12	6.2	75%
16	2	40	16	6000	0.5061	Y	9	6.0	73%
23	4	40	16	6000	0.5061	Y	6	6.0	72%
24	6	40	16	6000	0.5061	Y	10	5.7	69%
25	2	60	24	4000	0.75915	Y	6	4.7	87%
26	2	40	16	4000	0.75915	Y	5	5.9	73%
33	2	60	16	6000	0.75915	Y	6	4.5	84%
40	4	40	16	4000	0.75915	Y	7	6.0	73%
41	4	60	16	6000	0.75915	Y	7	4.4	81%
42	6	40	16	4000	0.75915	Y	7	5.9	73%
43	2	40	24	2000	1.0122	Y	3	6.5	80%
44	4	40	24	2000	1.0122	Y	5	6.6	81%
49	6	40	24	2000	1.0122	Y	5	6.6	80%
50	2	60	16	4000	1.13872	Y	3	4.5	83%
51	4	60	16	4000	1.138725	Y	5	4.5	83%
52	2	60	24	2000	1.5183	Y	3	4.7	88%
67	4	60	24	2000	1.5183	Y	5	4.7	87%
68	4	40	16	2000	1.5183	Y	4	5.0	73%
69	6	40	16	2000	1.5183	Y	6	5.3	65%
70	6	60	8	6000	1.5183	N	4	3.3	61%
75	4	60	16	2000	2.27745	N	4	4.0	74%
76	6	60	16	2000	2.27745	N	5	4.0	75%



Of the 24 test cases determined to be successful, only 4 were successful without the use of APC distributions at some point during the iterations. This indicates a QMIL sensitivity to the initial propeller distributions provided for the design case. Recall that the original initial conditions used in this study were of a constant chord distribution. It is important to note that even though the APC distribution was used as an input parameter for those cases, the final outcome is a QMIL designed output that differs, often drastically, from the APC distributions.

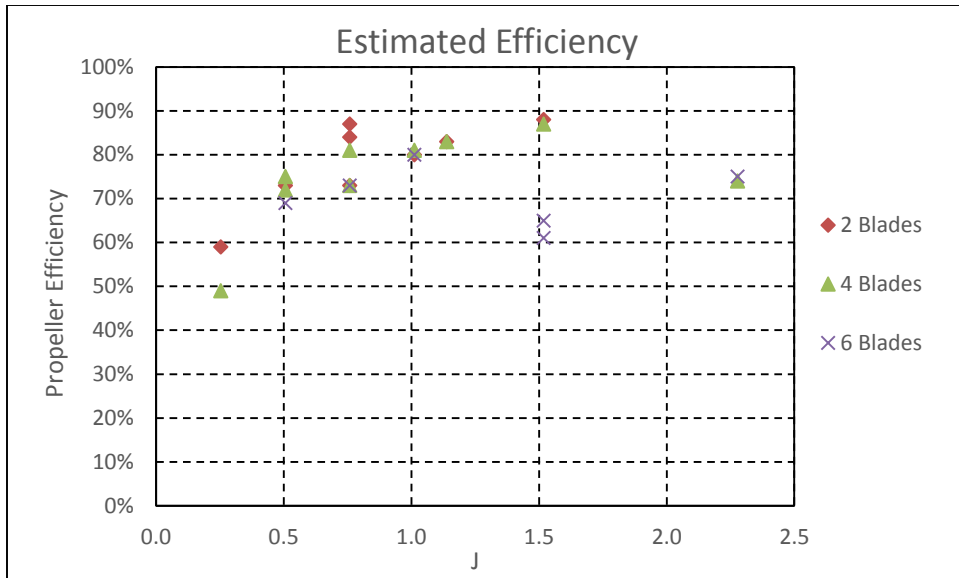
The average number of iterations performed for the successful cases was 9, however success was achieved in as few as 3 iterations and as many as 14 in one case (Design Case #14). By examining the successful cases based on the important propeller design variables (blades, velocity, diameter, and RPM), one can see if any of the variables appear to impact the success rate of the design cases. This is obviously limited to the range of the variables used in this study.

From Figure 64 below, one can see an indication that the diameter appears to be the most sensitive of the variable ranges tested. Only 1 of the 8" diameter cases was successful (6 Blades at 6000 RPM and 60 KIAS). Since the remaining variables were at their maximum range tested, more testing would be required at higher speeds and RPMs to determine if PROPDES would be more successful at faster cruising speeds or higher RPMs. Similarly, the velocity range appears to also be a sensitive parameter for PROPDES since only 2 of the 27 20KIAS test cases were successful. Again, these observations are qualitative in nature and give indications rather than absolute rules for selecting the governing variables when designing a propeller using PROPDES. Ultimately, the design variables would be selected based upon other air vehicle properties and desired cruise conditions and may be adjusted as necessary to optimize the propeller efficiency or to ensure that the UAV can meet take-off or other off design specifications as required.

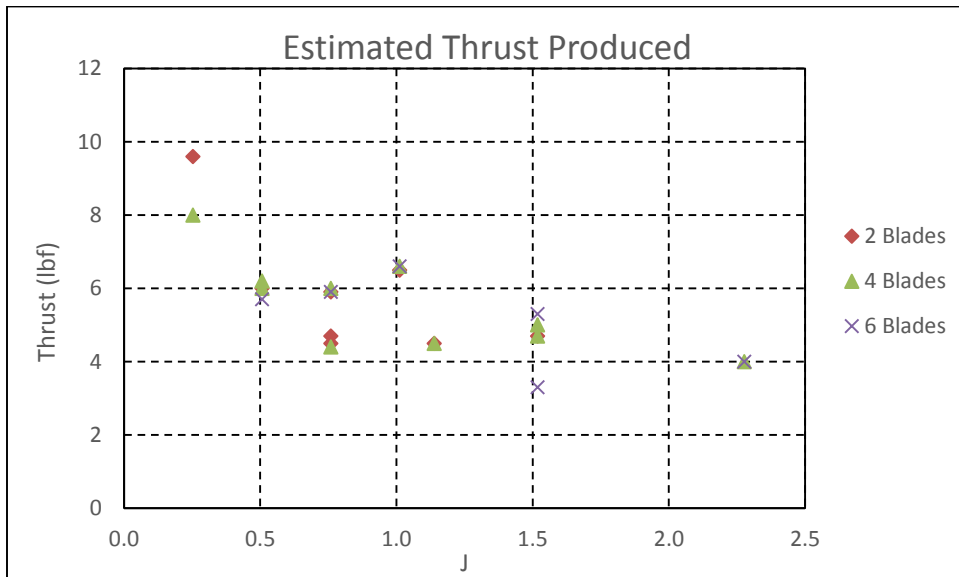


**Figure 64: Breakdown of Successful Cases by Propeller Design Variable**

The propellers designed using PROPDES for these design cases can also be compared based on the estimated efficiency and the estimated thrust produced when those propellers are operating at their design point.



**Figure 65: Further Testing Maximum Estimated Efficiency Compared with Advance Ratio of Design Cases**



**Figure 66: Further Testing Estimated Thrust Produced Compared to Advance Ratio**

The above efficiency chart shows that, for these design variable ranges, the peak efficiency is achieved by a 2 bladed propeller but 4 bladed and 6 bladed can achieve greater than 80% at certain advance ratios. The thrust chart, as expected, shows that the thrust produced is inversely related to the advance ratio.

## 6.5 – Full-Scale Test Case

Upon completion of the previous test cases, it was observed that there is a rather large percent difference for the back side of the efficiency curves with respect to the advance ratio. As discussed in Paragraph

6.2.2.1, one reason for this difference is a shift in the advance ratio when comparing the predicted values to the experimentally obtained values. An additional source of error was identified due to an inexact airfoil being used in the PROPDES predictions (Clark Y assumed when APC website states a “modified Clark Y” is used). Also, the very low Reynolds number flow is handled by a quadratic estimation within QPROP so this presents some additional difference. With all of this in mind, it was decided to perform one final test case using a 5868-9, Clark-Y Section, 3-bladed propeller given in McCormick’s text book *Aerodynamics, Aeronautics, and Flight Mechanics* and further explained in NACA Report 640.

NACA Report 640 explains the experimental set up and identified that the CT, CP and efficiency charts were generated for the 10 foot diameter, 3-bladed 5868-9 propeller for the 800 RPM case only. A propeller file was created for input into PROPDES using XFOIL to determine the airfoil properties at a Reynolds Number of 1,000,000 and using the beta distribution for the 35 degree case. The CT, CP, and efficiency charts given in NACA Report 640 are shown below with the PROPDES predictions shown in red.



**Figure 67: Thrust Coefficient Chart for Propeller 5868-9, Clark-Y, 3 Blades (NACA Report 640) with PROPDES Predictions**

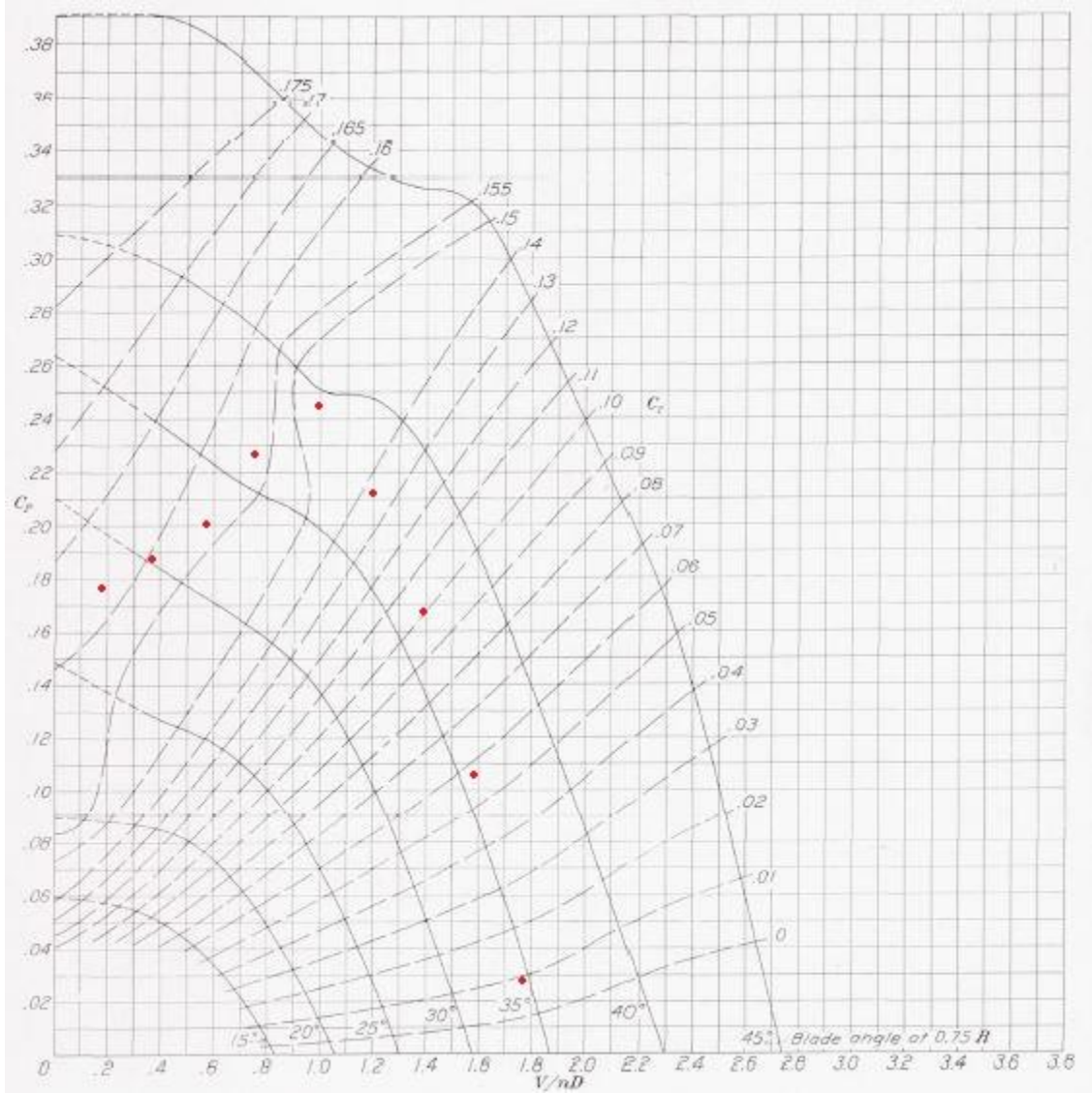
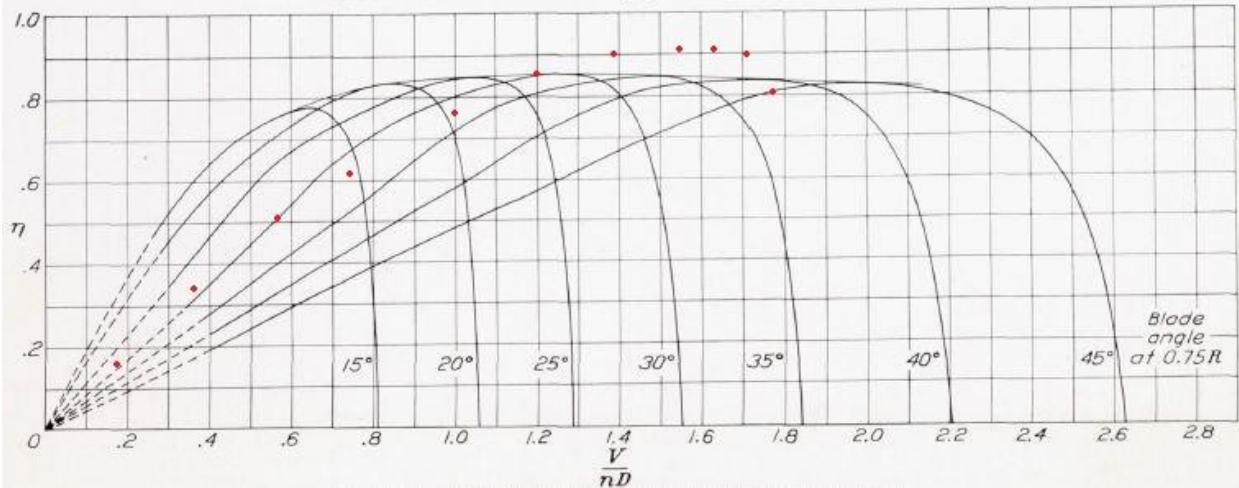


Figure 68: Power Coefficient Chart for Propeller 5868-9, Clark-Y, 3 Blades (NACA Report 640) with PROPDES Predictions



**Figure 69: Propeller Efficiency Chart for Propeller 5868-9, Clark-Y, 3 Blades (NACA Report 640) with PROPDES Predictions**

In order to compare the published wind tunnel results from the NACA Report with the PROPDES results, tables showing the percent difference of the experimental values and the PROPDES predicted values are given below. Table 27 shows the maximum percent difference in advance ratio from each of the data points extracted from the NACA Report when compared with the PROPDES advance ratios used in the following tables.

**Table 27: Advance Ratio Comparison between Data Points used from NACA Report 640 for  $C_T$ ,  $C_P$ , and  $\eta$**

$J_{C_P}$	$C_T$	$J_{C_T}$	$C_P$	$J_\eta$	$\eta$	Max J Percent Difference
#N/A	#N/A	#N/A	#N/A	0.175	0.114	#N/A
#N/A	#N/A	#N/A	#N/A	0.231	0.154	#N/A
0.329	0.166	0.338	0.240	0.287	0.193	2.4%
0.377	0.164	0.375	0.238	0.375	0.256	0.3%
0.445	0.163	0.448	0.233	0.427	0.296	0.9%
0.497	0.162	0.499	0.229	0.503	0.351	0.4%
0.562	0.160	0.550	0.225	0.566	0.398	0.9%
0.654	0.157	0.638	0.218	0.598	0.418	1.4%
0.694	0.156	0.696	0.215	0.698	0.493	0.1%
0.754	0.155	0.747	0.212	0.746	0.525	0.4%
0.798	0.154	0.798	0.209	0.838	0.596	0.7%
0.899	0.152	0.901	0.204	0.897	0.643	0.4%
0.951	0.149	0.944	0.201	0.973	0.698	0.6%
0.999	0.145	0.996	0.197	0.997	0.718	0.4%
1.055	0.139	1.047	0.193	1.093	0.773	0.7%

$J_{C_P}$	$C_T$	$J_{C_T}$	$C_P$	$J_\eta$	$\eta$	Max J Percent Difference
1.099	0.133	1.142	0.182	1.161	0.797	0.9%
1.199	0.117	1.193	0.174	1.197	0.808	0.2%
1.272	0.109	1.288	0.158	1.296	0.827	0.6%
1.332	0.093	1.332	0.149	1.396	0.843	1.2%
1.400	0.081	1.383	0.139	1.396	0.843	0.2%
1.464	0.069	1.464	0.119	1.496	0.846	0.7%
1.520	0.059	1.493	0.112	1.552	0.838	0.5%
1.572	0.049	1.581	0.089	1.595	0.821	0.2%
1.653	0.034	1.654	0.069	1.639	0.797	0.1%
1.701	0.025	1.691	0.058	1.695	0.741	0.3%
1.781	0.010	1.772	0.033	1.775	0.561	0.1%
1.829	0.000	1.838	0.010	1.835	0.102	0.1%
#N/A	#N/A	1.860	0.000	1.843	-0.001	0.2%

The average percent differences over the three ranges of advance ratio described previously in Paragraph 6.2.2.1 are shown in the following table. The average percent differences for all J are consistent with the values obtained for other smaller propellers tested under the QV test cases. However, the average percent differences for the data consisting of subsets of the advance ratio are worse than those observed for the QV test cases where the worst efficiency prediction was still within 10%.

**Table 28: Full Scale Test Results - Average Percent Differences**

	J	$C_T$	$C_P$	$\eta$
<b>Average Percent Differences for all J:</b>	<b>2.44%</b>	<b>23.65%</b>	<b>17.37%</b>	<b>20.59%</b>
<b>Average Percent Difference for J = 0 to J at PROPDES Predicted Max Efficiency</b>	<b>2.31%</b>	<b>22.95%</b>	<b>18.30%</b>	<b>16.73%</b>
<b>Average Percent Difference for J = 0 to J at Experimental Max Efficiency</b>	<b>2.40%</b>	<b>22.29%</b>	<b>18.43%</b>	<b>17.29%</b>

Table 28 seems to indicate that the PROPDES predictions were degraded for the larger propeller with accurate airfoil data, however the peak efficiency estimate was 9.45% higher than the experimental value and the advance ratio corresponding to the peak efficiency was shifted to the right by only 5.74% which

outperforms several of the QV test cases. This improvement in the prediction of the J at peak efficiency is most likely due to the more accurate airfoil data used however more research is needed to determine if that is truly the case. It is encouraging to note that the PROPDES prediction capability appears to be consistent for large scale and small scale propellers.

## 6.6 – Future Work

The current research provides a framework for further validation of QPROP/QMIL using the developed PROPDES Excel/VBA program. The current work was limited by the decision to only use a Clark Y airfoil. This decision was made based on the APC propeller website claiming that a “modified” Clark Y airfoil is used in their propeller design. To further refine the PROPDES validation efforts, the true airfoil must be considered. This scenario may be achieved by using a piece of solder to form the cross sectional outline of each APC propeller at several radial locations to better define the airfoil. The airfoil found using this method can then be input into XFOIL for more accurate airfoil data which can then be input into PROPDES. The process of using solder to determine the airfoil geometry is well described on the QPROP website in the prop\_measure.pdf file.

In order to further refine the accuracy of PROPDES, several modifications and improvements would be necessary. Ideally, these improvements would be made to PROPDES and then the presented test cases could be re-validated to determine a baseline accuracy gain. The improved PROPDES could then be used to run a multitude of test cases using the UIUC database, which provides an abundant number of test points. The specific improvements that the author has identified for PROPDES are discussed in detail in Section 4.4 and are listed briefly below for clarity:

1. Create a loop to run QMIL and QPROP to perform design-analysis-design-analysis-etc until multiple analysis conditions are satisfied
2. Manufacturability limitations considered (minimum thickness, chord limits, hub limits, etc)
3. Include QPROP’s motor analysis within PROPDES



4. Additional airfoils must be considered
5. Develop an XFOIL VBA module to allow the automatic inclusion of updated XFOIL data based on local Reynolds Number and local defined airfoils

Once these improvements are made, PROPDES could be used to test a great number of propeller cases.

The data collected from a much larger validation effort would be of great use in determining QPROP accuracy across more design variables (such as Power Available, number of blades, varying airfoils) and work could be performed to quantify the accuracy based on the variation with these variables with the end goal being a correction factor that would be implemented within PROPDES such that all reasonable design cases are estimated to within a few percent of the experimental data collected.

Additional work must also be done to accurately capture the uncertainty in the experimental data used to validate design and analysis programs. The data set used in this work did not provide enough information to determine whether or not the program predictions were within the uncertainty of the values captured during wind tunnel testing.

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## APPENDIX A QPROP OUTPUT QUICK REFERENCE

The QPROP Quick Reference Card was created to assist any QPROP user in reviewing the QPROP outputs. It captures information on where each of the output variables is defined within the QPROP code structure as well as additional conversion factors and reminders regarding other expressions. The quick reference card is attached on the next page.

QPROP Output Cheat Sheet

Column Number Output Title (Variable Name) Function Additional Details	ASSUMES THAT QPROP IS RUN WITH A GIVEN RPM									
	<div style="border: 1px solid red; display: inline-block; padding: 2px;">[ ]</div> = Function of Motor Parameters (Not used by PROPDES) All others are functions of RPM, VEL and Prop Geometry ONLY.									
1 Velocity (m/s) (VEL)  Set by Input Parameters File	2 RPM (RPM)  Set by Input Parameters File  =OMG*30/PI	3 Dbeta (DBET)  Do Loop within qprop.f DBET=DBET1+DBET2+...	4 Thrust (N) (TP)  Defined in TQCALC.f	5 Torque (N*m) (QP)  Defined in TQCALC.f	6 Shaft Power (W) (POWER)  =QP*OMG	7 Volts (VOLT)  Defined in VOLTM Subroutine  =VM	8 Amps (AMPS)  Defined in VOLTM Subroutine  =AM	9 Motor Efficiency (EFFM)  If PINPUT≠0 Then EFFM=(POWER/PINPUT) Else EFFM=0	10 Propeller Efficiency (EFFP)  If POWER≠0 Then EFFP=(PPROP/POWER)	
11 Advance Ratio (ADV)  If OMG>0 Then ADV=(VEL/OMG*RAD) Else ADV=0 =VEL/(RPM*PI/30*RAD) =VEL/(2*PI*n*Rad) = J/PI	12 Coefficient of Thrust (CT)  =TP*WRI**2*2.0/(RHO*PI*RAD**2) =(8/PI^3)*(TP/(RHO*n^2*d^4))	13 Coefficient of Power (CP)  =QP*WRI**2*2.0/(RHO*PI*RAD**3) =(8/PI^4)*(2*PI*QP)/(RHO*n^2*D^5)	14 DV (m/s) (DV)  =sqrt(VEL**2+TP**2.0/(RHO*PI*RAD**2))-VEL	15 Total Efficiency (EFF)  =EFFM*EFFP	16 Electric Power (PINPUT)  =VOLT*AMPS	17 Propeller Power (PPROP)  =TP*VEL	18 CL Average (CLAVG)  Do Loop below line 110	19 CD Average (CDAVG)  Do Loop below line 110		
Additional Conversion Factors and Reminders										
WRI = 0 if OMG = 0 WRI = 1/(OMG*RAD) if OMG≠0	OMG = RPM*PI/30 = n*2*PI	Pitch = 2*PI*RAD*tan(BETA)  BETA = arctan((Pitch)/(2*PI*RAD))					CT_UIUC = TP/(RHO*n^2*D^4) = ((PI^3)/8)*CT_QPROP			
							CP_UIUC = (2*PI*QP)/(RHO*n^2*D^5) = ((PI^4)/8)*CP_QPROP			
n=RPM/60	RAD = Radius listed in Prop File or QPROP uses last radial station in prop file if RAD is absent					J = VEL/(n*D)=(PI*VEL)/(OMG*RAD)=Adv_QPROP*PI				
d=2*RAD						Eta = J*CT/(CP*2*PI)				
_QPROP is used to specify terms that are outputs of QPROP										



## APPENDIX B PROPDES VBA CODE

This appendix contains the VBA code used to create PROPDES and to run the design and analysis cases of QMIL and QPROP respectively, as discussed in this thesis. The code is broken into Modules for ease of use/troubleshooting. This appendix has been broken up by headings corresponding to the module names as used by the author. The user may simply create new modules within a new Excel file and copy and paste each of the following module codes into the newly created modules. There are of course other constraints on the names of the worksheets, workbook, and additional files required but those details are given in the body of this thesis and are not repeated here. Appendix C contains screenshots of each of the Excel worksheets used in the PROPDES.xlsm workbook so that one would be able to recreate the Excel file discussed within this thesis if desired.

It is important to note that since PROPDES uses Drela's QPROP, PROPDES is released under the same software license as QPROP. That software license is the Gnu General Public License, Version 2 (1991) and can be found here:

<http://web.mit.edu/drela/Public/web/gpl.txt>

# AnalyzePropeller

```
*****
' Module:      AnalyzePropeller
'
' Copyright (C) 2015 Trevor Lowe
'
' This program is free software; you can redistribute it and/or modify
' it under the terms of the GNU General Public License as published by
' the Free Software Foundation; either version 2 of the License, or
' (at your option) any later version.
'
' This program is distributed in the hope that it will be useful,
' but WITHOUT ANY WARRANTY; without even the implied warranty of
' MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
' GNU General Public License for more details.
'
' You should have received a copy of the GNU General Public License
' along with this program; if not, write to the Free Software
' Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
*****

'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis
'AnalyzeProp() creates input files and batchfiles to run QPROP and print the
'results to the worksheet "Analyze Prop". A propeller file must be selected
'from the drop down menu on the "Analyze Prop" worksheet. Motor properties
'are not considered and a default motor file is used for QPROP's purposes.

Option Explicit
Public A_RPM1 As Single, A_RPM2 As Single, A_Vinf1 As Single, A_Vinf2 As Single
Public A_rho As Single, A_mu As Single, A_sos As Single
Public A_FilePath As String, A_propfilepath As String, A_qpropfilepath As String
Public A_motorfilepath As String, A_qproprunfilepath As String
Public A_qprop_outputfilepath As String, A_propfile As String
Public A_qprop_outputfile As String, A_qconfilepath As String
Public A_RPM_Sweep_Steps As Integer, A_Vinf_Sweep_Steps As Integer

Dim A_fnum As Integer

'-----Define Batch File used to run QPROP
Public A_batchfilepath As String
Public A_BatchFile As TextStream
Public A_fso As New FileSystemObject

Sub AnalyzeProp()
'----Read in variables to support running QPROP() as stand-alone
A_RPM1 = Worksheets("Analyze Prop").Cells(4, 3)
A_RPM2 = Worksheets("Analyze Prop").Cells(4, 4)
A_Vinf1 = Worksheets("Analyze Prop").Cells(5, 7) / 3.28084 'Converts fps on sheet to m/s
A_Vinf2 = Worksheets("Analyze Prop").Cells(5, 8) / 3.28084 'Converts fps on sheet to m/s
A_rho = Worksheets("Analyze Prop").Cells(6, 3) * 515.379 'Converts slugs/ft^3 to kg/m^3
A_mu = Worksheets("Analyze Prop").Cells(7, 3) * 47.88 'Converts lbf-s/ft^2 to kg/m-s
A_sos = Worksheets("Analyze Prop").Cells(8, 3) * 0.3048 'Converts fps to m/s
A_RPM_Sweep_Steps = Worksheets("Analyze Prop").Cells(5, 3)
A_Vinf_Sweep_Steps = Worksheets("Analyze Prop").Cells(6, 7)

'----Read in File Paths to support running as stand alone
A_FilePath = Worksheets("Initial Setup").Cells(2, 2)
A_propfile = Worksheets("Analyze Prop").Cells(2, 4)
A_propfilepath = Worksheets("Initial Setup").Cells(5, 2) & A_propfile
A_qpropfilepath = A_FilePath & "qprop.exe"
A_motorfilepath = A_FilePath & "motor.txt"
A_qproprunfilepath = A_FilePath & "qprop_run.txt"
A_batchfilepath = A_FilePath & "batchfile.bat"
A_qprop_outputfile = Worksheets("Analyze Prop").Cells(3, 4) & ".dat"
A_qprop_outputfilepath = A_FilePath & "QPROP_Outputs\" & A_qprop_outputfile

'----Read in File Path for Air Properties
'----This file path is currently set to work only for the
'----C:\PROPDES\qcon.def location in the QPROP code.
'----Line from qcget.f in the QPROP src folder: FNAME = 'C:\PROPDES\qcon.def'
'----PROPDES uses the A_FilePath variable here to define where the qcon.def file
'----is located.
'----MUST UPDATE THE QCON FILEPATH IN DRELA'S CODE BASED ON WHERE PROPDES IS INSTALLED
'----OR USE THE DEFAULT LOCATIONS - PROPDES INSTALLED IN C:\PROPDES\
A_qconfilepath = A_FilePath & "qcon.def"

'---Create Batch File used to run QPROP
Set A_fso = CreateObject("Scripting.FileSystemObject")
Set A_BatchFile = fso.CreateTextFile(A_batchfilepath, True)

A_BatchFile.Write (A_qpropfilepath & " " & A_propfilepath & " " & A_motorfilepath & " " & A_qproprunfilepath & " " & A_qprop_outputfilepath)

A_BatchFile.Close

'---Call necessary subroutines to set-up and run QPROP
```

```

Call A_CreateQcon
Call A_CreateQPROPrun

'----Run QPROP at dos-prompt
Call ShellandWait("cmd.exe /c " & A_batchfilepath, 100)

Call AnalyzeQPROPReader
Call A_Chart
End Sub

'-----CreateQcon() will write the air properties file for QPROP-----
Sub A_CreateQcon()
'-----Set and open file for output
A_fnum = FreeFile + 1
Open A_qconfilepath For Output As A_fnum
'-----Write Density (rho) Line
Print #A_fnum, A_rho & "          ! rho (kg/m^3)    density"
'-----Write Dynamic Viscosity (mu) Line
Print #A_fnum, A_mu & "          ! mu (kg/m·s)    dynamic viscosity"
'-----Write Speed of Sound (a) Line
Print #A_fnum, A_sos & "          ! a (m/s)      speed of sound"
'-----Write Timestamp
Print #A_fnum, "!" & Format(Now(), "m/d/yy h:m:s AMPM")

'-----Close file
Close #A_fnum
End Sub

'-----CreateQPROPrun() will write the run file for QPROP----
Sub A_CreateQPROPrun()
'-----Set and open file for output
A_fnum = FreeFile + 2
Open A_qproprunfilepath For Output As A_fnum

'-----Write line by line to QPROP run file (Run only at design point)
'-----Write Velocity Line (Vel1 Vel2 Nvel ! m/s)
Print #A_fnum, A_Vinf1 & " " & A_Vinf2 & " " & A_Vinf_Sweep_Steps & " ! Airspeed in m/s"

'-----Write RPM Line (RPM1 RPM2 NRPM)
Print #A_fnum, A_RPM1 & " " & A_RPM2 & " " & A_RPM_Sweep_Steps & " ! RPM"

'-----Write Volt Line (Volt1 Volt2 NVolt) (NOT USED)
Print #A_fnum, "0 0 0"
'-----Write Pitch Change Line (Dbet1 Dbet2 NDbet) (NOT USED)
Print #A_fnum, "0 0 0"

'-----Write Timestamp
Print #A_fnum, "!" & Format(Now(), "m/d/yy h:m:s AMPM")

'-----Close file
Close #A_fnum
End Sub

Sub AnalyzeQPROPReader()
'---Define locally used variables
Dim File As String, Number As Single
Dim Counter As Integer, n As Integer, rstart As Integer, cstart As Integer
Dim LineText As String, SplitLineText As Variant, errLineText As Variant
Dim i As Integer, nn As Integer
Dim Hashtag As Integer
Dim FirstNum As Single, SecondNum As Single, MsgInput As Variant

rstart = 14
cstart = 4

'---If running this sub by itself:
qprop_outputfilepath = "C:\PROPDES\QPROP_Output.dat"

'-----Set constants
File = FreeFile + 3
Counter = 0
i = 0

'-----Open QPROP Output file and read in Results
Open A_qprop_outputfilepath For Input As File
While Not EOF(File)
i = 0
Line Input #File, LineText ' Saves current line of text into LineText
Counter = Counter + 1 ' Keeps track of which line you are currently on
Hashtag = InStr(1, LineText, "#") 'Returns number of '#' in LineText as Integer
' If LineText contains # then test to see if on titles line
If Hashtag > 0 Then
'Test for Titles line and if on it parse and print as strings.
If InStr(1, LineText, "V(m/s)") > 0 Then
SplitLineText = Split(LineText, " ") 'Parses text seperated by a space
For n = 0 To UBound(SplitLineText)
If Not SplitLineText(n) = "" Then
i = i + 1 'i keeps track of how many non-space values have been stored
'Prints Parsed Strgs
Worksheets("Analyze Prop").Cells(Counter + rstart, i + cstart) _

```

```

        = SplitLineText(n)
    End If
Next n
Else
    'Print LineText to cstart col if LineText contains # but is not the titles row
    Worksheets("Analyze Prop").Cells(Counter + rstart, 1 + cstart) = LineText
End If
Else
    'Parse LineText and save each portion as a number (single) then print to each column
    SplitLineText = Split(LineText, " ") 'Parses text into parts seperated by a space
    For n = 0 To UBound(SplitLineText)
        If Not SplitLineText(n) = "" Then
            i = i + 1 'i keeps track of how many non-space values have been stored
            On Error GoTo errHandler
            Number = CSng(SplitLineText(n)) 'Converts string stored into a single
            Worksheets("Analyze Prop").Cells(Counter + rstart, i + 1 + cstart) = Number
1000
        End If
    Next n
End If
On Error GoTo 0
Wend
Close File
Worksheets("Analyze Prop").Calculate 'Added on 10/3

If Not Dir(A_qpropunfilepath) = vbNullString Then Kill A_qpropunfilepath
If Not Dir(A_batchfilepath) = vbNullString Then Kill A_batchfilepath
If Not Dir(A_qconfilepath) = vbNullString Then Kill A_qconfilepath
'Commented out line below due to desire to save QPROP outputs in the QPROP_Outputs Folder
'If Not Dir(A_qprop_outputfilepath) = vbNullString Then Kill A_qprop_outputfilepath
Exit Sub
errHandler:
    'Print SplitLineText(n) to messagebox and ask user to split the number into 2.
    MsgBox = InputBox(SplitLineText(n) & _
        " Problem reading output file data. The number above should be split into 2 numbers. " _
        & "Please input the first number now:", "QPROP Reader Error")
    If Not MsgBox = "" Then
        FirstNum = CSng(MsgBox)
        Worksheets("Analyze Prop").Cells(Counter + rstart, i + 1 + cstart) = FirstNum
    Else
        Worksheets("Analyze Prop").Cells(Counter + rstart, i + 1 + cstart) = MsgBox
    End If

    i = i + 1

    MsgBox = InputBox(SplitLineText(n) & _
        " Please input the second number now:", "QPROP Reader Error")
    If Not MsgBox = "" Then
        SecondNum = CSng(MsgBox)
        Worksheets("Analyze Prop").Cells(Counter + rstart, i + 1 + cstart) = SecondNum
    Else
        Worksheets("Analyze Prop").Cells(Counter + rstart, i + 1 + cstart) = MsgBox
    End If

    Err.Clear
    Resume 1000
End Sub

Sub A_Chart()
    '----Define locally used variables
    Dim DataRow As Integer, R As Integer
    Dim count As Integer, Blank As Integer, Current_S As Integer, D As Integer

    '----Define Static Variables
    DataRow = 32 'Row that output data begins on Analyze Prop Worksheet
    count = 0 'Resets Count variable (used to count number of rows per data series)
    Blank = 0 'Resets Blank Row Counter (Used to end Sub once 2 blank rows are found together)

    'Select CT Chart and remove current series
    Worksheets("Analyze Prop").ChartObjects("Chart 1").Activate
    With ActiveChart
        For D = .SeriesCollection.count To 1 Step -1
            .SeriesCollection(D).Delete
        Next D
    End With

    'Select CP Chart and remove current series
    Worksheets("Analyze Prop").ChartObjects("Chart 4").Activate
    With ActiveChart
        For D = .SeriesCollection.count To 1 Step -1
            .SeriesCollection(D).Delete
        Next D
    End With

    'Select Efficiency Chart and remove current series
    Worksheets("Analyze Prop").ChartObjects("Chart 5").Activate
    With ActiveChart
        For D = .SeriesCollection.count To 1 Step -1
            .SeriesCollection(D).Delete
        Next D
    End With

```

```

        Next D
    End With

    For R = DataRow To 1000 '1000 is the limit of the current output charts
        If Blank > 1 Then Exit For

        If Not Worksheets("Analyze Prop").Cells(R, 7) = "" Then
            count = count + 1
            Blank = 0
        Else
            'Blank counts the number of Blank rows of data to test for the end of the data set
            Blank = Blank + 1

            'Test if there are 2 blank lines together then end of data has been reached
            'No need to add additional blank series
            If Blank > 1 Then Exit For

            'Select CT Chart and establish series for each RPM Sweep
            Worksheets("Analyze Prop").ChartObjects("Chart 1").Activate
            With ActiveChart.SeriesCollection.NewSeries
                .Name = Worksheets("Analyze Prop").Cells(R - 1, 7)
                .Values = Range(Worksheets("Analyze Prop").Cells(R - count, 31), _
                    Worksheets("Analyze Prop").Cells(R - 1, 31))
                .XValues = Range(Worksheets("Analyze Prop").Cells(R - count, 30), _
                    Worksheets("Analyze Prop").Cells(R - 1, 30))
            End With

            'Select CP Chart and establish series for each RPM Sweep
            Worksheets("Analyze Prop").ChartObjects("Chart 4").Activate
            With ActiveChart.SeriesCollection.NewSeries
                .Name = Worksheets("Analyze Prop").Cells(R - 1, 7)
                .Values = Range(Worksheets("Analyze Prop").Cells(R - count, 32), _
                    Worksheets("Analyze Prop").Cells(R - 1, 32))
                .XValues = Range(Worksheets("Analyze Prop").Cells(R - count, 30), _
                    Worksheets("Analyze Prop").Cells(R - 1, 30))
            End With

            'Select Efficiency Chart and establish series for each RPM Sweep
            Worksheets("Analyze Prop").ChartObjects("Chart 5").Activate
            With ActiveChart.SeriesCollection.NewSeries
                .Name = Worksheets("Analyze Prop").Cells(R - 1, 7)
                .Values = Range(Worksheets("Analyze Prop").Cells(R - count, 29), _
                    Worksheets("Analyze Prop").Cells(R - 1, 29))
                .XValues = Range(Worksheets("Analyze Prop").Cells(R - count, 30), _
                    Worksheets("Analyze Prop").Cells(R - 1, 30))
            End With

            count = 0 'Resets Count variable (used to count number of rows per data series)
        End If
    Next R
End Sub

Sub A_Clear()
    ' Clears ranges that were printed to screen during previous runs
    Range("E15:Y1000").Select
    Selection.ClearContents
    Range("A1").Select
End Sub

```

## APC

```

*****
Module:      APC
,
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,
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,      Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
*****

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis
'UseAPC() is called if QMIL fails to produce a propeller chord or beta distribution.
'UseAPC() will use the APC distribution provided in the hidden worksheet "APC Electric" to
'provide a scaled distribution for input to the next iteration of QMIL.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Dim n As Integer
Dim IdealPitch As Single
Sub UseAPC()
    Count_APC = Count_APC + 1
    APC_Used = True
    ReDim APC_X(0 To Xsta), APC_Chord(0 To Xsta), APC_Beta(0 To Xsta) 'APC_X not used anywhere

    If Count_APC < 4 Then
        '---Define Constants
        Count_Iter = m
        AVGDISTROS = False
        '-----Interpolate APC Chord Distribution at XIds locations
        For n = 0 To Xsta
            If n = 0 Then
                APC_Chord(n) = Hub_rad
                APC_Beta(n) = 0
            End If
            If n > 0 Then
                'Define APC Chord Distro in meters
                '(2*Radius) term converts chord/Diameter to Chord.
                '2 = Column where Chord/Diameter data is stored, HOWEVER THAT VALUE IS NOT USED
                'INTERP CODE WAS UPDATED TO HAVE 1 COLUMN TO CHOOSE FROM SO NO MATTER THE VALUE
                'OF THE SECOND FIELD, INTERP ALWAYS CHOOSES THE 2ND COLUMN
                APC_Chord(n) = Interp("APC Electric", 2, XIds(n), "Chord") * (2 * Radius)
                '---Define Beta Distribution to be used in Degrees
                '6 = Column where Beta data is stored, HOWEVER THAT VALUE IS NOT USED
                'THE INTERP CODE WAS UPDATED TO ONLY HAVE 1 COLUMN TO CHOOSE FROM SO NO MATTER THE
                VALUE
                'OF THE SECOND FIELD, INTERP ALWAYS CHOOSES THE 2ND COLUMN
                APC_Beta(n) = Interp("APC Electric", 6, XIds(n), "Beta")
            End If

            '---Print out Radius Location, Chord, and Beta
            Worksheets("Create Prop Inputs").Cells(RowStart + 4 + m * 7, ColStart + n) = _
                XIds(n) * Radius * 39.37 'Radius in Inches

            Worksheets("Create Prop Inputs").Cells(RowStart + 5 + m * 7, ColStart + n) = _
                APC_Chord(n) * 39.37 'Chord in Inches

            Worksheets("Create Prop Inputs").Cells(RowStart + 6 + m * 7, ColStart + n) = _
                APC_Beta(n) 'Beta in degrees
        Next n
    Else
        AVGDISTROS = True
        For k = Count_Iter To m
            '---Reset Variables
            If k = Count_Iter Then
                For n = 0 To Xsta
                    APC_Chord(n) = 0
                    APC_Beta(n) = 0
                Next n
            End If

            '---Calculate the average Chord and Beta since the last time APC chord was used
            For n = 0 To Xsta
                'Chord in inches
                APC_Chord(n) = APC_Chord(n) + _
                    Worksheets("Create Prop Inputs").Cells(RowStart + 5 + k * 7, ColStart + n)
            Next n
        Next k
    End Sub

```

```

'Beta in degrees
APC_Beta(n) = APC_Beta(n) + _
Worksheets("Create Prop Inputs").Cells(RowStart + 6 + k * 7, ColStart + n)

If k = m Then
    APC_Chord(n) = APC_Chord(n) / (m - Count_Iter)
    APC_Beta(n) = APC_Beta(n) / (m - Count_Iter)

    '---Print out Radius Location, Chord, and Beta
    Worksheets("Create Prop Inputs").Cells(RowStart + 4 + m * 7, ColStart + n) = _
    Xides(n) * Radius * 39.37 'Radius in Inches

    Worksheets("Create Prop Inputs").Cells(RowStart + 5 + m * 7, ColStart + n) = _
    APC_Chord(n) 'Chord in Inches
    Worksheets("Create Prop Inputs").Cells(RowStart + 6 + m * 7, ColStart + n) = _
    APC_Beta(n) 'Beta in degrees
End If
Next n
Next k
End If
End Sub

```

## Functions

```
*****
' Module:      Functions
'
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'
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' along with this program; if not, write to the Free Software
' Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
*****

'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis
'These functions are used during the Analyze Prop and Design Prop cases. Each function is
'either self-explanatory or has a 1-line description within the function itself.

Option Explicit

Dim x As Single, Number As Single

Public Function Velocity(RPS, x)
    Velocity = 2 * Pi() * x * RPS
End Function

Public Function sqrt(Number)
    'Finds the square root of Number
    sqrt = Number ^ (1 / 2)
End Function

Public Function Pi()
    'Makes Pi() variable equal the worksheet function
    Pi = WorksheetFunction.Pi
End Function

Public Function Re(RHO, V, l, MU) As Double
    'Calculates Reynold's Number
    Re = (RHO * V * l) / MU
End Function

Sub Titles()
    'Sets titles for each iteration. Titles appear on the left hand side.
    Cells(RowStart + 4 + m * 7, 1).Select
    If AVGDISTROS = False Then
        ActiveCell.FormulaR1C1 = "Iteration " & (m + 1)
    Else
        ActiveCell.FormulaR1C1 = "AVG Distribution:"
    End If
    Range(Cells(RowStart + 4 + m * 7, 1), Cells(RowStart + 9 + m * 7, 2)).Select
    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
        .WrapText = False
        .Orientation = 0
        .AddIndent = False
        .IndentLevel = 0
        .ShrinkToFit = False
        .ReadingOrder = xlContext
        .MergeCells = False
    End With
    Selection.Merge
    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlCenter
        .WrapText = False
        .Orientation = 0
        .AddIndent = False
        .IndentLevel = 0
        .ShrinkToFit = False
        .ReadingOrder = xlContext
        .MergeCells = True
    End With
    Selection.Font.Bold = True
    Selection.Font.Underline = xlUnderlineStyleSingle
End Sub
```



```

Sub UpdatePropFileNames()
    'In VBE, click Tools, References, find "Microsoft Scripting Runtime"
    'and check it off for this program to work
    'Adapted from dbrown14's code found here:
    'http://www.ozgrid.com/forum/showthread.php?t=156742

    Dim fsso As FileSystemObject
    Dim fold As Folder
    Dim f As File
    Dim folderPath As String
    Dim i As Integer

    folderPath = Worksheets("Initial Setup").Cells(5, 2)

    Set fsso = New FileSystemObject
    Set fold = fsso.GetFolder(folderPath)
    i = 1
    For Each f In fold.Files
        If LCase(Right(f.Name, 3)) = ".txt" Then
            Worksheets("Analyze Prop").Range("AH" & i).Value = f.Name
            i = i + 1
        End If
    Next
End Sub

Sub Clear()
    ' Clears ranges that were printed to screen during previous runs
    Range("D13:AH14").Select
    Selection.ClearContents
    Range("A16:AH845").Select
    Selection.ClearContents
    Range("A1").Select

    Worksheets("Create Prop Output").Select
    Range("A1:A40").Select
    Selection.ClearContents
    Rows("15:150").Select
    Selection.ClearContents
    Range("A1").Select

    Worksheets("Create Prop Inputs").Select
    Range("A11:B14").Select
    Range("A1").Select
End Sub

Function SetSquareAxes(cht As Chart, dBuf As Double, dInc As Double, _
    ByVal xMin As Double, ByVal xMax As Double, _
    ByVal yMin As Double, ByVal yMax As Double) As Boolean
    ' shg 2009-0220
    ' See more at:
    ' http://www.andypope.info/charts/SetSquareAxis.htm#sthash.8sRBpg0U.dpuf
    ' Sets the chart scales to
    ' o be of equal span
    ' o start and end on a multiple of dInc, and have dInc as the major unit
    ' o contain all points with a minimum buffer distance of dBuf to the edges
    ' o center the points in the plot area within the constraints above

    ' E.g.,

    ' SetSquareAxes Sheet1.ChartObjects(1).Chart, 100, 500, _
    ' WorksheetFunction.Min(rngX.Value), _
    ' WorksheetFunction.Max(rngX.Value), _
    ' WorksheetFunction.Min(rngY.Value), _
    ' WorksheetFunction.Max(rngY.Value)

    ' Returns True if successful

    Static WF As WorksheetFunction
    Dim xCtr As Double
    Dim yCtr As Double
    Dim dRad As Double ' half-dimension of bounding box
    Dim dDelta As Double ' common span of x and y scales

    ' verify cht is a scatterchart
    Select Case cht.SeriesCollection(1).ChartType
        Case xlXYScatter, xlXYScatterLines, xlXYScatterSmooth, _
            xlXYScatterLinesNoMarkers, xlXYScatterSmoothNoMarkers
        Case Else
            MsgBox "Chart type must be XY (Scatter)", vbOKOnly, "SetSquareAxes"
            Exit Function
    End Select

    If WF Is Nothing Then Set WF = WorksheetFunction

    ' compute center and bounding box radius
    xCtr = (xMax + xMin) / 2#
    yCtr = (yMax + yMin) / 2#
    dRad = WF.Max(xMax - xCtr, yMax - yCtr) + dBuf

    ' compute the scale minima
    xMin = Int((xCtr - dRad) / dInc) * dInc
    yMin = Int((yCtr - dRad) / dInc) * dInc

```

```

' compute the common span and the scale maxima
dDelta = WF.Ceiling(WF.Max(xMax - xMin, yMax - yMin) + dBuf, dInc)
xMax = xMin + dDelta
yMax = yMin + dDelta

'T Lowe added the following to correct for my specific case where _
  I want the bottom left corner of charts to be 0,0
If xMin < 0 Then
  xMax = xMax '+ Abs(xMin)
  xMin = 0
End If

If yMin < 0 Then
  yMax = yMax '+ Abs(yMin)
  yMin = 0
End If
'End of Trevor's edits

With cht.Axes(xlCategory)
  .MinimumScale = xMin
  .MaximumScale = xMax
  .MinorUnitIsAuto = True
  .MajorUnitIsAuto = False
  .MajorUnit = dInc
  'Edit by T Lowe to set number of decimal points on labels to 1
  .TickLabels.NumberFormat = "0.0"
End With

With cht.Axes(xlValue)
  .MinimumScale = yMin
  .MaximumScale = yMax
  .MinorUnitIsAuto = True
  .MajorUnitIsAuto = False
  .MajorUnit = dInc
  'Edit by T Lowe to set number of decimal points on labels to 1
  .TickLabels.NumberFormat = "0.0"
End With
SetSquareAxes = True
End Function

Sub SaveResults()
  Dim x As Workbook
  Dim y As Workbook

  '## Open both workbooks first:
  Set x = Workbooks.Open(Worksheets("Initial Setup").Cells(2, 2))
  Set y = Workbooks.Open(Worksheets("Initial Setup").Cells(2, 2))

  'Now, copy what you want from x:
  x.Sheets("name of copying sheet").Range("A1").Copy

  'Now, paste to y worksheet:
  y.Sheets("sheetname").Range("A1").PasteSpecial

  'Close x:
  x.Close
End Sub

```

# Interpolation

```
'*****
' Module:      Interpolation
'
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'
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' Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
'*****

'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis
'The following sources were used to develop this code:
'http://www.quantcode.com/modules/mydownloads/singlefile.php?lid=247
'http://stackoverflow.com/questions/13030660/interpolation-in-vba

'Defines the functions necessary for linear interpolation of a 2 dimensional data set
'This Interpolation Module will not extrapolate under any circumstances and will
'simply return the value at the extreme of the data set if the bounds of the data set
'are broken.

Option Explicit
Dim x1 As Single, x2 As Single, y1 As Single, y2 As Single, x As Single, y As Single
Dim Q11 As Single, Q12 As Single, Q21 As Single, Q22 As Single, den As Single
Dim fx1 As Single, fx2 As Single, fy1 As Single, fy2 As Single
Dim P1 As Double, P2 As Double, P3 As Double, P4 As Double

Dim ColChoice As Integer, n As Integer
Dim RowChoice As Integer

Public xCOL1 As Integer, xCOL2 As Integer, yROW1 As Integer, yROW2 As Integer
Public Sheet As String, Choice As String

Sub define(Sheet, Choice)
'---INPUT BEGINNING AND END OF COLUMNS AND ROWS OF DATA SET
'---NOTE: Make sure that data set begins in R3C3 or change the given values in sub define(Sheet)
'---NOTE: Any changes in order of the Excel sheets will require sub define to be updated

'---CL Data listed in Sheet CL vs Alpha
If Sheet = "Clark Y" And Choice = "CL" Then
    xCOL1 = 20
    xCOL2 = 32
    yROW1 = 3
    yROW2 = 54
End If

'---CD Data listed in Sheet CD vs Alpha
If Sheet = "Clark Y" And Choice = "CD" Then
    xCOL1 = 3
    xCOL2 = 15
    yROW1 = 3
    yROW2 = 63
End If

'---APC Propeller Data listed in Sheet APC Electric
If Sheet = "APC Electric" And Choice = "Chord" Then
    xCOL1 = 2
    xCOL2 = 2
    yROW1 = 2
    yROW2 = 20
End If

'---APC Propeller Beta Data listed in Sheet APC Electric Beta
If Sheet = "APC Electric" And Choice = "Beta" Then
    xCOL1 = 5
    xCOL2 = 5
    yROW1 = 2
    yROW2 = 20
End If

End Sub

Public Function Interp(Sheet, x, y, Choice)
'---Interpolates between the 4 points of the lookup table bounding X, Y
'---Sheet variable is used to change look up tables (CL, CD, or APC Geom)
'---Interp will NOT extrapolate.
```

```

'---Define the bounds of the lookup table data
Call define(Sheet, Choice)

'---ColChoice and RowChoice Functions are defined below
'---they are used to find the rows/cols bounding X, Y
x1 = ColChoiceA(Sheet, x, Choice)
x2 = ColChoiceB(Sheet, x, Choice)
y1 = RowChoiceA(Sheet, y, Choice)
y2 = RowChoiceB(Sheet, y, Choice)

'For the case where X, Y are bounded inside the lookup table on all 4 sides
If x1 <> x2 And y1 <> y2 Then
    Q11 = Worksheets(Sheet).Cells(y1, x1).Value
    Q21 = Worksheets(Sheet).Cells(y1, x2).Value
    Q12 = Worksheets(Sheet).Cells(y2, x1).Value
    Q22 = Worksheets(Sheet).Cells(y2, x2).Value

    fx1 = Worksheets(Sheet).Cells(yROW1 - 1, x1).Value
    fx2 = Worksheets(Sheet).Cells(yROW1 - 1, x2).Value
    fy1 = Worksheets(Sheet).Cells(y1, xCOL1 - 1).Value
    fy2 = Worksheets(Sheet).Cells(y2, xCOL1 - 1).Value

    If x < fx1 Then x = fx1
    If x > fx2 Then x = fx2
    If y < fy1 Then y = fy1
    If y > fy2 Then y = fy2

    den = ((fx2 - fx1) * (fy2 - fy1))

    P1 = (Q11 / den) * ((fx2 - x) * (fy2 - y))
    P2 = (Q21 / den) * ((x - fx1) * (fy2 - y))
    P3 = (Q12 / den) * ((fx2 - x) * (y - fy1))
    P4 = (Q22 / den) * ((x - fx1) * (y - fy1))

    Interp = P1 + P2 + P3 + P4
End If

'For the case where X is bounded but Y is equal to a look up value
If x1 <> x2 And y1 = y2 Then
    fx1 = Worksheets(Sheet).Cells(yROW1 - 1, x1).Value
    fx2 = Worksheets(Sheet).Cells(yROW1 - 1, x2).Value

    Q11 = Worksheets(Sheet).Cells(y1, x1).Value
    Q12 = Worksheets(Sheet).Cells(y1, x2).Value

    Interp = ((Q11 - Q12) / (fx1 - fx2)) * (x - fx2) + Q12
End If

'For the case where X is equal to a look up value but y is bounded
If x1 = x2 And y1 <> y2 Then
    fy1 = Worksheets(Sheet).Cells(y1, xCOL1 - 1).Value
    fy2 = Worksheets(Sheet).Cells(y2, xCOL1 - 1).Value

    Q11 = Worksheets(Sheet).Cells(y1, x1).Value
    Q21 = Worksheets(Sheet).Cells(y2, x1).Value

    Interp = ((Q11 - Q21) / (fy1 - fy2)) * (y - fy2) + Q11
End If

'For the case where X, Y falls exactly on a look up value given in the tables
If x1 = x2 And y1 = y2 Then
    Interp = Worksheets(Sheet).Cells(y1, x1).Value
End If

End Function

Public Function ColChoiceA(Sheet, x, Choice)
'Chooses first column to the left of X (smaller than X)
'    Call define(Sheet, Choice) 'defines lookup table parameters

'If X is smaller than 1st col value then choose 1st column (Prevents extrapolation)
If x <= Worksheets(Sheet).Cells(yROW1 - 1, xCOL1) Then ColChoice = xCOL1

'If X greater than 1st col value then step through cols
If x > Worksheets(Sheet).Cells(yROW1 - 1, xCOL1) Then
    For n = xCOL1 To xCOL2
        'While stepping thru cols,
        'choose col only if X > current col value
        If x >= Worksheets(Sheet).Cells(yROW1 - 1, n) Then
            ColChoice = n
        End If
    Next n
End If

'If X is greater than the last col value then choose last column (Prevents extrapolation)
If x >= Worksheets(Sheet).Cells(yROW1 - 1, xCOL2) Then ColChoice = xCOL2

'Set Function equal to ColChoice
ColChoiceA = ColChoice

```

```

End Function

Public Function ColChoiceB(Sheet, x, Choice)
'Chooses first column to the right of X (greater than X)
' Call define(Sheet, Choice) 'defines lookup table parameters

'If X is smaller than 1st col value then choose 1st col (Prevents extrapolation)
If x <= Worksheets(Sheet).Cells(yROW1 - 1, xCOL1) Then ColChoice = xCOL1

'If X is greater than 1st col value then step through cols
If x > Worksheets(Sheet).Cells(yROW1 - 1, xCOL1) Then
    For n = xCOL1 To xCOL2
        'While stepping thru cols,
        'choose 1 col to right only if X > current col value
        If x > Worksheets(Sheet).Cells(yROW1 - 1, n) Then
            ColChoice = n + 1
        End If

        'Check to see if X does equals the current Col
        'If X = current col value then choose current col instead of 1 col to right
        If x = Worksheets(Sheet).Cells(yROW1 - 1, n) Then
            ColChoice = n
        End If
    Next n
End If

'If X is greater than the last col value then choose last column (Prevents extrapolation)
If x >= Worksheets(Sheet).Cells(yROW1 - 1, xCOL2) Then ColChoice = xCOL2
ColChoiceB = ColChoice
End Function

Public Function RowChoiceA(Sheet, y, Choice)
'Chooses first row above Y (smaller than Y)
' Call define(Sheet, Choice) 'defines lookup table parameters

'If y is smaller than 1st row, then choose 1st row (Prevents Extrapolation)
If y <= Worksheets(Sheet).Cells(yROW1, xCOL1 - 1) Then RowChoice = yROW1

'If y is greater than 1st row values, then step thru rows
If y > Worksheets(Sheet).Cells(yROW1, xCOL1 - 1) Then
    For n = yROW1 To yROW2
        'While stepping thru rows,
        'choose row only if y >= current row value
        If y >= Worksheets(Sheet).Cells(n, xCOL1 - 1) Then
            RowChoice = n
        End If
    Next n
End If

'If y is greater than last row value, then choose last row (Prevents Extrapolation)
If y >= Worksheets(Sheet).Cells(yROW2, xCOL1 - 1) Then RowChoice = yROW2
RowChoiceA = RowChoice
End Function

Public Function RowChoiceB(Sheet, y, Choice)
'Chooses first row below Y (greater than Y)
' Call define(Sheet, Choice) 'defines lookup table parameters

'If y is smaller than 1st row, then choose 1st row (Prevents Extrapolation)
If y <= Worksheets(Sheet).Cells(yROW1, xCOL1 - 1) Then RowChoice = yROW1

'If y is greater than 1st row values, then step thru rows
If y > Worksheets(Sheet).Cells(yROW1, xCOL1 - 1) Then
    For n = yROW1 To yROW2
        'While stepping thru rows,
        'choose row below current row if Y is greater than current row
        If y > Worksheets(Sheet).Cells(n, xCOL1 - 1) Then
            RowChoice = n + 1
        End If

        'Check to see if y equals the current row value
        'If y = current row value, then choose current row instead of row below
        If y = Worksheets(Sheet).Cells(yROW1 - 1, n) Then
            RowChoice = n
        End If
    Next n
End If

'If y is greater than last row value, then choose last row (Prevents Extrapolation)
If y >= Worksheets(Sheet).Cells(yROW2, xCOL1 - 1) Then RowChoice = yROW2
RowChoiceB = RowChoice
End Function

```

# Main

```
*****
' Module:      Main
'
'   Copyright (C) 2015 Trevor Lowe
'
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'   it under the terms of the GNU General Public License as published by
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'   along with this program; if not, write to the Free Software
'   Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
*****
.....
'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis '
'Program runs QMIL iteratively until the QMIL solution converges. It then runs QPROP '
'for the final QMIL designed propeller (or if QMIL doesn't converge, the final propeller '
'is used) and outputs all of the results to the worksheets. '
'Create Prop Inputs, Output Charts, and Create Prop Outputs. '
.....

'---Module 'Main' contains the main sub-routines used to run QPROP and QMIL.
'---Main contains the sub-routines CreateProp, DesignCL, ReyNum, and CheckConv.

Option Explicit
'-----Define all Public Variables-----
Public Reynolds() As Single, CD_0 As Single, Alpha_CD0 As Single, CLdes() As Single
Public B As Integer, Hub_rad As Single, Radius As Single, Vinf1 As Single, Vinf2 As Single
Public RPM1 As Single, RPM2 As Single, RPS As Single, Thrust As Single, Power As Single
Public Xides() As Single, RHO As Single, MU As Single, SOS As Single
Public m As Integer, cont As Boolean, APC_Used As Boolean
Public Xsta As Integer, inputfilepath As String
Public outputfilepath As String, qmilfilepath As String
Public qpropfilepath As String, qprop_outputfilepath As String, motorfilepath As String
Public qproprunfilepath As String, FilePath As String, qconfilepath As String
Public batchfilepath As String, PropSaveFileName As String

Public RowStart As Integer, ColStart As Integer
Public Count_APC As Integer, Count_Iter As Integer, count As Integer
Public ConvergenceFactor As Single
Public APC_Chord() As Single, APC_Beta() As Single
Public AVGDISTROS As Boolean

'-----Define Airfoil paramaters that are input into QMIL-----
Public QMIL_CL0 As Single, QMIL_CL_a As Single, QMIL_CLmin As Single, QMIL_CLmax As Single
Public QMIL_CD0 As Single, QMIL_CD2U As Single, QMIL_CD2L As Single, QMIL_CLCDO As Single
Public QMIL_REref As Single, QMIL_REexp As Single

'-----Define Batch File used to run QPROP
Public BatchFile As TextStream
Public fso As New FileSystemObject

'-----Define any variables that will only be used locally-----
Dim n As Integer, a As Single, CD As Single, fnum_M As Integer

Sub CreateProp()
'Main Design Prop Program subroutine. Sets up hard coded variables, file paths,
'reads in initial data from sheet, and runs the necessary sub-routines from other Modules.
'Also, creates batch file to run QPROP/QMIL

'----Define Hard Coded Variables
Xsta = 30          'number of blade stations
CD_0 = 10         '
Count_APC = 0     '
ConvergenceFactor = 1# 'currently compared to the sum of the differences at each Xsta
cont = True       'boolean,
AVGDISTROS = False

'----Define the Row and Col Re Number start positions on the "Inputs" Sheet
RowStart = 12
ColStart = 4

'-----Define Arrays
ReDim Reynolds(0 To Xsta), CLdes(Xsta), Xides(Xsta)

'---Set up file paths, batch file will be created using these filepaths
FilePath = Worksheets("Initial Setup").Cells(2, 2)

'---File Paths used by QMILsubs Module
qmilfilepath = FilePath & "qmil.exe"
inputfilepath = FilePath & "QMIL_Input.txt"
```

```

outputfilepath = FilePath & "QMIL_Output.txt"

'---File Paths used by QPROSubs Module
qpropfilepath = FilePath & "qprop.exe"
motorfilepath = FilePath & "motor.txt"
qpropunfilepath = FilePath & "qprop_run.txt"
batchfilepath = FilePath & "batchfile.bat"
qprop_outputfilepath = FilePath & "QPROP_Output.dat"

'---Create Batch File used to run QPROP
Set fso = CreateObject("Scripting.FileSystemObject")
Set BatchFile = fso.CreateTextFile(batchfilepath, True)

BatchFile.Write (qpropfilepath & " " & outputfilepath & " " & motorfilepath _
& " " & qpropunfilepath & " > " & qprop_outputfilepath)

BatchFile.Close

'----Read in Necessary data from sheet
B = Worksheets("Create Prop Inputs").Cells(5, 3)           'Number of Blades
Hub_rad = Worksheets("Create Prop Inputs").Cells(5, 7)     'Hub Radius in inches
Radius = Worksheets("Create Prop Inputs").Cells(1, 3) / 2  'Prop Radius in inches
Vinf1 = Worksheets("Create Prop Inputs").Cells(2, 7)      'Cruise Velocity in fps
Vinf2 = Vinf1                                             'Set for a Single Vinf Point
RPM1 = Worksheets("Create Prop Inputs").Cells(2, 3)       'RPM
RPM2 = RPM1                                              'Set for a Single RPM value
Power = Worksheets("Create Prop Inputs").Cells(4, 7)      'Power in HP
RHO = Worksheets("Create Prop Inputs").Cells(3, 3)        'Read in density (slugs/ft^3)
MU = Worksheets("Create Prop Inputs").Cells(4, 3)         'Read in viscosity (lbf*s/ft^2)
SOS = Worksheets("Create Prop Inputs").Cells(6, 3)        'Read in speed of sound in fps

'---File Path used to Save Propeller File (QMIL Output) to Prop Folder
'---Must be done prior to data conversions for proper propeller file names
PropSaveFileName = Worksheets("Initial Setup").Cells(5, 2) & "PROPDES" & "_Blades" & CInt(B) _
& "_Dia" & CInt(Radius * 2) & "_RPM" & CInt(RPM1) & "_Vinf" & _
CInt(Vinf1 / 1.687) & ".txt"

'-----Convert input data to units needed for QMIL Input
RPS = RPM1 / 60           'n in rev/sec
Hub_rad = Hub_rad / 39.37 'Hub Radius converted to meters
Radius = Radius / 39.37  'Prop Radius converted to meters
Vinf1 = Vinf1 / 3.28084  'Cruise Velocity in m/s
Vinf2 = Vinf1           'Set for a single Vinf
Power = Power * 745.69987 'Power in Watts
SOS = SOS * 0.3048      'Speed of Sound converted from fps to m/s

'Read in File Path for Air Properties and create qcon.def file
'QCON file path is currently set to work only for C:\PROPDES\qcon.def in the QPROP code
'Line from qcget.f in the QPROP src folder: FNAME = 'C:\PROPDES\qcon.def'
'MUST UPDATE THE QCON FILEPATH IN DRELA'S CODE BASED ON WHERE QPROP IS INSTALLED
qconfilepath = FilePath & "qcon.def"
Call CreateQcon

'-----Establish Iterative loop to negate effects of initial conditions in QMIL
For m = 0 To 100           'maximum of 100 iterations
    APC_Used = False
    Call DesignCL         'Chooses best CL value as a function of alpha based on Re number
    Call QMIL
    Call ReyNum
    Call checkConv
    If cont = False Then Exit For
Next m

'Check to see if QMIL has failed and if it has, create a propeller file for
'QPROP to analyze based on average APC geometry
If AVGDISTROS = True Then
    Call CreatePropellerFile
End If

'QPROP is used to analyze the propeller design and will output all of it's data
'to "Create Prop Output" Sheet
Call QPROP

10 'Charts correctly display the iterations performed by QMIL on the "Output Charts" sheet
Call Charts

'Save QMIL Output as a Propeller in the Prop Folder
If Not Dir(PropSaveFileName) = vbNullString Then Kill PropSaveFileName
Name outputfilepath As PropSaveFileName
Call UpdatePropFileNames

'Remove files created during CreateProp() execution
If Not Dir(outputfilepath) = vbNullString Then Kill outputfilepath
If Not Dir(qpropunfilepath) = vbNullString Then Kill qpropunfilepath
If Not Dir(qprop_outputfilepath) = vbNullString Then Kill qprop_outputfilepath

End Sub

'-----CreateQcon() will write the air properties file for QPROP-----
Sub CreateQcon()

```

```

'-----Set and open file for output
fnum_M = FreeFile
Open qconfilepath For Output As fnum_M
'-----Write Density (rho) Line
Print #fnum_M, RHO * 515.379 & "          ! rho (kg/m^3)   density" ' Converts RHO to kg/m^3
'-----Write Dynamic Viscosity (mu) Line
Print #fnum_M, MU * 47.88 & "          ! mu (kg/m-s)   dynamic viscosity" ' Converts MU to kg/m*s
'-----Write Speed of Sound (a) Line
Print #fnum_M, SOS & "          ! a (m/s)   speed of sound"
'-----Write Timestamp
Print #fnum_M, "!" & Format(Now(), "m/d/yy h:m:s AMPM")

'-----Close file
Close #fnum_M

End Sub

Sub DesignCL()
'----DesignCL uses CL vs CD vs Reynolds number data to determine the
'----lowest drag point on the drag polar. It then uses the corresponding
'----alpha to determine the design CL that is input into QMIL as CLdes.

'---Step through each Radial Station from 0 to Xsta
For n = 0 To Xsta
'---Calc Re, *7 is spacing factor for rows on the Excel Sheet
Reynolds(n) = Worksheets("Create Prop Inputs").Cells(RowStart + m * 7, ColStart + n)
'---Check to see if this is the first iteration, m=0
If m = 0 Then
'---on 1st iter, set Xides(n) = x(n) as calculated on sheet
'---e.g. Xsta = 30, Xides(0) = 0, Xides(1) = 1/30, Xides(2) = 2/30, etc.
Xides(n) = Worksheets("Create Prop Inputs").Cells(8, 4 + n)

'-----
'
'   If n = 0 Then
'       CLdes(n) = 0
'       GoTo 15
'   End If
End If

If Not m = 0 Then
Xides(n) = Worksheets("Create Prop Inputs").Cells _
(RowStart + 4 + (m - 1) * 7, ColStart + n) / (Radius * 39.37)
End If
For a = -10 To 20 Step 0.1
CD = Interp("Clark Y", Reynolds(n), a, "CD")
If CD < CD_0 Then CD_0 = CD
If CD_0 = CD Then Alpha_CD0 = a
Next a
CLdes(n) = Interp("Clark Y", Reynolds(n), Alpha_CD0, "CL")
15
Worksheets("Create Prop Inputs").Cells(RowStart + 1 + m * 7, ColStart + n) = Xides(n)
Worksheets("Create Prop Inputs").Cells(RowStart + 2 + m * 7, ColStart + n) = CLdes(n)

Next n
End Sub

Sub ReyNum()
'---Calculates Re at each radius station from final iteration and prints to sheet
Dim k As Integer
For k = 0 To Xsta
Worksheets("Create Prop Inputs").Cells(RowStart + 7 + m * 7, ColStart + k) = _
Re(RHO, Vinf1 * 3.28084, Worksheets("Create Prop Inputs").Cells(RowStart + 5 + m * 7, _
ColStart + k) / 12, MU)
Next k
End Sub

Sub checkConv()
'----Compares current iteration results to previous iteration results
'to determine if chord and beta have converged.
Dim j As Integer, compareC() As Single, compareB() As Single
ReDim compareC(0 To Xsta + 1), compareB(0 To Xsta + 1)
If m = 0 Then GoTo 99 'If first iteration,
'continue to next iteration before checking convergence

If APC_Used = True Then
If Count_APC < 4 Then
GoTo 99 'If APC has been used, skip conv check for back to back APC uses
End If
If Count_APC >= 4 Then
cont = False
MsgBox ("QMIL has failed " & Count_APC & _
" times. Average distributions will be used. " _
& m & " iterations were performed.")
GoTo 99
End If
End If
compareC(0) = 0
compareB(0) = 0

'----Use compareC(j) to calculate change in chord at each X station
'----Use compareB(j) to calculate change in Beta at each X station
For j = 1 To Xsta + 1

```



```

compareC(j) = _
Abs(Worksheets("Create Prop Inputs").Cells(RowStart + 5 + (m - 1) * 7, ColStart - 1 + j) _
- Worksheets("Create Prop Inputs").Cells(RowStart + 5 + m * 7, ColStart - 1 + j)) _
+ compareC(j - 1)

compareB(j) = _
Abs(Worksheets("Create Prop Inputs").Cells(RowStart + 6 + (m - 1) * 7, ColStart - 1 + j) _
- Worksheets("Create Prop Inputs").Cells(RowStart + 6 + m * 7, ColStart - 1 + j)) _
+ compareB(j - 1)

Next j

'----Once Chord or Beta distro does not change by more than 0.1 end program
If compareC(j - 1) < ConvergenceFactor Or compareB(j - 1) < ConvergenceFactor Then

'-----Print Msg box showing number of iterations performed
'Account for m=0 iteration
m = m + 1
MsgBox ("Convergence a success! " & m & " iterations performed.")
cont = False

99
End If
End Sub

Sub Charts()
'-----Define locally used variables
Dim DataRow As Integer, R As Integer
Dim RowSp As Integer, D As Integer, Blank As Integer
Dim Xmajor As Double, Xmaximum As Double, Xminimum As Double

'-----Define Static Variables
DataRow = 9# 'Row that output data begins on "Create Prop Inputs" Worksheet
RowSp = 7# 'Number of Rows between DataRow and Iteration 1 Data
Blank = 0# 'Resets Blank
Xminimum = 0#

'-----Calculate Major Axis Points and Max X
Xmaximum = Sheets("Create Prop Inputs").Cells(1, 3) / 2# 'Xmaximum = Radius
Xmajor = Xmaximum / 10# 'Xmajor = 1/10 Radius

'Select Chord Convergence Chart and remove current series
Worksheets("Output Charts").ChartObjects("Chart 9").Activate
With ActiveChart
For D = .SeriesCollection.count To 1 Step -1
.SeriesCollection(D).Delete
Next D
End With

'Select Beta Convergence Chart and remove current series
Worksheets("Output Charts").ChartObjects("Chart 4").Activate
With ActiveChart
For D = .SeriesCollection.count To 1 Step -1
.SeriesCollection(D).Delete
Next D
End With

count = 0

For R = DataRow + RowSp To 1000 '1000 is the limit of the current output charts
If Blank > 1 Then Exit For

If Not Worksheets("Create Prop Inputs").Cells(R, 3) = "" Then
Blank = 0
Else
'Blank counts the number of Blank rows of data to test for the end of the data set
Blank = Blank + 1

'Test if there are 2 blank lines together then end of data has been reached
'No need to add additional blank series
If Blank > 1 Then Exit For

'Select Chord Convergence Chart and establish series for each RPM Sweep
Worksheets("Output Charts").ChartObjects("Chart 9").Activate
With ActiveChart.SeriesCollection.NewSeries
count = count + 1
If count = 10 Then count = 1
.Name = Worksheets("Create Prop Inputs").Cells(R + 1 - RowSp, 1)
.Values = Range(Worksheets("Create Prop Inputs").Cells(R + 2 - RowSp, 4), _
Worksheets("Create Prop Inputs").Cells(R + 2 - RowSp, 34))
.XValues = Range(Worksheets("Create Prop Inputs").Cells(R + 1 - RowSp, 4), _
Worksheets("Create Prop Inputs").Cells(R + 1 - RowSp, 34))
.MarkerStyle = count
End With

'Select Beta Convergence Chart and establish series for each RPM Sweep
Worksheets("Output Charts").ChartObjects("Chart 4").Activate
With ActiveChart.SeriesCollection.NewSeries
.Name = Worksheets("Create Prop Inputs").Cells(R + 1 - RowSp, 1)
.Values = Range(Worksheets("Create Prop Inputs").Cells(R + 3 - RowSp, 4), _
Worksheets("Create Prop Inputs").Cells(R + 3 - RowSp, 34))
.XValues = Range(Worksheets("Create Prop Inputs").Cells(R + 1 - RowSp, 4), _

```

```

        Worksheets("Create Prop Inputs").Cells(R + 1 - RowSp, 34))
        .MarkerStyle = count
    End With

End If
Next R

'Set Chart Areas Correctly for Convergence of Chord and Beta on 'Output Charts' Sheet
' dBuf = buffer distance, dInc = Major Unit, E.g.,
'   SetSquareAxes Sheet1.ChartObjects(1).Chart, dBuf, dInc, _
'   WorksheetFunction.Min(rngX.Value), _
'   WorksheetFunction.Max(rngX.Value), _
'   WorksheetFunction.Min(rngY.Value), _
'   WorksheetFunction.Max(rngY.Value)

'Sheets("Create Prop Inputs").Cells(17,4) = Chord at Hub... Not a good reference.
'Need to establish a method to find the range of the Chord listed on the last iteration
'and use that to find the max (see example above using Max(rngY.Value))
'Set Chord v Radius Chart Axes
SetSquareAxes Worksheets("Output Charts").ChartObjects("Chart 9").Chart, 0#, _
    Xmajor, 0#, Xmaximum, 0#, Sheets("Create Prop Inputs").Cells(17, 4)

'Set Beta v Radius X-Axis only
With Worksheets("Output Charts").ChartObjects("Chart 4").Chart.Axes(xlCategory)
    .MinimumScale = 0#
    .MaximumScale = Xmaximum
    .MinorUnitIsAuto = True
    .MajorUnitIsAuto = False
    .MajorUnit = Xmajor
    'Edit by T Lowe to set number of decimal points on labels to 1
    .TickLabels.NumberFormat = "0.0"
End With

'Set Remaining Charts X-Axis only
With Worksheets("Output Charts").ChartObjects("Chart 2").Chart.Axes(xlCategory)
    .MinimumScale = 0#
    .MaximumScale = Xmaximum
    .MinorUnitIsAuto = True
    .MajorUnitIsAuto = False
    .MajorUnit = Xmajor
    'Edit by T Lowe to set number of decimal points on labels to 1
    .TickLabels.NumberFormat = "0.0"
End With

With Worksheets("Output Charts").ChartObjects("Chart 3").Chart.Axes(xlCategory)
    .MinimumScale = 0#
    .MaximumScale = Xmaximum
    .MinorUnitIsAuto = True
    .MajorUnitIsAuto = False
    .MajorUnit = Xmajor
    'Edit by T Lowe to set number of decimal points on labels to 1
    .TickLabels.NumberFormat = "0.0"
End With

With Worksheets("Output Charts").ChartObjects("Chart 5").Chart.Axes(xlCategory)
    .MinimumScale = 0#
    .MaximumScale = Xmaximum
    .MinorUnitIsAuto = True
    .MajorUnitIsAuto = False
    .MajorUnit = Xmajor
    'Edit by T Lowe to set number of decimal points on labels to 1
    .TickLabels.NumberFormat = "0.0"
End With

With Worksheets("Output Charts").ChartObjects("Chart 6").Chart.Axes(xlCategory)
    .MinimumScale = 0#
    .MaximumScale = Xmaximum
    .MinorUnitIsAuto = True
    .MajorUnitIsAuto = False
    .MajorUnit = Xmajor
    'Edit by T Lowe to set number of decimal points on labels to 1
    .TickLabels.NumberFormat = "0.0"
End With

With Worksheets("Output Charts").ChartObjects("Chart 7").Chart.Axes(xlCategory)
    .MinimumScale = 0#
    .MaximumScale = Xmaximum
    .MinorUnitIsAuto = True
    .MajorUnitIsAuto = False
    .MajorUnit = Xmajor
    'Edit by T Lowe to set number of decimal points on labels to 1
    .TickLabels.NumberFormat = "0.0"
End With

With Worksheets("Output Charts").ChartObjects("Chart 8").Chart.Axes(xlCategory)
    .MinimumScale = 0#
    .MaximumScale = Xmaximum
    .MinorUnitIsAuto = True
    .MajorUnitIsAuto = False
    .MajorUnit = Xmajor
    'Edit by T Lowe to set number of decimal points on labels to 1

```

```
        .TickLabels.NumberFormat = "0.0"  
    End With  
End Sub
```

## QMILsubs

```
*****
Module:      QMILsubs
,
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,
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,
,   You should have received a copy of the GNU General Public License
,   along with this program; if not, write to the Free Software
,   Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
*****

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis '
'The QMILsubs Module contains subroutines necessary for creating run files, input files, '
'running QMIL, extracting QMIL outputs, printing those outputs to the appropriate sheet, '
'and cleaning up the files created during the course of running QMIL.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Option Explicit
Dim XIstring As String, CLstring As String, i As Integer
Dim Input_File As String, fnum As Integer
Sub QMIL()
    'Write input file required for QMIL
    Call CreateQMILinput
    'Run QMIL
    Call ShellandWait("cmd.exe /c " & qmilfilepath & " " & inputfilepath _
        & " " & outputfilepath, 10000)
    'Read QMIL Results and print Radius, Chord, and Beta Distributions to Worksheet "Create Prop
Inputs"
    Call QMILreader
End Sub

'-----CreateQMILinput() writes the input file required for QMIL----
Sub CreateQMILinput()
    If m = 0 Then
        '-----Read in QMIL Airfoil Data
        QMIL_CL0 = Worksheets("Create Prop Inputs").Cells(1, 11)
        QMIL_CL_a = Worksheets("Create Prop Inputs").Cells(2, 11)
        QMIL_CLmin = Worksheets("Create Prop Inputs").Cells(3, 11)
        QMIL_CLmax = Worksheets("Create Prop Inputs").Cells(4, 11)

        QMIL_CD0 = Worksheets("Create Prop Inputs").Cells(1, 13)
        QMIL_CD2U = Worksheets("Create Prop Inputs").Cells(2, 13)
        QMIL_CD2L = Worksheets("Create Prop Inputs").Cells(3, 13)
        QMIL_CLCD0 = Worksheets("Create Prop Inputs").Cells(4, 13)

        QMIL_REref = Worksheets("Create Prop Inputs").Cells(1, 15)
        QMIL_REexp = Worksheets("Create Prop Inputs").Cells(2, 15)

        '-----Set a string which contains the path to the new file
        Input_File = Worksheets("Create Prop Inputs").Cells(3, 16)
    End If

    '-----Reset String Values
    XIstring = " "
    CLstring = " "

    '-----Set and open file for output
    fnum = FreeFile
    Open inputfilepath For Output As fnum

    '-----Write line by line to QMIL input file
    '-----Propeller Title
    Print #fnum, "Blades: " & B & " " & " " & " Radius: " & Format(Radius * 39.37, "###.##") _
        & " inches" & " RPM: " & RPM1
    '-----Write Timestamp
    Print #fnum, "!" & Format(Now(), "m/d/yy h:m:s AMPM")

    '-----Number of Blades
    Print #fnum, " " & B
    Write #fnum,

    '-----CL0, CL_a, CLmin, CLmax
    Print #fnum, " " & QMIL_CL0 & " " & QMIL_CL_a
    Print #fnum, " " & QMIL_CLmin & " " & QMIL_CLmax
    Write #fnum,

    '----CD0, CD2u, CD2l, CLCD0, ReRef, Reexp
    Print #fnum, " " & QMIL_CD0 & " " & QMIL_CD2U & " " & QMIL_CD2L & _
        " " & QMIL_CLCD0

```

```

Print #fnum, " " & QMIL_REref & " " & QMIL_REexp
Write #fnum,

'----Define XIdes and CLdes
For i = 1 To Xsta
    XIstring = XIstring & XIdes(i) & " "
    CLstring = CLstring & CLdes(i) & " "
Next i
Print #fnum, XIstring
Print #fnum, CLstring

Write #fnum,
'----Hub radius, tip radius, speed, rpm
Print #fnum, " " & Hub_rad
Print #fnum, " " & Radius
Print #fnum, " " & Vinf1
Print #fnum, " " & RPM1
Write #fnum,

'----Thrust and Power
Print #fnum, " " & O#
Print #fnum, " " & Power
Write #fnum,

'----Ldes and KQdes
Print #fnum, " " & O
Write #fnum,

'----Number of output stations
Print #fnum, " " & 30

'----Close file
Close #fnum
End Sub

Sub QMILreader()
'---Define locally used variables
Dim File As String, Number As Single
Dim Counter As Integer, n As Integer
Dim LineText As String, SplitLineText As Variant
'----Set constants and optional read in outputfilepath if running independent of CreateProp()
' outputfilepath = Worksheets("Inputs").Cells(4, 15)
File = FreeFile
Counter = 0
i = 0

'----Check to ensure that QMIL ran and therefore output file was created
' If outputfilepath does not exist then use APC chord and Beta Distro
If Dir(outputfilepath) = vbNullString Then
' use APC Chord and Beta Distro
30 MsgBox _
    ("QMIL FAILED TO OUTPUT PROPELLER FILE! APC DATA WILL BE USED INSTEAD OF QMIL PROP.")
    Call UseAPC
    GoTo 41
Else

'----Open QMIL Output file and read in R, C, and Beta Distributions
Open outputfilepath For Input As File
While Not EOF(File)
    Line Input #File, LineText ' Saves current line of text into LineText
    Counter = Counter + 1 ' Keeps track of which line you are currently on
    If Counter > 15 Then ' QMIL Data (R,C, Beta) starts on line 16
        SplitLineText = Split(LineText, " ") 'Parses text into parts separated by a space
        For n = 0 To UBound(SplitLineText)
            If Not SplitLineText(n) = "" Then
                i = i + 1 'i keeps track of how many non-space values have been stored
                'Check for error where SplitLineText(n) does not equal a number
                'If SplitLineText is not numeric,
                'then perform next iteration using APC Values.
                If Not IsNumeric(SplitLineText(n)) Then
                    MsgBox _
                        ("QMIL output failed! Output file could not be read due to the following "
                            & "QMIL error: " & SplitLineText(n) & "'")
                    Call UseAPC
                    Close File
                    GoTo 41
                End If
                Number = CSng(SplitLineText(n)) 'Converts string stored into a single
                'Check if i=3 (Then Number = Beta Value).
                'If so, do not apply conversion factor from meters to inches
                'In QMIL output, radius is column 1, chord is column 2 and Beta is column 3
                'Conversion factor must be applied to radius and chord
                '(col 1 & 2) from meters to inches
                If i = 3 Then
                    '---Print Number as is (do not convert)
                    Worksheets("Create Prop Inputs").Cells(RowStart + 3 + i + m * 7, _
                        Counter - 12) = Number
                    GoTo 40
                End If
            End If
        Next n
    End If
End While
End Sub

```

```

        End If
        '---Convert Number from meters to inches and print to sheet
        Number = Number * 39.37
        Worksheets("Create Prop Inputs").Cells(RowStart + 3 + i + m * 7, Counter - 12)
= Number
40
        End If
        Next n
        i = 0
    End If
    Wend
    Close File
    End If
41
    'Delete the QMIL input file that was used but is no longer needed
    If Not Dir(inputfilepath) = vbNullString Then Kill (inputfilepath)

    Worksheets("Create Prop Inputs").Cells(RowStart + 4 + m * 7, ColStart - 1) = "Radius:"
    Worksheets("Create Prop Inputs").Cells(RowStart + 5 + m * 7, ColStart - 1) = "Chord:"
    Worksheets("Create Prop Inputs").Cells(RowStart + 6 + m * 7, ColStart - 1) = "Beta:"
    Worksheets("Create Prop Inputs").Cells(RowStart + 7 + m * 7, ColStart - 1) = "Reynolds:"
    Worksheets("Create Prop Inputs").Cells(RowStart + 8 + m * 7, ColStart - 1) = "Xlides:"
    Worksheets("Create Prop Inputs").Cells(RowStart + 9 + m * 7, ColStart - 1) = "CLdes:"
    Call Titles

End Sub

```

## QPROSubs

```

*****
Module:      QPROSubs
,
,      Copyright (C) 2015 Trevor Lowe
,
,      This program is free software; you can redistribute it and/or modify
,      it under the terms of the GNU General Public License as published by
,      the Free Software Foundation; either version 2 of the License, or
,      (at your option) any later version.
,
,      This program is distributed in the hope that it will be useful,
,      but WITHOUT ANY WARRANTY; without even the implied warranty of
,      MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
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,
,      You should have received a copy of the GNU General Public License
,      along with this program; if not, write to the Free Software
,      Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
*****

////////////////////////////////////
'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis '
'The QPROSubs Module contains subroutines necessary for creating run files, input files, '
'running QPROP, extracting QPROP outputs, printing those outputs to the appropriate sheet, '
'and cleaning up the files created during the course of running QPROP.
////////////////////////////////////

Dim SA As Boolean, rad As Single, chord As Single, beta As Single

Sub QPROP()
'---If Running QPROP by itself for troubleshooting make SA = True
SA = False
'----Read in variables if running QPROP() as stand-alone
If SA = True Then
    RPM1 = 2500
    RPM2 = RPM1
    Vinf1 = Worksheets("Create Prop Inputs").Cells(2, 7) / 3.28084
    Vinf2 = Vinf1      'PROPDES Runs for only 1 Vinf Point

    '----Read in File Paths if running as stand alone
    FilePath = Worksheets("Initial Setup").Cells(2, 2)
    outputfilepath = FilePath & "PROPDES_Output.txt"
    qpropfilepath = FilePath & "qprop.exe"
    motorfilepath = FilePath & "motor.txt"
    qproprunfilepath = FilePath & "qprop_run.txt"
    batchfilepath = FilePath & "batchfile.txt"
    qprop_outputfilepath = FilePath & "QPROP_Output.dat"
End If

'---Call necessary subs to set-up and run QPROP
Call CreateQPROPrun
'----Run QPROP at dos-prompt
Call ShellandWait("cmd.exe /c " & batchfilepath, 100)
Call QPROPReader
End Sub
'-----CreateQPROPrun() will write the run file for QPROP----
Sub CreateQPROPrun()
'-----Set and open file for output
fnum = FreeFile
Open qproprunfilepath For Output As fnum

'-----Write line by line to QPROP run file (Run only at design point)
'-----Write Velocity Line (Vel1 Vel2 Nvel ! m/s)
Print #fnum, Vinf1 & " " & Vinf2 & " " & "1"

'-----Write RPM Line (RPM1 RPM2 NRPM)
Print #fnum, RPM1 & " " & RPM2 & " " & "1"

'-----Write Volt Line (Volt1 Volt2 NVolt) (NOT USED)
Print #fnum, "0 0 0"
'-----Write Pitch Change Line (Dbet1 Dbet2 NDbet) (NOT USED)
Print #fnum, "0 0 0"

'-----Write Timestamp
Print #fnum, "!" & Format(Now(), "m/d/yy h:m:s AMPM")

'-----Close file
Close #fnum
End Sub

Sub QPROPReader()
'---Define locally used variables
Dim File As String, LineText As String
Dim Number As Single
Dim Counter As Integer, n As Integer, rstart As Integer
Dim cstart As Integer, i As Integer, Hashtag As Integer
Dim TitleCount As Integer
Dim SplitLineText As Variant

```

```

rstart = 1
cstart = 1

'---If running this sub by itself:
qprop_outputfilepath = "C:\PROPDES\QPROP_Output.dat"

'-----Set constants
File = FreeFile
Counter = 0
TitleCount = 0
i = 0

'----Open QPROP Output file and read in Results
Open qprop_outputfilepath For Input As File
While Not EOF(File)
    i = 0
    Line Input #File, LineText          ' Saves current line of text into LineText
    Counter = Counter + 1              ' Keeps track of which line you are currently on
    Hashtag = InStr(1, LineText, "#")  ' Returns number of '#' in LineText as integer
    If Hashtag > 0 Then                ' If LineText contains "#" then check for Titles line
        'Check for titles line
        If InStr(1, LineText, "V(m/s)") > 0 Or InStr(1, LineText, "adv_wake") Then
            SplitLineText = Split(LineText, " ") 'Parses text into parts separated by a space
            TitleCount = TitleCount + 1         'Counts how many title lines have been printed
            For n = 0 To UBound(SplitLineText)
                If Not SplitLineText(n) = "" Then
                    i = i + 1                  'i keeps track of how many non-space values have been stored
                    'Prints SplitLineText as text
                    Worksheets("Create Prop Output").Cells(Counter + rstart - 1, _
                        i + cstart - 1) = SplitLineText(n)
                End If
            Next n
        Else
            'Prints LineText to cstart column if LineText contains "#" but is not a titles row
            Worksheets("Create Prop Output").Cells(Counter + rstart - 1, cstart) = LineText
        End If
    Else
        'If no "#" in LineText then parse LineText by space and store as a number.
        SplitLineText = Split(LineText, " ") 'Parses text into parts separated by a space
        For n = 0 To UBound(SplitLineText)
            If Not SplitLineText(n) = "" Then
                i = i + 1 'i keeps track of how many non-space values have been stored
                'Test to ensure that SplitLineText is numeric, if not end program due to QPROP
                error.
                If Not IsNumeric(SplitLineText(n)) Then
                    MsgBox ("QPROP Output Failed!" & _
                        " Output file could not be read due to the following QPROP error: " & _
                        & SplitLineText(n))
                    GoTo 91
                End If

                Number = CSng(SplitLineText(n)) ' Converts string stored into a number
                'Checks if both title lines have printed and if the number stored is the
                'Radius or Chord (Column 1 & 2 respectively).
                'If so, converts number from meters to inches and then prints to sheet.
                If TitleCount = 2 And i = 1 Or TitleCount = 2 And i = 2 Then
                    Number = Number * 39.37
                End If

                Worksheets("Create Prop Output").Cells(Counter + rstart - 1, i + cstart) _
                    = Number
            End If
        Next n
    End If
90    End If
Wend
91    Close File
End Sub

'-----CreatePropellerFile() will write the prop file for QPROP if QMIL fails.
'-----QMIL provides Propeller file if it runs successfully.

Sub CreatePropellerFile()
    '-----Read in QMIL Airfoil Data
    QMIL_CLO = Worksheets("Create Prop Inputs").Cells(1, 11)
    QMIL_CL_a = Worksheets("Create Prop Inputs").Cells(2, 11)
    QMIL_CLmin = Worksheets("Create Prop Inputs").Cells(3, 11)
    QMIL_CLmax = Worksheets("Create Prop Inputs").Cells(4, 11)

    QMIL_CD0 = Worksheets("Create Prop Inputs").Cells(1, 13)
    QMIL_CD2U = Worksheets("Create Prop Inputs").Cells(2, 13)
    QMIL_CD2L = Worksheets("Create Prop Inputs").Cells(3, 13)
    QMIL_CLCD0 = Worksheets("Create Prop Inputs").Cells(4, 13)

    QMIL_REref = Worksheets("Create Prop Inputs").Cells(1, 15)
    QMIL_REexp = Worksheets("Create Prop Inputs").Cells(2, 15)

    '-----Set and open file for output
    If Not Dir(outputfilepath) = vbNullString Then Kill outputfilepath
    fnum = FreeFile

```



```

Open outputfilepath For Output As fnum

'-----Write line by line to Propeller file
'-----Propeller Title
Write #fnum,
Print #fnum, "Blades: " & B & " " & " Radius: " & Format(Radius * 39.37, "###.##") & _
" inches" & " RPM: " & RPM1

'-----Write Timestamp
Print #fnum, "#" & Format(Now(), "m/d/yy h:m:s AMPM")
Write #fnum,

'-----Number of Blades
Print #fnum, " " & B & " ! Nblades"
Write #fnum,

'-----CL0 and CL_a
Print #fnum, " " & QMIL_CL0 & " " & QMIL_CL_a & "! CL0 CL_a"

'-----CLmin, CLmax
Print #fnum, " " & QMIL_CLmin & " " & QMIL_CLmax & "! CLmin CLmax"
Write #fnum,

'-----CD0, CD2u, CD2l, CLCD0, ReRef, Reexp
Print #fnum, " " & QMIL_CD0 & " " & QMIL_CD2U & " " & QMIL_CD2L & _
" " & QMIL_CLCD0 & "! CD0 CD2u CD2l CLCD0"
Print #fnum, " " & QMIL_REref & " " & QMIL_REexp & "! REref REexp"
Write #fnum,

'-----Set Units Conv and Additions
Print #fnum, " " & "1.0" & " " & "1.0" & " " & "1.0" & " " ! Rfac Cfac Bfac"
Print #fnum, " " & "0.0" & " " & "0.0" & " " & "0.0" & " " ! Radd Cadd Badd"
Write #fnum,

'-----Set up titles line
Print #fnum, "# r c beta"

'-----Print r, c, and beta columns
For i = 1 To Xsta
    rad = Xlides(i) * Radius 'Radius is in meters
    chord = APC_Chord(i) / 39.37 'Chord converted to meters
    beta = APC_Beta(i)
    Print #fnum, " " & Format(rad, "00.00000") & " " & Format(chord, "00.00000") & _
    " " & Format(beta, "00.00000")
Next i

'-----Close file
Close #fnum
End Sub

```

## shellwait

```
*****
Module:      shellwait
,
,      Copyright (C) 2015 Trevor Lowe
,
,      This program is free software; you can redistribute it and/or modify
,      it under the terms of the GNU General Public License as published by
,      the Free Software Foundation; either version 2 of the License, or
,      (at your option) any later version.
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,      This program is distributed in the hope that it will be useful,
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,
,      You should have received a copy of the GNU General Public License
,      along with this program; if not, write to the Free Software
,      Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
*****

////////////////////////////////////
'Written by Trevor Lowe, Oklahoma State University, 2015, MS Aerospace Engineering Thesis '
'Modified for use here from C. Pearson; more info available at the following website: '
'http://www.cpearson.com/excel/ShellAndWait.aspx
////////////////////////////////////

Option Explicit

#If VBA7 Then      'If using VBA7 then use 64-bit declaration.
Private Declare PtrSafe Function OpenProcess Lib "kernel32" _
    (ByVal dwDesiredAccess As LongPtr, ByVal bInheritHandle As Long, _
    ByVal dwProcessId As Long) As Long

Private Declare PtrSafe Function GetExitCodeProcess Lib "kernel32" _
    (ByVal hProcess As LongPtr, lpExitCode As Long) As Long
#Else      'If not using VBA7, then use 32-bit declaration.
Private Declare Function OpenProcess Lib "kernel32" _
    (ByVal dwDesiredAccess As Long, ByVal bInheritHandle As Long, _
    ByVal dwProcessId As Long) As Long

Private Declare Function GetExitCodeProcess Lib "kernel32" _
    (ByVal hProcess As Long, lpExitCode As Long) As Long
#End If

Private Const STATUS_PENDING = &H103&
Private Const PROCESS_QUERY_INFORMATION = &H400

Public Function ShellAndWait(ExeFullPath As String, _
Optional TimeOutValue As Long = 0) As Boolean

    Dim lInst As Long
    Dim lStart As Long
    Dim lTimeToQuit As Long
    Dim sExeName As String
    Dim lProcessId As Long
    Dim lExitCode As Long
    Dim bPastMidnight As Boolean

    On Error GoTo ErrorHandler

    lStart = CLng(Timer)
    sExeName = ExeFullPath

    'Deal with timeout being reset at Midnight
    If TimeOutValue > 0 Then
        If lStart + TimeOutValue < 86400 Then
            lTimeToQuit = lStart + TimeOutValue
        Else
            lTimeToQuit = (lStart - 86400) + TimeOutValue
            bPastMidnight = True
        End If
    End If

    lInst = Shell(sExeName, vbMinimizedNoFocus)

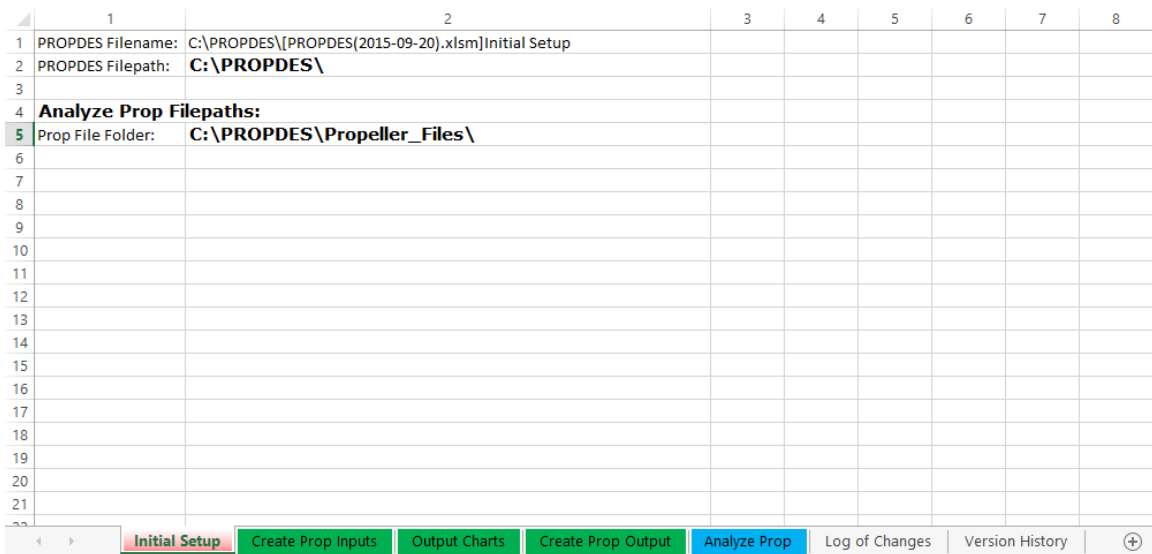
    lProcessId = OpenProcess(PROCESS_QUERY_INFORMATION, False, lInst)

    Do
        Call GetExitCodeProcess(lProcessId, lExitCode)
        DoEvents
        If TimeOutValue And Timer > lTimeToQuit Then
            If bPastMidnight Then
                If Timer < lStart Then Exit Do
            Else
                Exit Do
            End If
        End If
    Loop While lExitCode = STATUS_PENDING
```

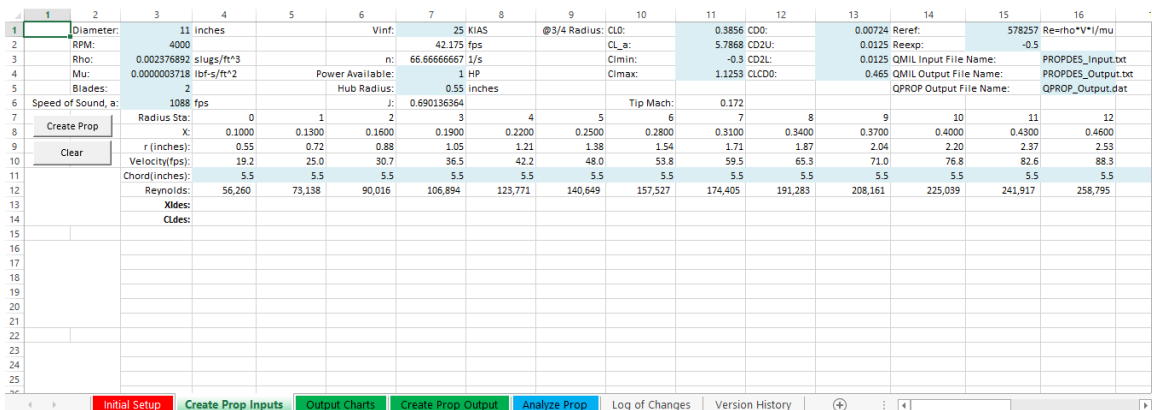
```
ShellandWait = True  
ErrorHandler:  
ShellandWait = False  
Exit Function  
End Function
```

## APPENDIX C PROPDES.XLSM WORKSHEETS

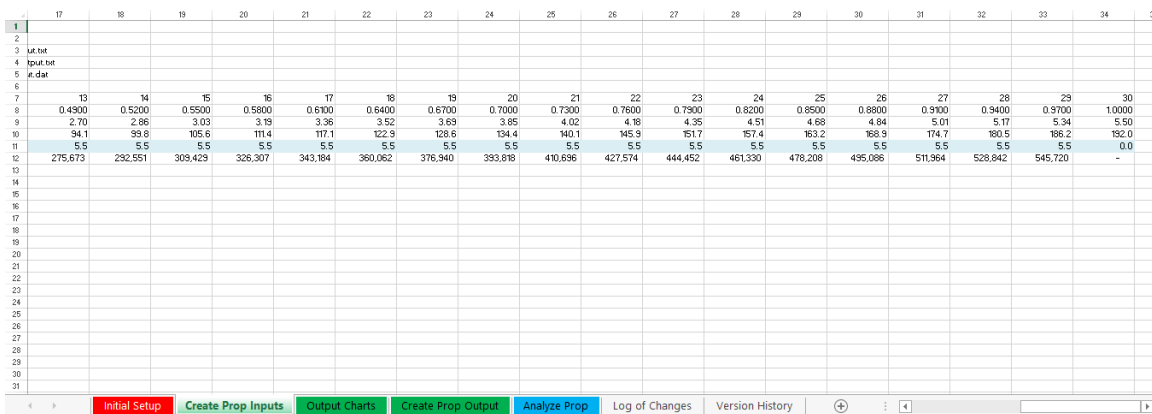
Screenshots of the PROPDES.xlsm Microsoft Excel file are contained in this appendix. These screenshots are provided to assist an individual in recreating the entire Excel file if desired.



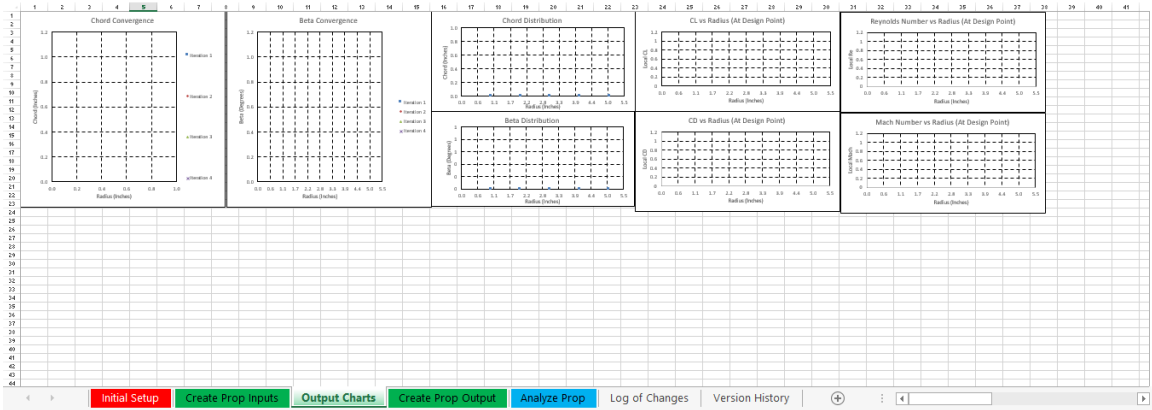
Appendix Figure 1: PROPDES.xism Worksheet: Initial Setup



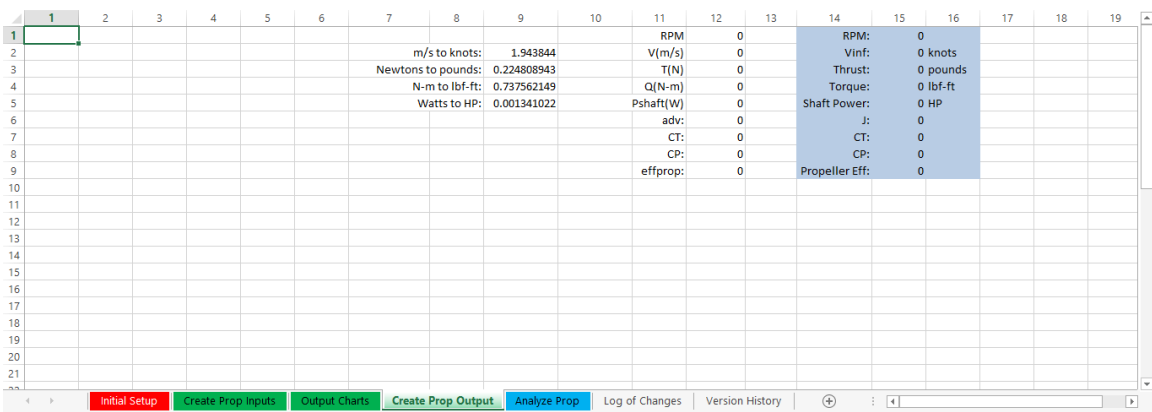
Appendix Figure 2: PROPDES.xism Worksheet: Create Prop Inputs



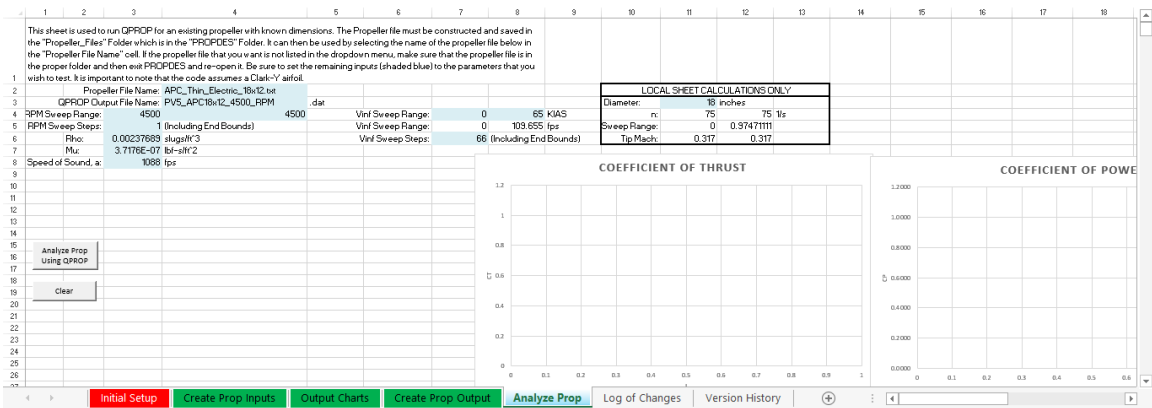
Appendix Figure 3: PROPDES.xism Worksheet: Create Prop Inputs, cont'd



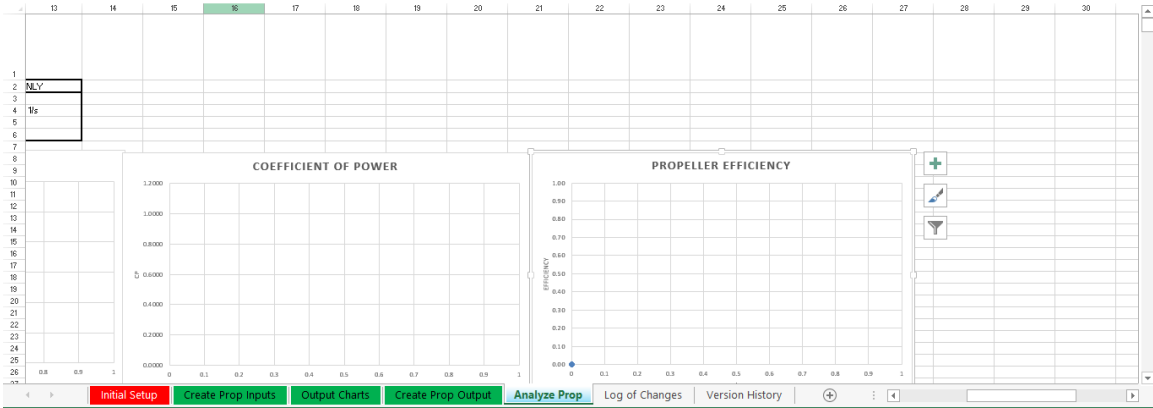
Appendix Figure 4: PROPDES.xlsm Worksheet: Output Charts



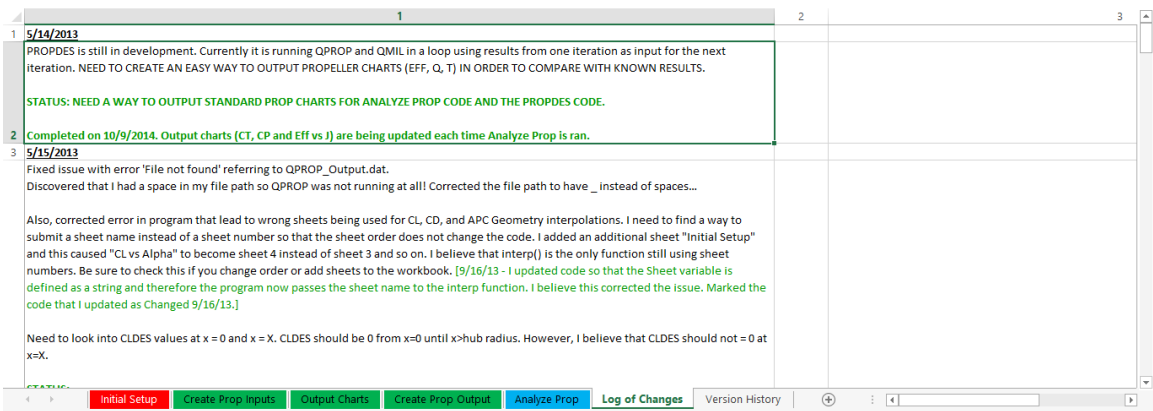
Appendix Figure 5: PROPDES.xlsm Worksheet: Create Prop Output



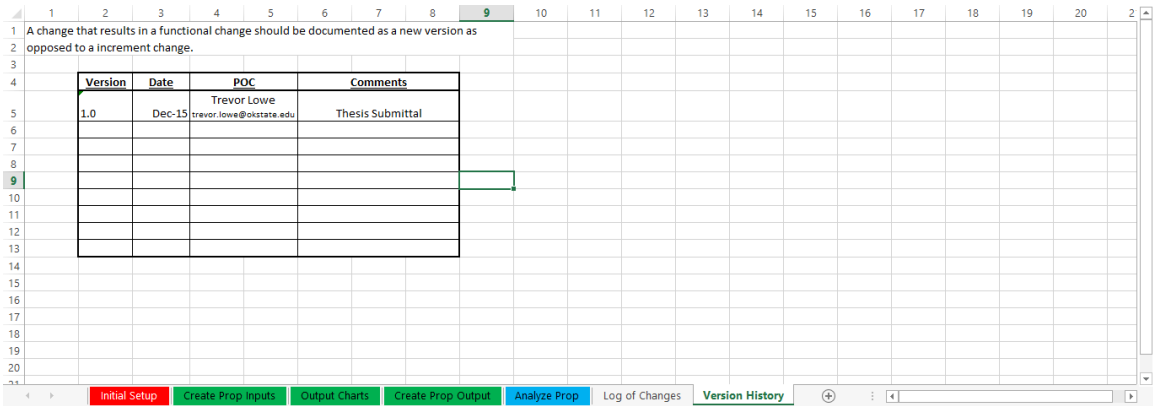
Appendix Figure 6: PROPDES.xlsm Worksheet: Analyze Prop



**Appendix Figure 7: PROPES.xlsm Worksheet: Analyze Prop, cont'd**



**Appendix Figure 8: PROPDES.xlsm Worksheet: Log of Changes**



**Appendix Figure 9: PROPDES.xlsm Worksheet: Version History**





## APPENDIX D QV TEST DETAILS

This appendix contains additional data collected while performing each of the QV cases. Specifically, the complete static test data tables and the dynamic test data sheets are provided herein.

## QV Static Data

Static Run QV1 - APC - Diameter: 9" - Pitch: 4.5" - Blades: 2 - UIUC											
Data Point			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
2499	0.0893	0.0393	2500	0.1052	0.0447	1	0.0159	0.0054	0.04%	17.75%	13.74%
2800	0.0925	0.0394	2800	0.1052	0.0441	0	0.0127	0.0047	0.00%	13.76%	11.81%
3119	0.0936	0.0392	3100	0.1053	0.0435	19	0.0117	0.0043	0.61%	12.55%	10.95%
3384	0.0938	0.0386	3400	0.1054	0.0430	16	0.0116	0.0044	0.47%	12.39%	11.45%
3679	0.0945	0.0383	3700	0.1055	0.0426	21	0.0110	0.0043	0.57%	11.64%	11.27%
3972	0.0956	0.0383	4000	0.1056	0.0423	28	0.0100	0.0040	0.70%	10.44%	10.32%
4271	0.0961	0.0383	4300	0.1057	0.0419	29	0.0096	0.0036	0.68%	9.94%	9.52%
4569	0.0971	0.0385	4600	0.1057	0.0417	31	0.0086	0.0032	0.68%	8.89%	8.23%
4830	0.0978	0.0384	4900	0.1058	0.0414	70	0.0080	0.0030	1.45%	8.19%	7.84%
5157	0.0985	0.0386	5200	0.1059	0.0412	43	0.0074	0.0026	0.83%	7.50%	6.71%
5450	0.0989	0.0386	5500	0.1060	0.0410	50	0.0071	0.0024	0.92%	7.14%	6.21%
5731	0.0992	0.0386	5800	0.1061	0.0408	69	0.0069	0.0022	1.20%	6.94%	5.77%
6043	0.0996	0.0387	6100	0.1062	0.0407	57	0.0066	0.0020	0.94%	6.58%	5.09%
6335	0.1001	0.0388	6400	0.1063	0.0405	65	0.0062	0.0017	1.03%	6.17%	4.44%
6641	0.1005	0.0389	6700	0.1064	0.0404	59	0.0059	0.0015	0.89%	5.82%	3.86%
6922	0.1012	0.0392	7000	0.1065	0.0403	78	0.0053	0.0011	1.13%	5.21%	2.75%
<b>Max:</b>									1.45%	17.75%	13.74%
<b>Average:</b>									0.76%	9.43%	8.12%

Static Run QV2 - APC - Diameter: 11" - Pitch: 5.5" - Blades: 2 - UIUC											
Experimental Data			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
1868	0.0777	0.0327	1868	0.0888	0.0361	0	0.0111	0.0034	0.00%	14.33%	10.40%
2200	0.0804	0.0323	2175	0.0889	0.0353	25	0.0085	0.0030	1.14%	10.59%	9.36%
2450	0.0824	0.0320	2482	0.0890	0.0347	32	0.0066	0.0027	1.31%	8.04%	8.44%
2800	0.0833	0.0314	2789	0.0891	0.0342	11	0.0058	0.0028	0.39%	6.97%	8.89%
3095	0.0838	0.0310	3096	0.0892	0.0338	1	0.0054	0.0028	0.03%	6.42%	8.92%
3406	0.0849	0.0313	3403	0.0893	0.0334	3	0.0044	0.0021	0.09%	5.13%	6.71%
3716	0.0857	0.0312	3710	0.0893	0.0331	6	0.0036	0.0019	0.16%	4.24%	6.07%
4043	0.0861	0.0312	4017	0.0894	0.0328	26	0.0033	0.0016	0.64%	3.85%	5.21%
4350	0.0862	0.0312	4324	0.0895	0.0326	26	0.0033	0.0014	0.60%	3.86%	4.47%
4651	0.0870	0.0314	4631	0.0896	0.0324	20	0.0026	0.0010	0.43%	3.00%	3.19%

Static Run QV2 - APC - Diameter: 11" - Pitch: 5.5"- Blades: 2 - UIUC											
Experimental Data			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
4968	0.0873	0.0313	4938	0.0897	0.0322	30	0.0024	0.0009	0.60%	2.78%	2.93%
5273	0.0877	0.0314	5245	0.0898	0.0321	28	0.0021	0.0007	0.53%	2.40%	2.10%
5577	0.0885	0.0317	5552	0.0899	0.0319	25	0.0014	0.0002	0.45%	1.60%	0.71%
5891	0.0890	0.0319	5859	0.0900	0.0318	32	0.0010	0.0001	0.54%	1.16%	0.26%
6213	0.0897	0.0322	6166	0.0902	0.0317	47	0.0005	0.0005	0.76%	0.50%	1.53%
6473	0.0903	0.0323	6473	0.0903	0.0316	0	0.0000	0.0007	0.00%	0.01%	2.10%
<b>Max:</b>									1.31%	14.33%	10.40%
<b>Average:</b>									0.48%	4.68%	5.08%

Static Run QV3 - APC - Diameter: 11" - Pitch: 7"- Blades: 2 - UIUC											
Experimental Data			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
1966	0.0987	0.0468	1966	0.1003	0.0527	0	0.0016	0.0059	0.00%	1.63%	12.53%
2322	0.1008	0.0452	2256	0.1003	0.0518	66	0.0005	0.0066	2.84%	0.45%	14.65%
2581	0.1024	0.0449	2547	0.1004	0.0511	34	0.0020	0.0062	1.32%	1.93%	13.87%
2869	0.1021	0.0446	2837	0.1005	0.0506	32	0.0016	0.0060	1.12%	1.61%	13.35%
3158	0.1031	0.0442	3127	0.1005	0.0501	31	0.0026	0.0059	0.98%	2.52%	13.25%
3438	0.1039	0.0440	3417	0.1005	0.0496	21	0.0034	0.0056	0.61%	3.24%	12.77%
3723	0.1052	0.0440	3708	0.1005	0.0492	15	0.0047	0.0052	0.40%	4.43%	11.91%
4034	0.1046	0.0434	3998	0.1006	0.0489	36	0.0040	0.0055	0.89%	3.85%	12.67%
4311	0.1054	0.0436	4288	0.1006	0.0486	23	0.0048	0.0050	0.53%	4.54%	11.48%
4572	0.1065	0.0439	4578	0.1007	0.0483	6	0.0058	0.0044	0.13%	5.49%	10.08%
4879	0.1067	0.0439	4869	0.1007	0.0481	10	0.0060	0.0042	0.20%	5.67%	9.53%
5181	0.1072	0.0439	5159	0.1007	0.0479	22	0.0065	0.0040	0.42%	6.07%	9.03%
5444	0.1080	0.0443	5449	0.1007	0.0477	5	0.0073	0.0034	0.09%	6.77%	7.58%
5749	0.1081	0.0443	5739	0.1007	0.0475	10	0.0074	0.0032	0.17%	6.82%	7.17%
5995	0.1092	0.0448	6030	0.1008	0.0473	35	0.0084	0.0025	0.58%	7.72%	5.56%
6320	0.1093	0.0448	6320	0.1008	0.0471	0	0.0085	0.0023	0.00%	7.80%	5.21%
<b>Max:</b>									2.84%	7.80%	14.65%
<b>Average:</b>									0.64%	4.41%	10.67%

Static Run QV4 - APC - Diameter: 11" - Pitch: 8" - Blades: 2 – UIUC												
Experimental Data			PROPDES Data			Difference			Percent Difference			
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	
1655	0.0951	0.0524	1655	0.1002	0.0538	0	0.0051	0.0014	0.00%	5.39%	2.68%	
2019	0.0977	0.0523	1959	0.1003	0.0527	60	0.0026	0.0004	2.97%	2.67%	0.74%	
2320	0.0987	0.0519	2263	0.1003	0.0518	57	0.0016	0.0001	2.46%	1.67%	0.17%	
2616	0.0994	0.0513	2567	0.1004	0.0511	49	0.0010	0.0002	1.87%	1.03%	0.41%	
2916	0.1011	0.0520	2870	0.1005	0.0505	46	0.0006	0.0015	1.58%	0.63%	2.90%	
3209	0.1018	0.0520	3174	0.1005	0.0500	35	0.0013	0.0020	1.09%	1.28%	3.88%	
3512	0.1023	0.0526	3478	0.1005	0.0495	34	0.0018	0.0031	0.97%	1.72%	5.83%	
3805	0.1025	0.0522	3782	0.1006	0.0492	23	0.0019	0.0030	0.60%	1.88%	5.83%	
4119	0.1030	0.0520	4086	0.1006	0.0488	33	0.0024	0.0032	0.80%	2.35%	6.13%	
4406	0.1039	0.0522	4390	0.1006	0.0485	16	0.0033	0.0037	0.36%	3.16%	7.07%	
4722	0.1046	0.0522	4694	0.1007	0.0482	28	0.0039	0.0040	0.59%	3.77%	7.61%	
5001	0.1058	0.0522	4998	0.1007	0.0480	3	0.0051	0.0042	0.06%	4.86%	8.07%	
5302	0.1082	0.0516	5301	0.1007	0.0478	1	0.0075	0.0038	0.02%	6.94%	7.45%	
5598	0.1089	0.0514	5605	0.1007	0.0476	7	0.0082	0.0038	0.13%	7.50%	7.47%	
5905	0.1114	0.0505	5909	0.1007	0.0474	4	0.0107	0.0031	0.07%	9.58%	6.21%	
6213	0.1136	0.0503	6213	0.1008	0.0472	0	0.0128	0.0031	0.00%	11.29%	6.17%	
									<b>Max:</b>	2.97%	11.29%	8.07%
									<b>Average:</b>	0.85%	4.11%	4.91%

Static Run QV5 - APC - Diameter: 11" - Pitch: 8.5" - Blades: 2 - UIUC											
Experimental Data			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
1973	0.0960	0.0584	1973	0.0982	0.0575	0	0.0022	0.0009	0.00%	2.26%	1.53%
2275	0.0968	0.0582	2250	0.0983	0.0567	25	0.0015	0.0015	1.10%	1.50%	2.55%
2557	0.0974	0.0577	2526	0.0983	0.0561	31	0.0009	0.0016	1.21%	0.91%	2.84%
2829	0.0985	0.0576	2803	0.0983	0.0555	26	0.0002	0.0021	0.92%	0.17%	3.65%
3115	0.0988	0.0571	3079	0.0984	0.0550	36	0.0004	0.0021	1.16%	0.44%	3.64%
3380	0.1004	0.0575	3356	0.0984	0.0546	24	0.0020	0.0029	0.71%	1.99%	5.05%
3642	0.1009	0.0574	3633	0.0984	0.0542	9	0.0025	0.0032	0.25%	2.43%	5.52%
3929	0.1011	0.0573	3909	0.0984	0.0539	20	0.0027	0.0034	0.51%	2.63%	5.93%
4205	0.1019	0.0577	4186	0.0985	0.0536	19	0.0034	0.0041	0.45%	3.35%	7.09%
4468	0.1023	0.0577	4462	0.0985	0.0533	6	0.0038	0.0044	0.13%	3.69%	7.55%
4730	0.1026	0.0578	4739	0.0985	0.0531	9	0.0041	0.0047	0.19%	3.97%	8.13%
5027	0.1031	0.0581	5016	0.0986	0.0529	11	0.0045	0.0052	0.22%	4.40%	8.98%
5284	0.1071	0.0561	5292	0.0986	0.0529	8	0.0085	0.0032	0.15%	7.97%	5.63%

Static Run QV5 - APC - Diameter: 11" - Pitch: 8.5"- Blades: 2 - UIUC												
Experimental Data			PROPDES Data			Difference			Percent Difference			
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	
5559	0.1078	0.0563	5569	0.0986	0.0528	10	0.0092	0.0035	0.18%	8.57%	6.29%	
5825	0.1079	0.0562	5845	0.0986	0.0526	20	0.0093	0.0036	0.34%	8.66%	6.45%	
6122	0.1083	0.0564	6122	0.0986	0.0524	0	0.0097	0.0040	0.00%	8.96%	7.08%	
									<b>Max:</b>	1.21%	8.96%	8.98%
									<b>Average:</b>	0.47%	3.87%	5.49%

Static Run QV6 - APC - Diameter: 11" - Pitch: 10"- Blades: 2 - UIUC												
Experimental Data			PROPDES Data			Difference			Percent Difference			
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	
1989	0.1023	0.0743	1989	0.0983	0.0695	0	0.0040	0.0048	0.00%	3.88%	6.52%	
2254	0.1016	0.0748	2237	0.0984	0.0687	17	0.0032	0.0061	0.75%	3.18%	8.11%	
2524	0.1022	0.0758	2485	0.0984	0.0681	39	0.0038	0.0077	1.55%	3.67%	10.12%	
2754	0.1028	0.0767	2733	0.0984	0.0676	21	0.0044	0.0091	0.76%	4.24%	11.85%	
2987	0.1033	0.0774	2982	0.0985	0.0672	5	0.0048	0.0102	0.17%	4.66%	13.24%	
3238	0.1040	0.0782	3230	0.0985	0.0668	8	0.0055	0.0114	0.25%	5.27%	14.63%	
3501	0.1045	0.0789	3478	0.0985	0.0664	23	0.0060	0.0125	0.66%	5.72%	15.85%	
3735	0.1048	0.0797	3726	0.0986	0.0661	9	0.0062	0.0136	0.24%	5.95%	17.09%	
3963	0.1052	0.0800	3974	0.0986	0.0658	11	0.0066	0.0142	0.28%	6.31%	17.77%	
4191	0.1053	0.0804	4222	0.0986	0.0655	31	0.0067	0.0149	0.74%	6.36%	18.51%	
4478	0.1051	0.0799	4470	0.0986	0.0653	8	0.0065	0.0146	0.18%	6.18%	18.29%	
4714	0.1065	0.0815	4718	0.0986	0.0651	4	0.0079	0.0164	0.08%	7.38%	20.18%	
4981	0.1071	0.0817	4967	0.0986	0.0649	14	0.0085	0.0168	0.28%	7.90%	20.62%	
5207	0.1066	0.0814	5215	0.0986	0.0647	8	0.0080	0.0167	0.15%	7.47%	20.56%	
5453	0.1073	0.0819	5463	0.0987	0.0645	10	0.0086	0.0174	0.18%	8.04%	21.26%	
5711	0.1075	0.0818	5711	0.0987	0.0643	0	0.0088	0.0175	0.00%	8.21%	21.36%	
									<b>Max:</b>	1.55%	8.21%	21.36%
									<b>Average:</b>	0.39%	5.90%	16.00%

Static Run QV7 - APC - Diameter: 14" - Pitch: 12"- Blades: 2 - UIUC											
Experimental Data			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
1496	0.0868	0.0623	1496	0.0819	0.0513	0	0.0049	0.0110	0.00%	5.70%	17.60%
1636	0.0866	0.0618	1630	0.0819	0.0509	6	0.0047	0.0109	0.37%	5.48%	17.64%
1741	0.0877	0.0628	1764	0.0819	0.0505	23	0.0058	0.0123	1.32%	6.62%	19.56%

Static Run QV7 - APC - Diameter: 14" - Pitch: 12" - Blades: 2 - UIUC												
Experimental Data			PROPDES Data			Difference			Percent Difference			
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	
1904	0.0881	0.0624	1898	0.0819	0.0502	6	0.0062	0.0122	0.32%	7.00%	19.59%	
2036	0.0881	0.0622	2032	0.0819	0.0499	4	0.0062	0.0123	0.20%	7.00%	19.82%	
2172	0.0892	0.0623	2166	0.0820	0.0496	6	0.0072	0.0127	0.28%	8.10%	20.38%	
2302	0.0892	0.0626	2300	0.0820	0.0493	2	0.0072	0.0133	0.09%	8.10%	21.17%	
2444	0.0895	0.0625	2434	0.0820	0.0491	10	0.0075	0.0134	0.41%	8.41%	21.41%	
2574	0.0898	0.0626	2568	0.0820	0.0489	6	0.0078	0.0137	0.23%	8.67%	21.87%	
2706	0.0901	0.0627	2702	0.0820	0.0487	4	0.0081	0.0140	0.15%	8.98%	22.30%	
2842	0.0902	0.0626	2836	0.0821	0.0485	6	0.0081	0.0141	0.21%	9.04%	22.47%	
2972	0.0909	0.0631	2970	0.0821	0.0484	2	0.0088	0.0147	0.07%	9.74%	23.35%	
3115	0.0912	0.0633	3104	0.0821	0.0482	11	0.0091	0.0151	0.35%	10.03%	23.85%	
3244	0.0916	0.0635	3238	0.0821	0.0481	6	0.0095	0.0154	0.18%	10.38%	24.32%	
3376	0.0919	0.0634	3372	0.0821	0.0479	4	0.0098	0.0155	0.12%	10.68%	24.41%	
3506	0.0929	0.0638	3506	0.0821	0.0478	0	0.0108	0.0160	0.00%	11.64%	25.09%	
									<b>Max:</b>	1.32%	11.64%	25.09%
									<b>Average:</b>	0.27%	8.47%	21.55%

Static Run QV8 - APC - Diameter: 17" - Pitch: 12" - Blades: 2 - UIUC											
Experimental Data			PROPDES Data			Difference			Percent Difference		
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP
1392	0.0851	0.0523	1392	0.0843	0.0454	0	0.0008	0.0069	0.00%	0.94%	13.16%
1538	0.0856	0.0520	1519	0.0843	0.0450	19	0.0013	0.0070	1.24%	1.48%	13.39%
1569	0.0861	0.0525	1645	0.0843	0.0447	76	0.0018	0.0078	4.84%	2.05%	14.86%
1793	0.0872	0.0522	1772	0.0844	0.0444	21	0.0028	0.0078	1.17%	3.24%	14.93%
1915	0.0875	0.0523	1898	0.0844	0.0441	17	0.0031	0.0082	0.89%	3.57%	15.63%
2041	0.0879	0.0519	2025	0.0844	0.0439	16	0.0035	0.0080	0.78%	3.97%	15.45%
2157	0.0886	0.0522	2151	0.0844	0.0437	6	0.0042	0.0085	0.28%	4.72%	16.35%
2291	0.0886	0.0523	2278	0.0844	0.0435	13	0.0042	0.0088	0.57%	4.72%	16.91%
2421	0.0891	0.0526	2404	0.0845	0.0433	17	0.0046	0.0093	0.70%	5.22%	17.73%
2546	0.0893	0.0524	2531	0.0845	0.0431	15	0.0048	0.0093	0.59%	5.43%	17.74%
2667	0.0900	0.0527	2657	0.0845	0.0429	10	0.0055	0.0098	0.37%	6.16%	18.51%
2803	0.0901	0.0527	2784	0.0845	0.0428	19	0.0056	0.0099	0.68%	6.27%	18.81%
2920	0.0903	0.0527	2910	0.0845	0.0427	10	0.0058	0.0100	0.34%	6.43%	19.06%
3061	0.0908	0.0528	3037	0.0845	0.0425	24	0.0063	0.0103	0.78%	6.95%	19.47%

Static Run QV8 - APC - Diameter: 17" - Pitch: 12" - Blades: 2 - UIUC												
Experimental Data			PROPDES Data			Difference			Percent Difference			
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	
3184	0.0914	0.0529	3163	0.0845	0.0424	21	0.0069	0.0105	0.66%	7.56%	19.85%	
3290	0.0915	0.0530	3290	0.0845	0.0423	0	0.0070	0.0107	0.00%	7.66%	20.23%	
									<b>Max:</b>	4.84%	7.66%	20.23%
									<b>Average:</b>	0.87%	4.77%	17.01%

Gamble did not present static runs.

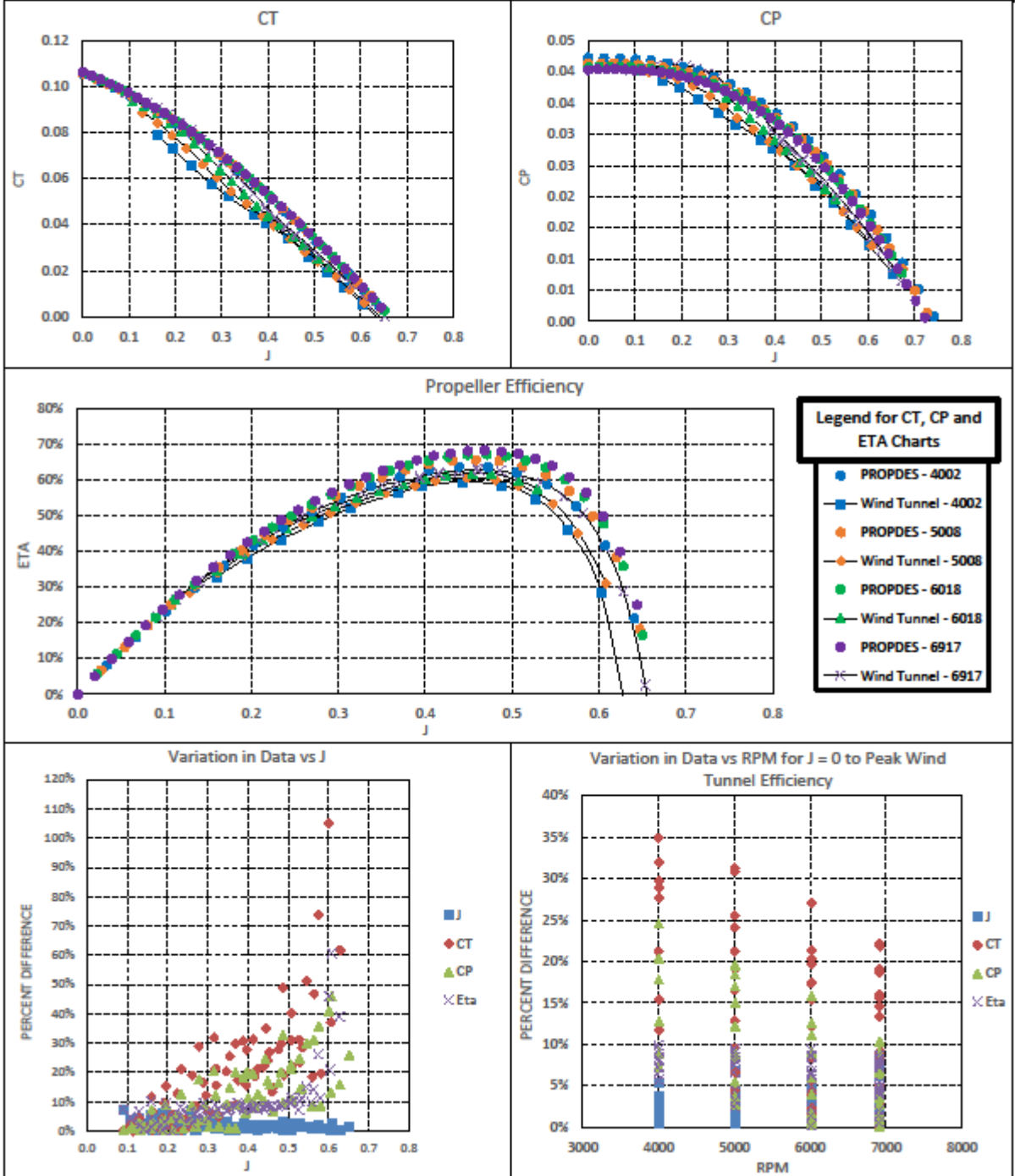
Static Run QV9 - APC - Diameter: 18" - Pitch: 12" - Blades: 2 - Gamble

N/A      N/A      N/A

Static Run QV10 - APC - Diameter: 19" - Pitch: 12" - Blades: 2 - UIUC												
Experimental Data			PROPDES Data			Difference			Percent Difference			
RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	RPM	CT	CP	
1261	0.0884	0.0403	1261	0.0822	0.0349	0	0.0062	0.0054	0.00%	7.05%	13.50%	
1376	0.0899	0.0403	1377	0.0822	0.0345	1	0.0077	0.0058	0.07%	8.56%	14.34%	
1505	0.0902	0.0404	1494	0.0822	0.0342	11	0.0080	0.0062	0.73%	8.82%	15.31%	
1612	0.0917	0.0400	1610	0.0823	0.0340	2	0.0094	0.0060	0.12%	10.27%	15.10%	
1721	0.0918	0.0399	1727	0.0823	0.0337	6	0.0095	0.0062	0.35%	10.32%	15.50%	
1833	0.0928	0.0401	1843	0.0824	0.0335	10	0.0104	0.0066	0.55%	11.25%	16.44%	
1955	0.0932	0.0399	1959	0.0824	0.0333	4	0.0108	0.0066	0.20%	11.59%	16.48%	
2070	0.0940	0.0398	2076	0.0824	0.0332	6	0.0116	0.0066	0.29%	12.30%	16.69%	
2191	0.0936	0.0397	2192	0.0825	0.0330	1	0.0111	0.0067	0.05%	11.88%	16.88%	
2309	0.0937	0.0398	2309	0.0825	0.0329	0	0.0112	0.0069	0.00%	11.94%	17.46%	
2426	0.0941	0.0400	2425	0.0825	0.0330	1	0.0116	0.0070	0.04%	12.31%	17.48%	
2537	0.0970	0.0390	2541	0.0826	0.0329	4	0.0144	0.0061	0.16%	14.89%	15.67%	
2652	0.0961	0.0394	2658	0.0826	0.0328	6	0.0135	0.0066	0.23%	14.06%	16.81%	
2776	0.0961	0.0396	2774	0.0826	0.0327	2	0.0135	0.0069	0.07%	14.01%	17.50%	
2889	0.0969	0.0399	2891	0.0827	0.0326	2	0.0142	0.0073	0.07%	14.68%	18.34%	
3007	0.0972	0.0399	3007	0.0827	0.0325	0	0.0145	0.0074	0.00%	14.91%	18.58%	
									<b>Max:</b>	0.73%	14.91%	18.58%
									<b>Average:</b>	0.18%	11.80%	16.38%

## QV1 Test Data Sheet

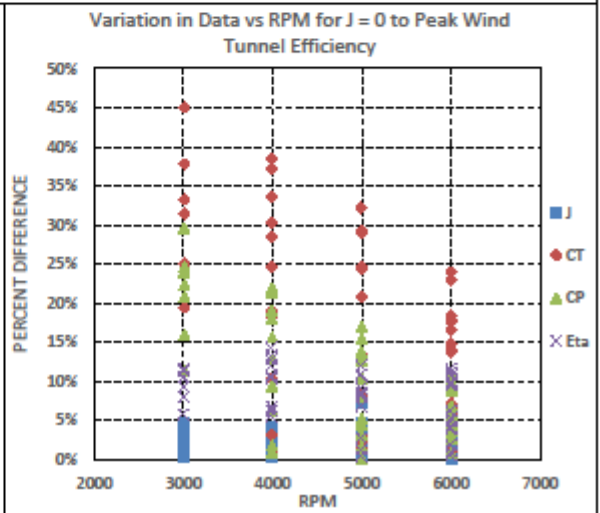
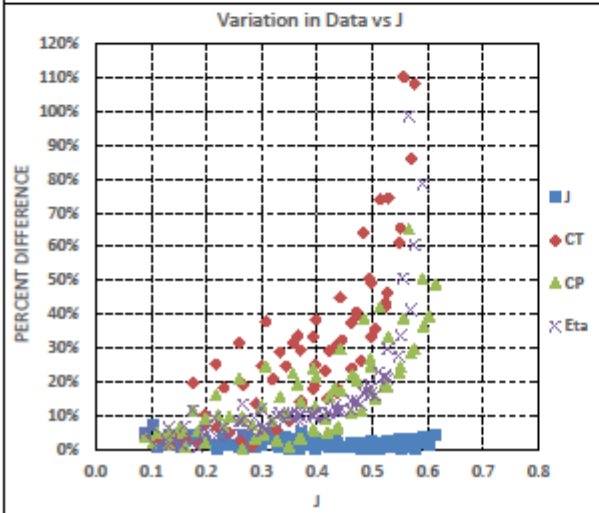
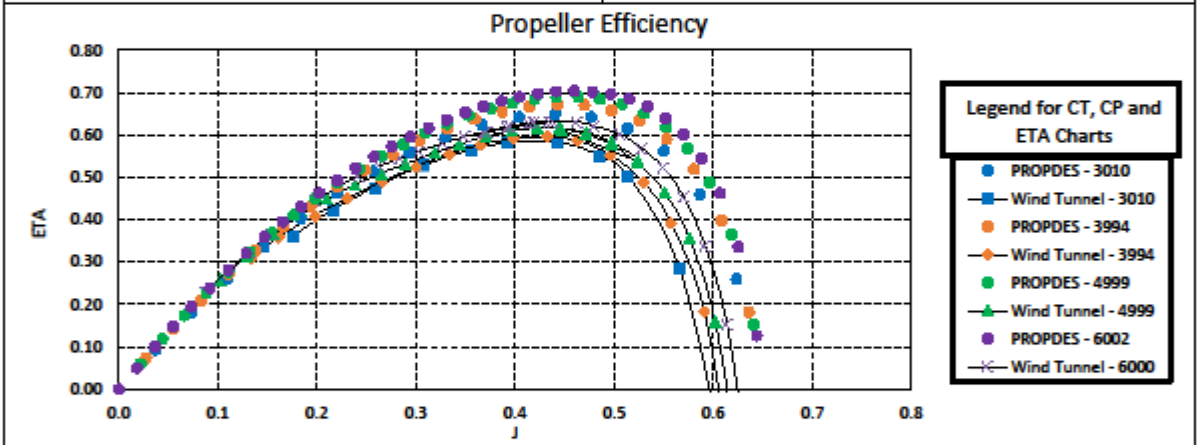
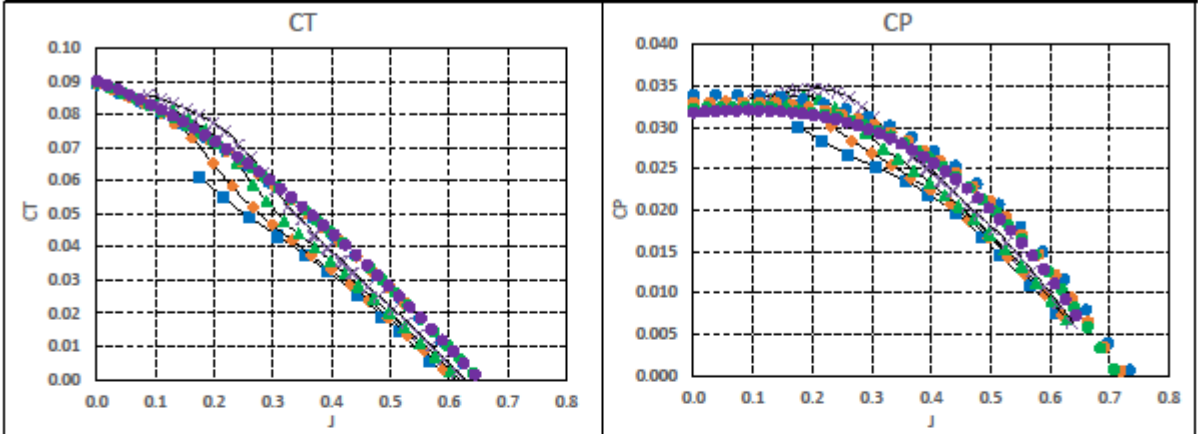
Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	9	4.5	0.5	5002, 5008, 6018, 6917	0-40	UIUC





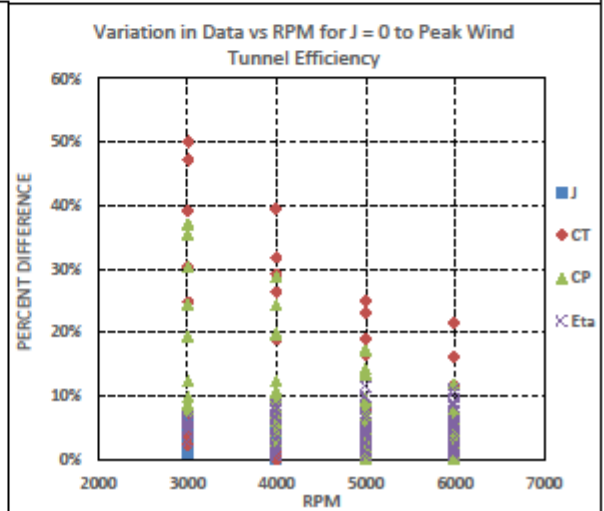
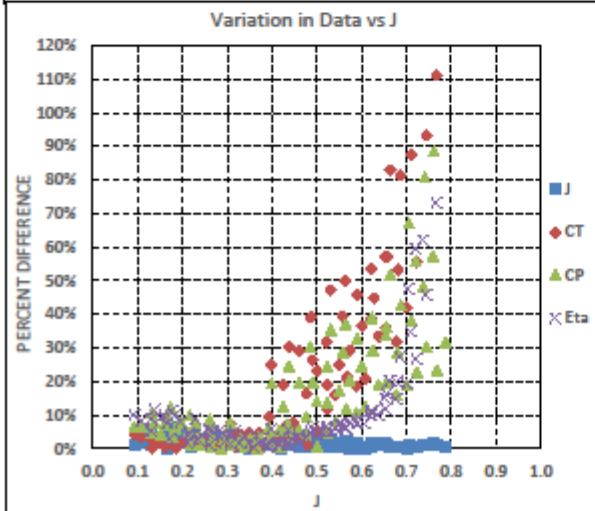
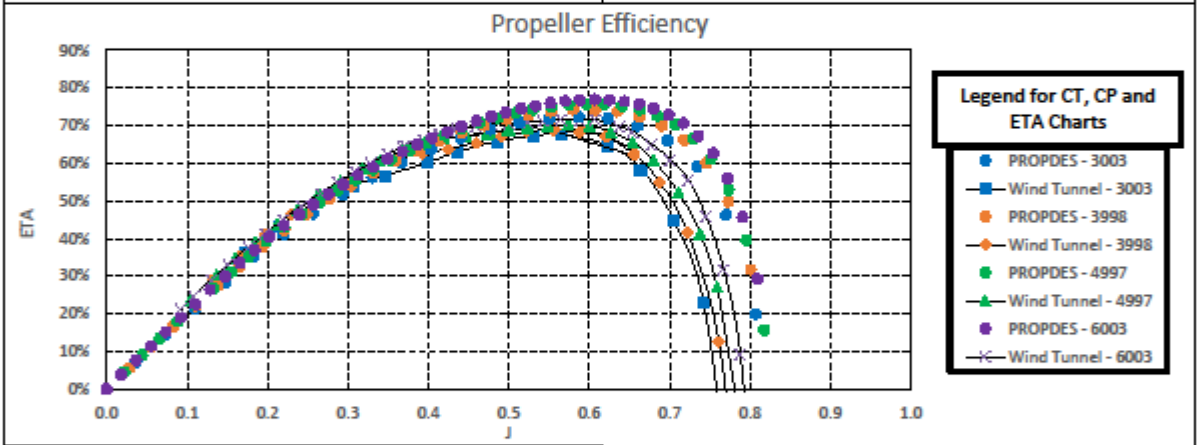
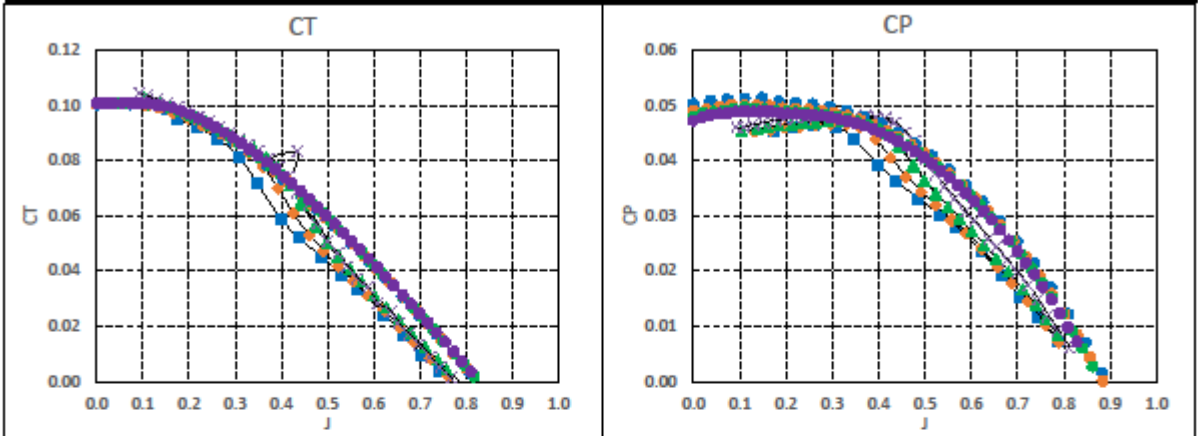
# QV2 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	11	5.5	0.5	3010, 3994, 4999, 6002	0-35	UIUC



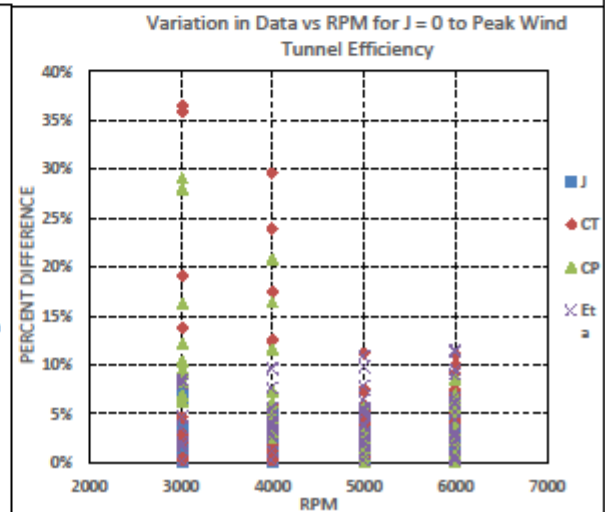
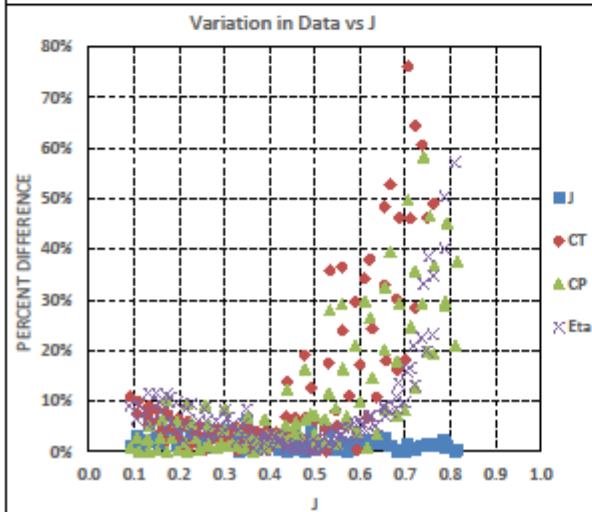
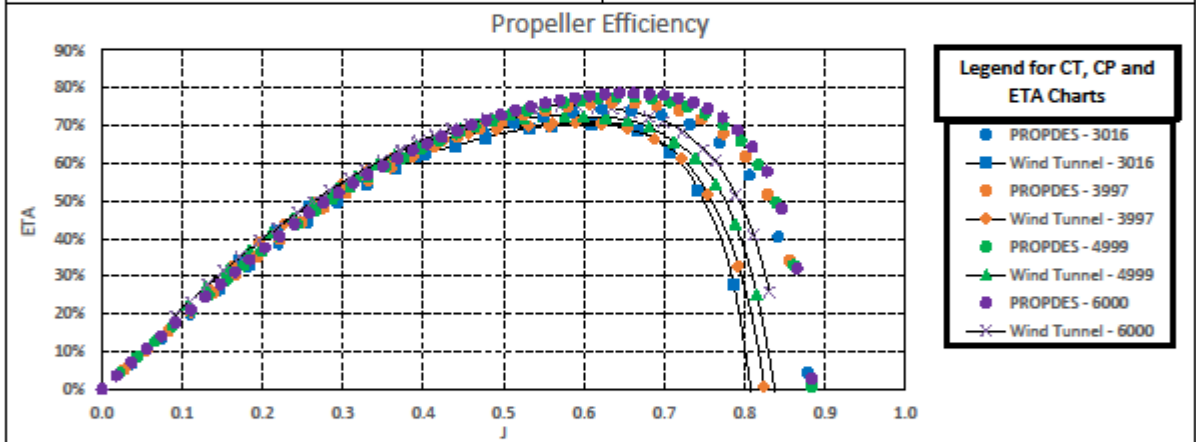
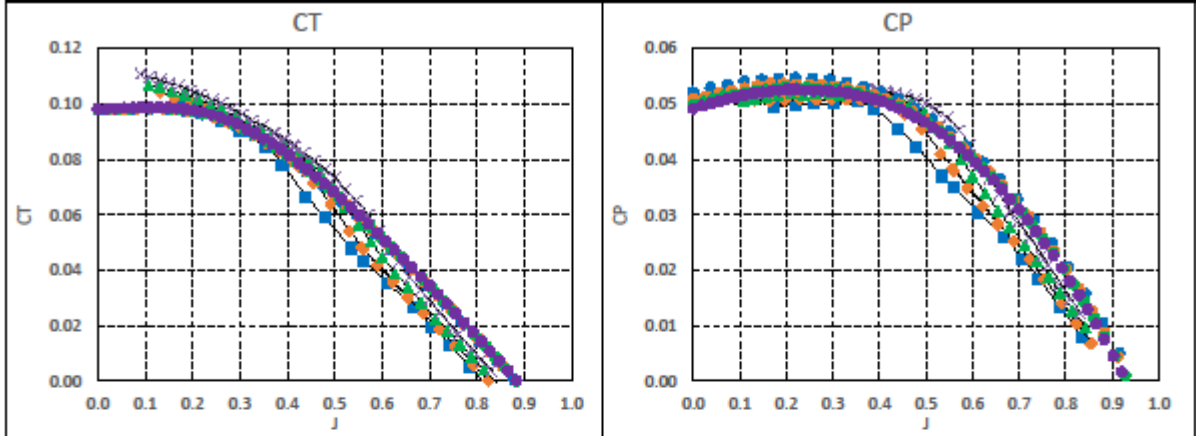
# QV3 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	11	7	0.636	3003, 3998, 4997, 6003	0-45	UIUC



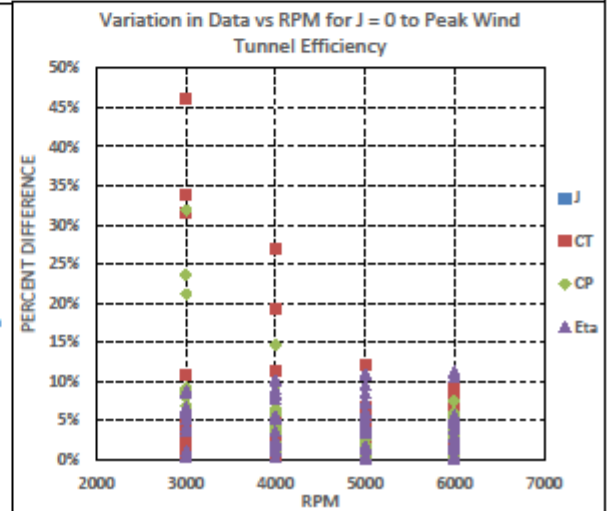
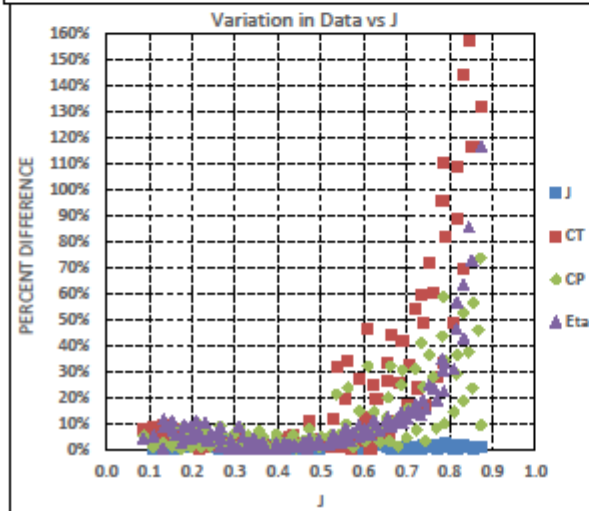
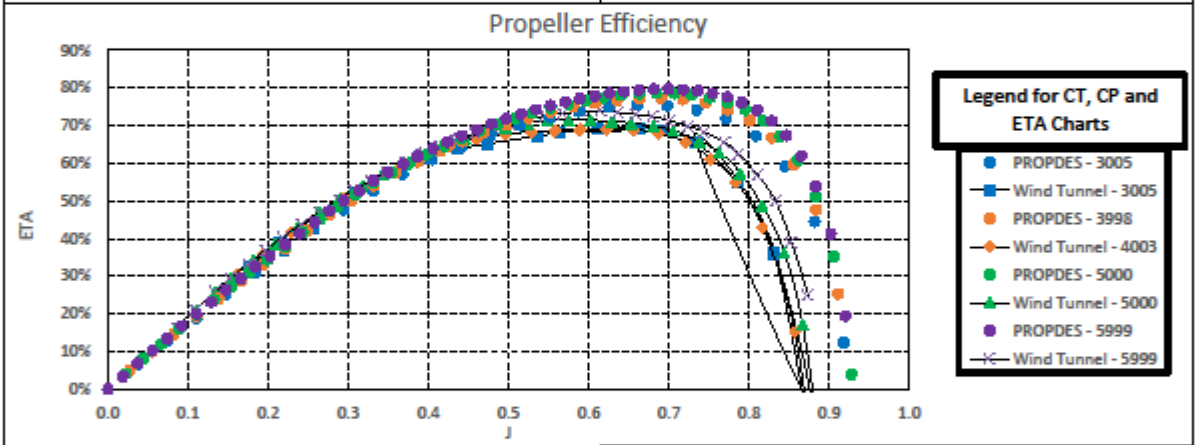
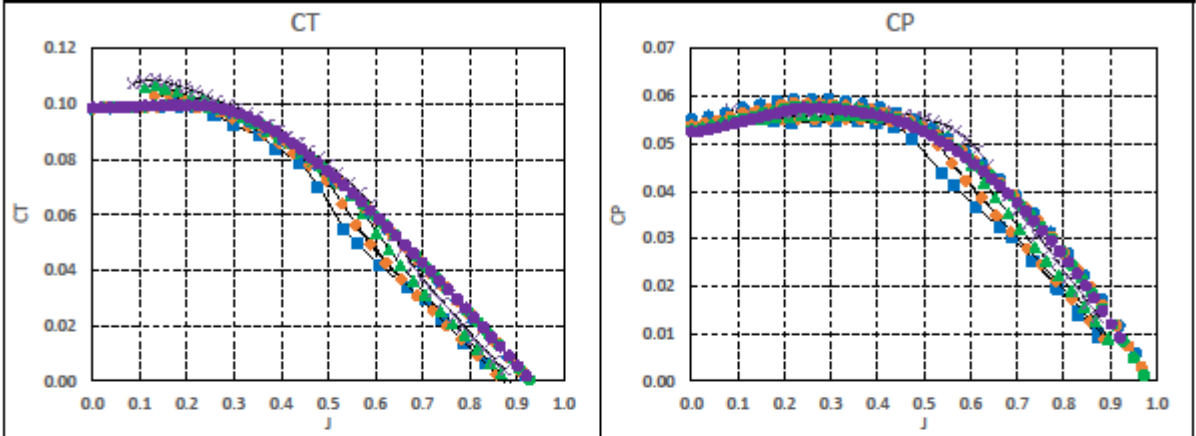
# QV4 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	11	8	0.727	3016, 3997, 4999, 6000	0-50	UIUC



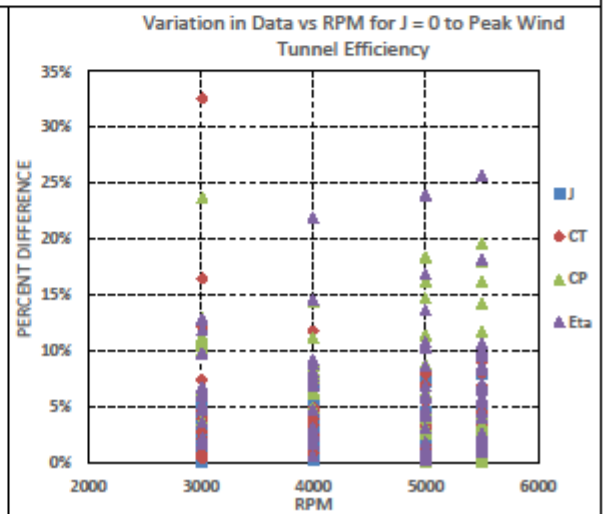
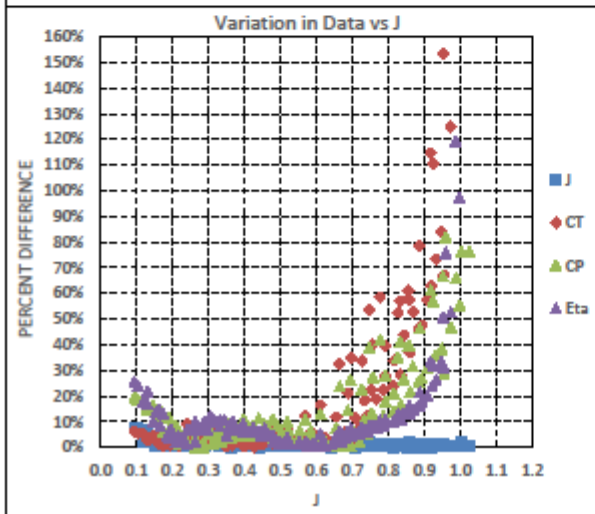
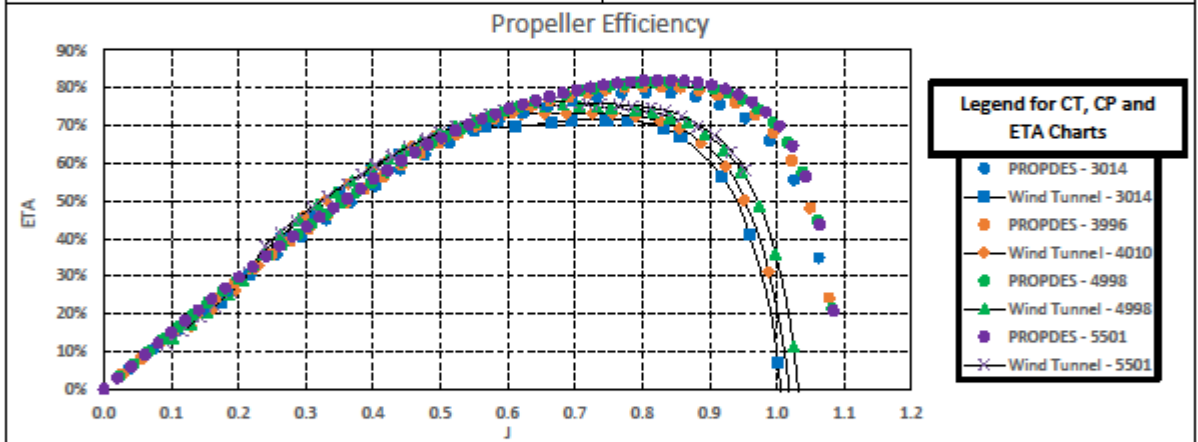
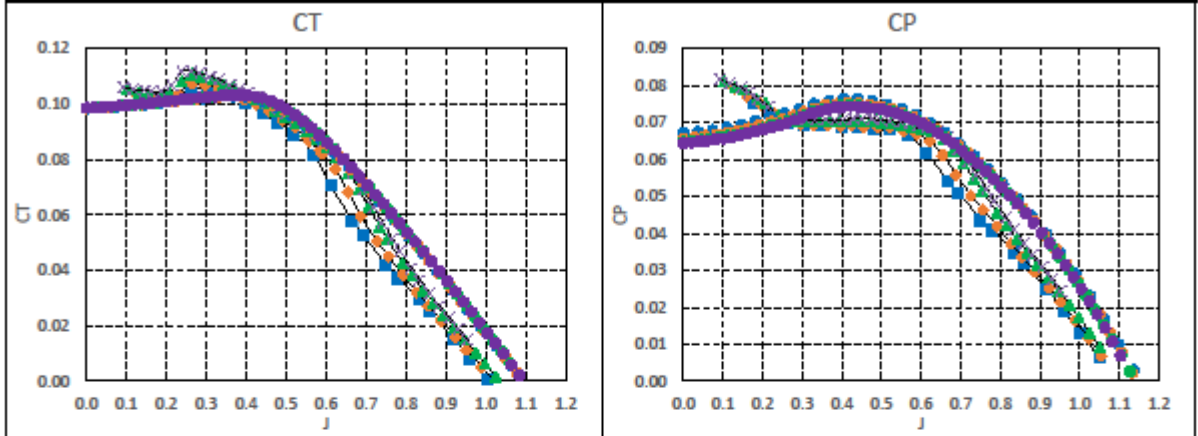
# QV5 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	11	8.5	0.773	3005, 3998, 5000, 5999	0-50	UIUC



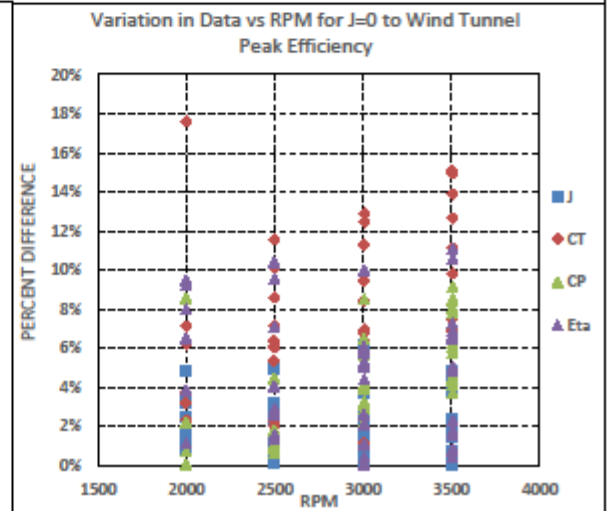
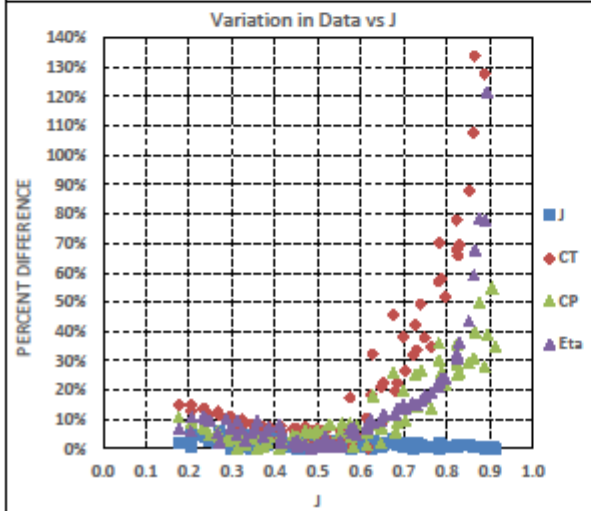
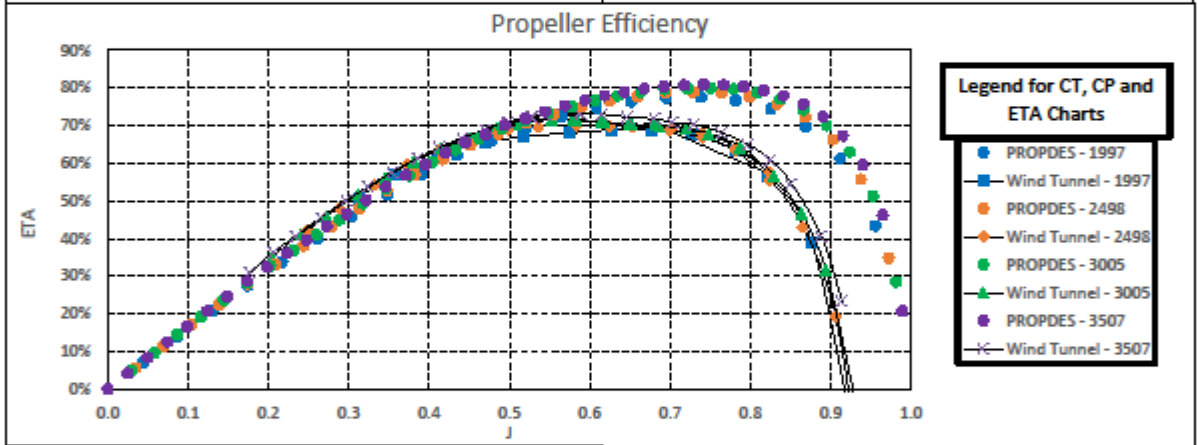
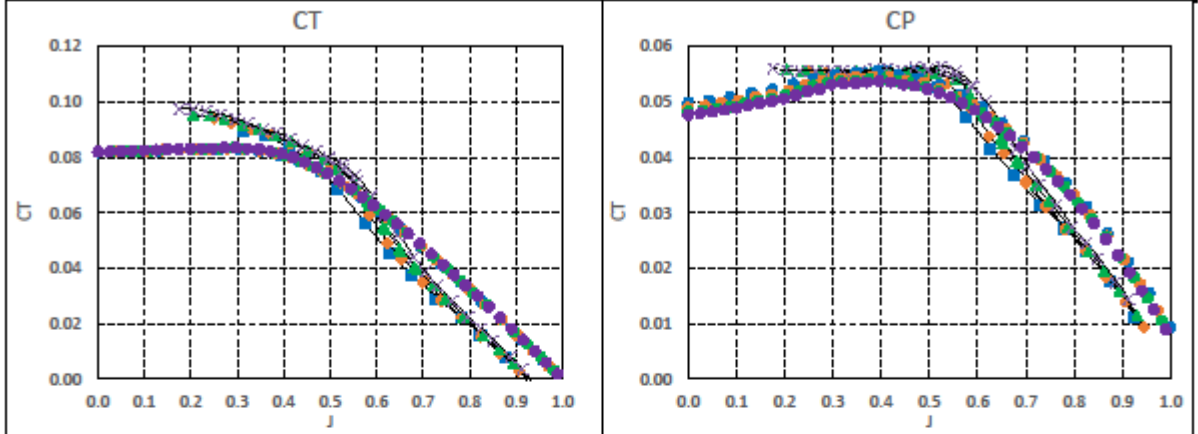
# QV6 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	11	10	0.909	3014, 3996, 4998, 5501	0-55	UIUC



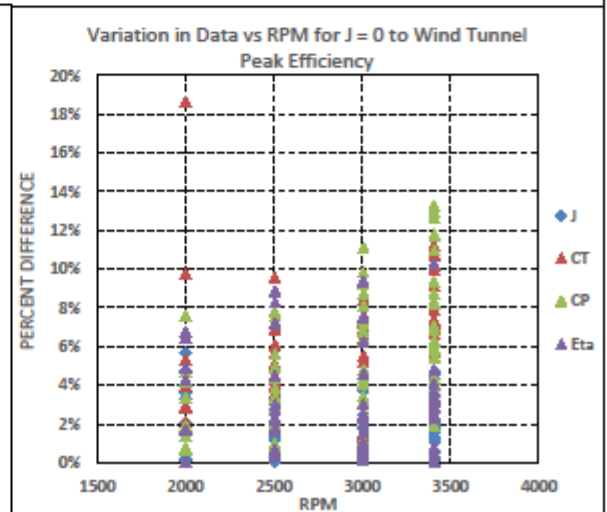
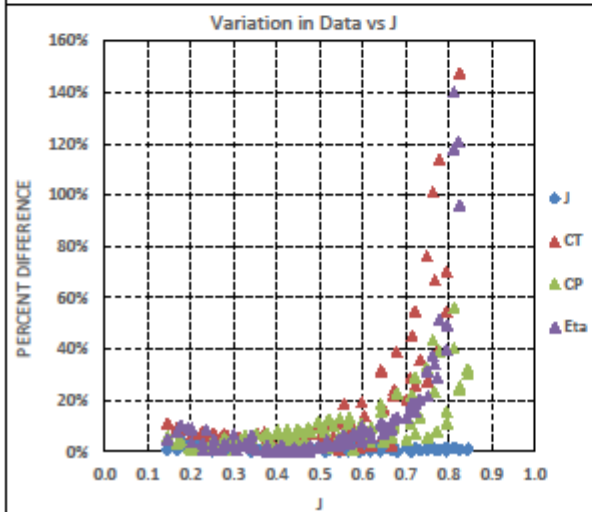
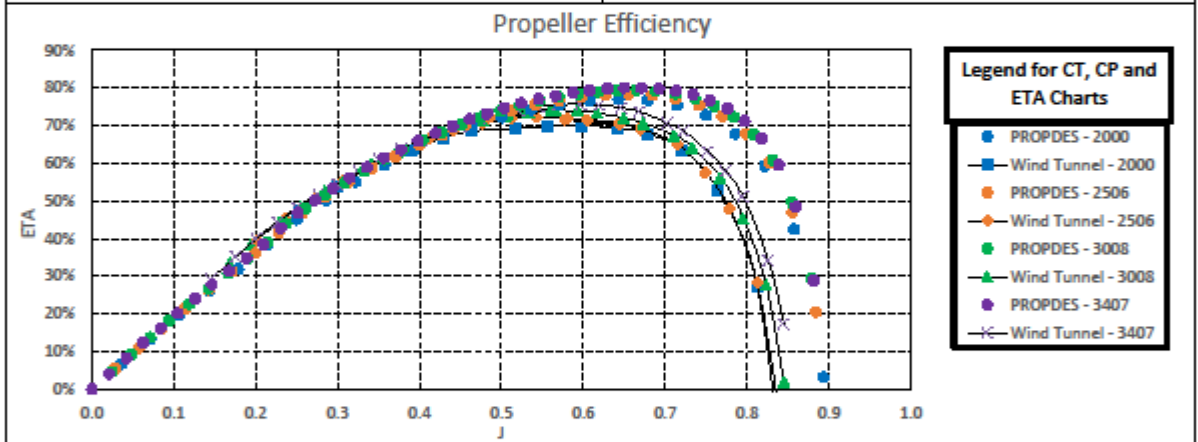
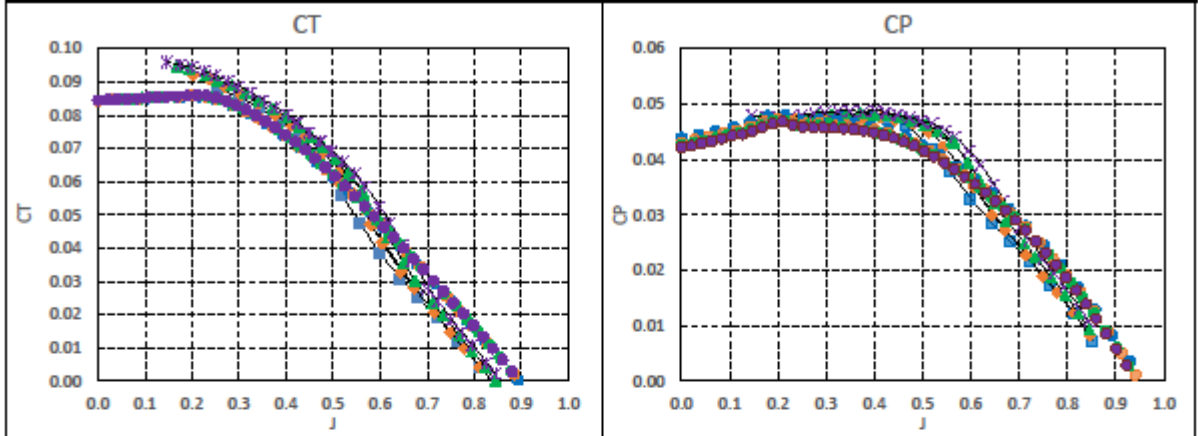
# QV7 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	14	12	0.857	1997, 2498, 3005, 3507	0-40	UIUC



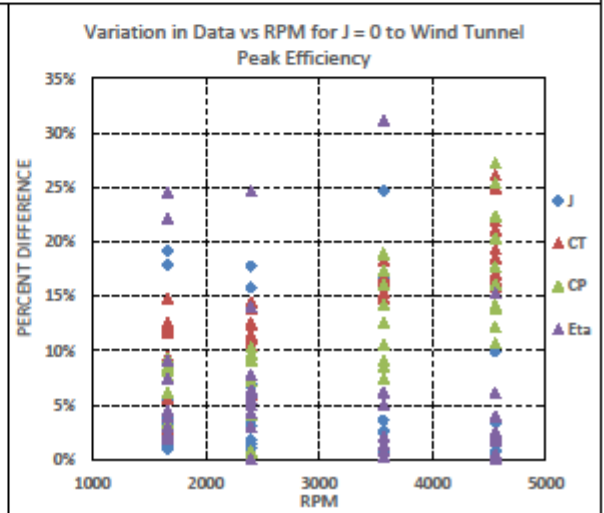
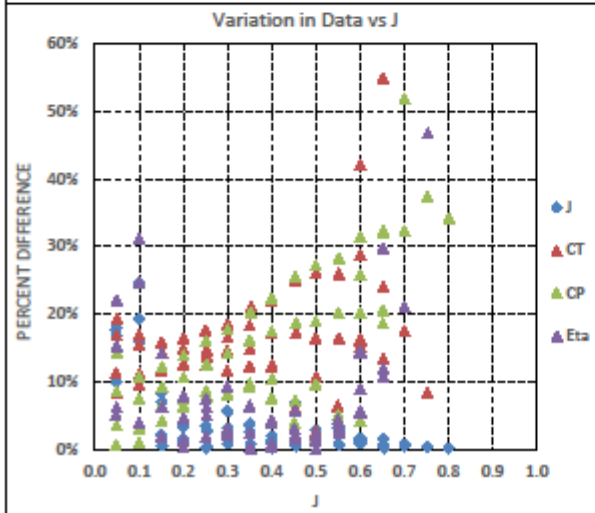
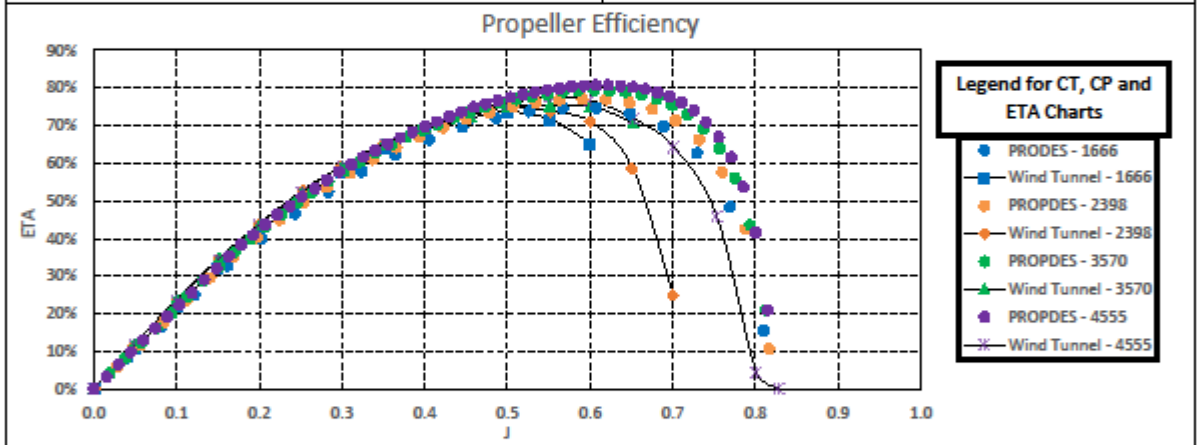
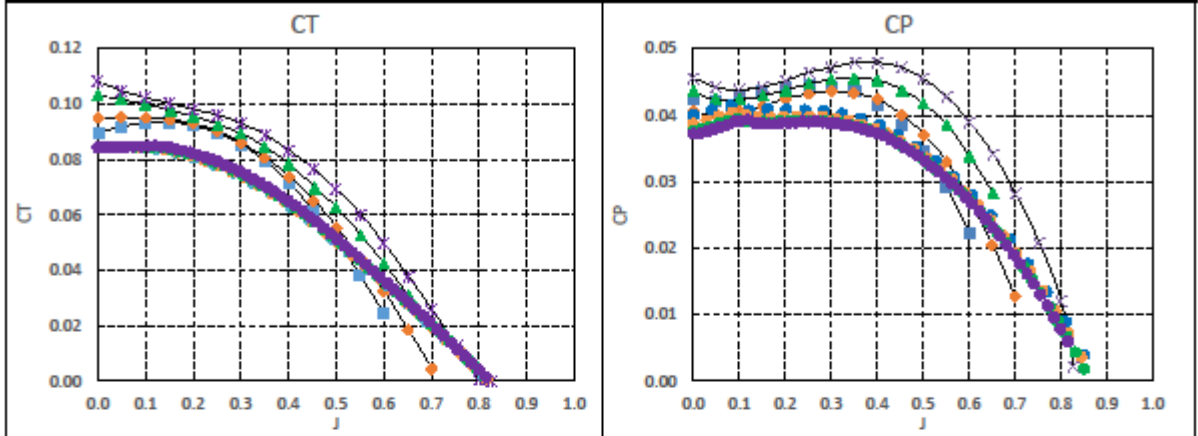
# QV8 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	17	12	0.857	2000, 2506, 3008, 3407	0-45	UIUC



# QV9 Test Data Sheet

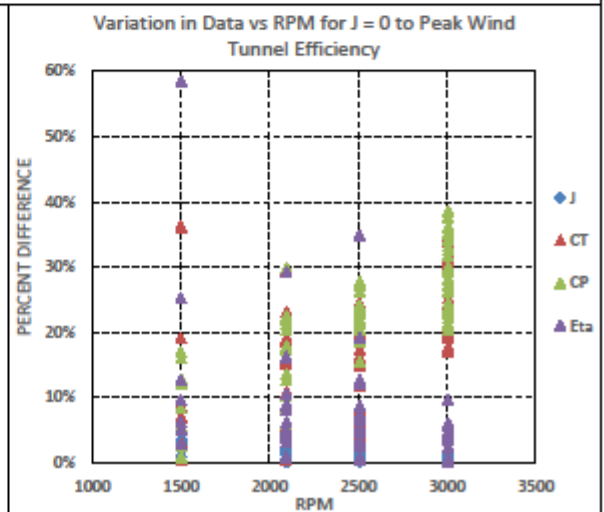
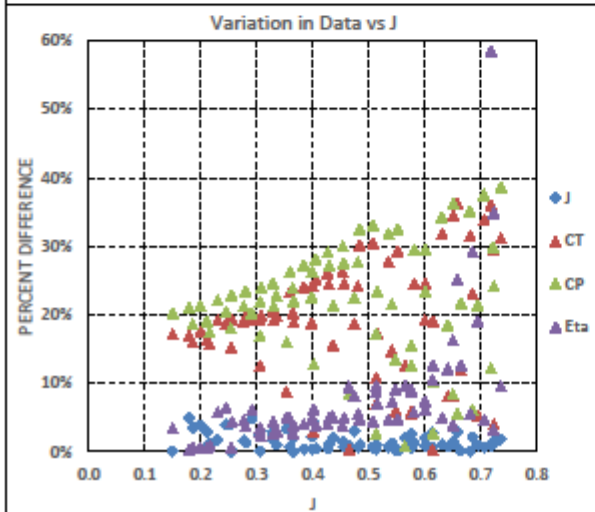
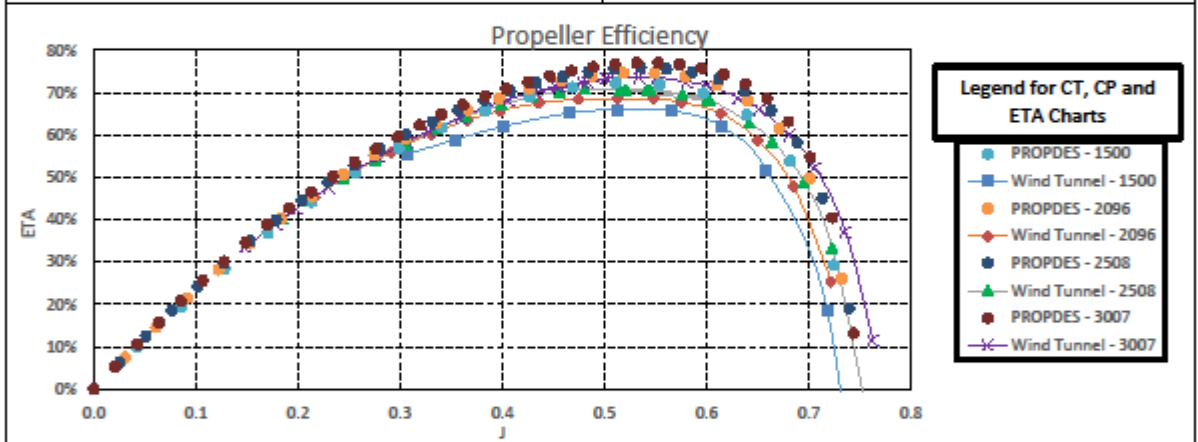
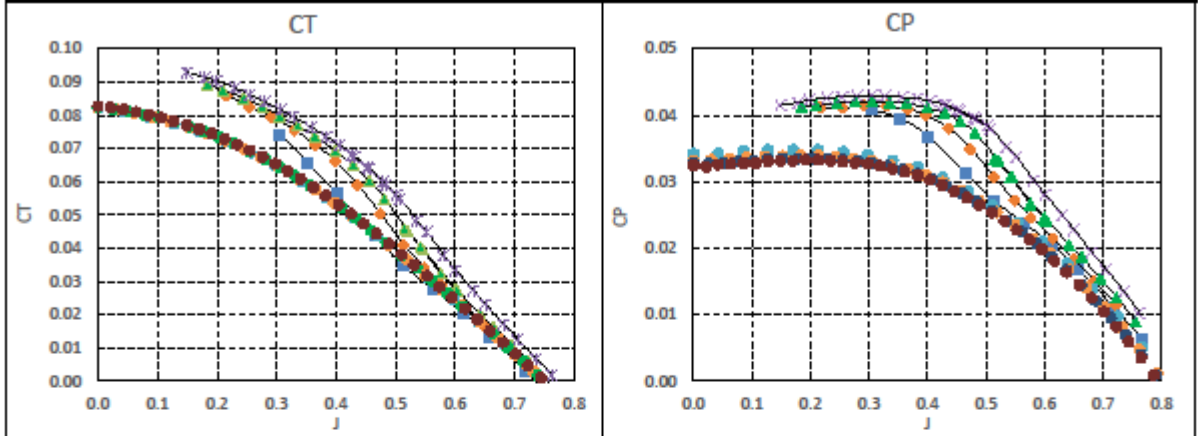
Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	18	12	0.667	1666, 2398, 3570, 4555	0-55	Gamble





# QV10 Test Data Sheet

Manufacturer	Model	Blades	Diameter (In)	Pitch (In)	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
APC	Thin Electric	2	19	12	0.632	1500, 2096, 2508, 3007	0-50	UIUC



## APPENDIX E PV TEST DETAILS

Additional data from the PV test cases is provided here. Specifically, the full single iteration PROPDES/QMIL comparison tables are provided to support the roll up table provided in Table 19. Additionally, the propeller files output by PROPDES/QMIL for PV5 and PV6 are provided since these cases were explored further in Chapter 6.

## PV Single Iteration PROPDES/QPROP Comparison Tables

<b>Run PV1 - Diameter:9" - RPM:6000 - V:40 - Blades:2</b>										
<b>Radial Position</b>		<b>QMIL Stand Alone</b>		<b>PROPDES</b>		<b>Difference</b>		<b>Percent Difference</b>		
r (in)	r/R	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord	Beta	
0.52	0.115	9.43	77.24	9.43	77.24	0.0000	0.0003	0.0000%	0.0004%	
0.65	0.145	8.29	75.41	8.29	75.41	0.0000	0.0005	0.0000%	0.0007%	
0.79	0.175	9.56	72.48	9.56	72.48	0.0000	0.0005	0.0000%	0.0007%	
0.92	0.205	11.20	69.42	11.20	69.42	0.0000	0.0006	0.0000%	0.0009%	
1.06	0.235	11.95	66.75	11.95	66.75	0.0000	0.0006	0.0000%	0.0009%	
1.19	0.265	12.77	64.09	12.77	64.09	0.0000	0.0007	0.0000%	0.0011%	
1.33	0.295	12.94	61.70	12.94	61.70	0.0000	0.0008	0.0000%	0.0013%	
1.46	0.325	15.00	58.81	15.00	58.81	0.0000	0.0007	0.0000%	0.0012%	
1.60	0.355	15.14	56.56	15.14	56.56	0.0000	0.0008	0.0000%	0.0014%	
1.73	0.385	13.91	54.76	13.91	54.76	0.0000	0.0010	0.0000%	0.0018%	
1.87	0.415	12.95	53.01	12.95	53.01	0.0000	0.0012	0.0000%	0.0023%	
2.00	0.445	11.68	51.51	11.68	51.51	0.0000	0.0015	0.0000%	0.0029%	
2.14	0.475	11.90	49.50	11.90	49.50	0.0000	0.0015	0.0000%	0.0030%	
2.27	0.505	11.33	47.89	11.33	47.89	0.0000	0.0018	0.0000%	0.0038%	
2.41	0.535	10.05	46.73	10.05	46.73	0.0000	0.0021	0.0000%	0.0045%	
2.54	0.565	8.45	46.01	8.45	46.00	0.0000	0.0027	0.0000%	0.0059%	
2.68	0.595	6.86	45.72	6.86	45.72	0.0000	0.0035	0.0000%	0.0077%	
2.81	0.625	5.47	45.86	5.47	45.85	0.0000	0.0046	0.0000%	0.0100%	
2.95	0.655	4.32	46.42	4.32	46.41	0.0000	0.0061	0.0000%	0.0131%	
3.08	0.685	4.07	45.26	4.07	45.26	0.0000	0.0066	0.0000%	0.0146%	
3.22	0.715	3.86	44.07	3.86	44.06	0.0000	0.0071	0.0000%	0.0161%	
3.35	0.745	3.62	42.93	3.62	42.92	0.0000	0.0076	0.0000%	0.0177%	
3.49	0.775	3.38	41.86	3.38	41.85	0.0000	0.0082	0.0000%	0.0196%	
3.62	0.805	3.12	40.83	3.12	40.82	0.0000	0.0089	0.0000%	0.0218%	
3.76	0.835	2.85	39.86	2.85	39.85	0.0000	0.0095	0.0000%	0.0238%	
3.89	0.865	2.56	38.93	2.56	38.92	0.0000	0.0102	0.0000%	0.0262%	
4.03	0.895	2.24	38.05	2.24	38.04	0.0000	0.0109	0.0000%	0.0286%	
4.16	0.925	1.87	37.21	1.87	37.20	0.0000	0.0116	0.0000%	0.0312%	
4.30	0.955	1.44	36.41	1.44	36.40	0.0000	0.0123	0.0000%	0.0338%	
4.43	0.985	0.82	35.65	0.82	35.63	0.0000	0.0131	0.0000%	0.0368%	
4.50	1.000	0.45	35.28	0.45	35.26	0.0000	0.0135	0.0000%	0.0383%	
						Max:	0.0000	0.0135	0.0000%	0.0383%
						Sum:	0.0000	0.1510	0.0000%	0.3720%

Run PV2 - Diameter:11" - RPM:4000 - V:15 - Blades:2										
Radial Position		QMIL Stand Alone		PROPDES		Difference		Percent Difference		
r (in)	r/R	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord	Beta	
0.63	0.115	34.75	76.55	34.75	76.55	0.0000	0.0000	0.0000%	0.0000%	
0.80	0.145	29.15	74.58	29.15	74.58	0.0000	0.0001	0.0000%	0.0001%	
0.96	0.175	31.98	71.51	31.98	71.51	0.0000	0.0001	0.0000%	0.0001%	
1.13	0.205	35.73	68.32	35.73	68.32	0.0000	0.0001	0.0000%	0.0001%	
1.29	0.235	36.14	65.56	36.14	65.56	0.0000	0.0001	0.0000%	0.0002%	
1.46	0.265	37.87	62.71	37.87	62.71	0.0000	0.0002	0.0000%	0.0003%	
1.62	0.295	36.78	60.24	36.78	60.24	0.0000	0.0002	0.0000%	0.0003%	
1.79	0.325	40.00	57.39	40.00	57.39	0.0000	0.0003	0.0000%	0.0005%	
1.95	0.355	39.20	55.06	39.20	55.06	0.0004	0.0003	0.0010%	0.0005%	
2.12	0.385	34.84	53.23	34.84	53.23	0.0000	0.0004	0.0000%	0.0008%	
2.28	0.415	31.52	51.45	31.52	51.45	0.0000	0.0004	0.0000%	0.0008%	
2.45	0.445	27.69	49.94	27.69	49.94	0.0000	0.0006	0.0000%	0.0012%	
2.61	0.475	27.59	47.91	27.59	47.91	0.0000	0.0007	0.0000%	0.0015%	
2.78	0.505	25.72	46.30	25.72	46.30	0.0000	0.0008	0.0000%	0.0017%	
2.94	0.535	22.39	45.14	22.39	45.14	0.0000	0.0010	0.0000%	0.0022%	
3.11	0.565	18.50	44.43	18.50	44.43	0.0000	0.0012	0.0000%	0.0027%	
3.27	0.595	14.80	44.16	14.80	44.16	0.0000	0.0017	0.0000%	0.0038%	
3.44	0.625	11.63	44.32	11.63	44.32	0.0000	0.0022	0.0000%	0.0050%	
3.60	0.655	9.08	44.92	9.08	44.91	0.0000	0.0030	0.0000%	0.0067%	
3.77	0.685	8.48	43.77	8.48	43.76	0.0000	0.0034	0.0000%	0.0078%	
3.93	0.715	7.94	42.59	7.94	42.59	0.0000	0.0037	0.0000%	0.0087%	
4.10	0.745	7.40	41.48	7.40	41.48	0.0000	0.0040	0.0000%	0.0096%	
4.26	0.775	6.85	40.43	6.85	40.43	0.0000	0.0044	0.0000%	0.0109%	
4.43	0.805	6.28	39.44	6.28	39.43	0.0000	0.0048	0.0000%	0.0122%	
4.59	0.835	5.69	38.49	5.69	38.49	0.0000	0.0052	0.0000%	0.0135%	
4.76	0.865	5.07	37.59	5.07	37.59	0.0000	0.0056	0.0000%	0.0149%	
4.92	0.895	4.41	36.74	4.41	36.73	0.0000	0.0061	0.0000%	0.0166%	
5.09	0.925	3.68	35.93	3.68	35.92	0.0000	0.0066	0.0000%	0.0184%	
5.25	0.955	2.81	35.15	2.81	35.15	0.0000	0.0070	0.0000%	0.0199%	
5.42	0.985	1.60	34.42	1.60	34.41	0.0000	0.0075	0.0000%	0.0218%	
5.50	1.000	0.87	34.06	0.87	34.05	0.0000	0.0077	0.0000%	0.0226%	
						Max:	0.0004	0.0077	0.0010%	0.0226%
						Sum:	0.0004	0.0794	0.0010%	0.2055%

Run PV3 - Diameter:11" - RPM:4000 - V:25 - Blades:2										
Radial Position		QMIL Stand Alone		PROPDES		Difference		Percent Difference		
r (in)	r/R	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord	Beta	
0.63	0.115	19.29	77.49	19.29	77.49	0.0000	0.0001	0.0000%	0.0001%	
0.80	0.145	16.73	75.74	16.73	75.74	0.0000	0.0002	0.0000%	0.0003%	
0.96	0.175	19.02	72.86	19.02	72.86	0.0000	0.0002	0.0000%	0.0003%	
1.13	0.205	22.01	69.85	22.01	69.85	0.0000	0.0002	0.0000%	0.0003%	
1.29	0.235	23.03	67.25	23.03	67.25	0.0000	0.0002	0.0000%	0.0003%	
1.46	0.265	24.91	64.52	24.91	64.52	0.0000	0.0003	0.0000%	0.0005%	
1.62	0.295	24.92	62.16	24.92	62.16	0.0004	0.0004	0.0016%	0.0006%	
1.79	0.325	27.83	59.41	27.83	59.41	0.0000	0.0004	0.0000%	0.0007%	
1.95	0.355	27.95	57.16	27.95	57.16	0.0000	0.0004	0.0000%	0.0007%	
2.12	0.385	25.39	55.38	25.39	55.38	0.0000	0.0005	0.0000%	0.0009%	
2.28	0.415	23.42	53.65	23.42	53.65	0.0000	0.0006	0.0000%	0.0011%	
2.45	0.445	20.93	52.17	20.93	52.17	0.0000	0.0008	0.0000%	0.0015%	
2.61	0.475	21.18	50.16	21.18	50.16	0.0000	0.0008	0.0000%	0.0016%	
2.78	0.505	20.02	48.56	20.02	48.56	0.0000	0.0009	0.0000%	0.0019%	
2.94	0.535	17.65	47.40	17.65	47.40	0.0000	0.0012	0.0000%	0.0025%	
3.11	0.565	14.75	46.68	14.75	46.68	0.0000	0.0016	0.0000%	0.0034%	
3.27	0.595	11.91	46.40	11.91	46.40	0.0000	0.0020	0.0000%	0.0043%	
3.44	0.625	9.44	46.55	9.44	46.55	0.0000	0.0026	0.0000%	0.0056%	
3.60	0.655	7.43	47.12	7.43	47.12	0.0000	0.0035	0.0000%	0.0074%	
3.77	0.685	6.99	45.95	6.99	45.94	0.0000	0.0038	0.0000%	0.0083%	
3.93	0.715	6.59	44.75	6.59	44.75	0.0000	0.0042	0.0000%	0.0094%	
4.10	0.745	6.17	43.61	6.17	43.61	0.0000	0.0045	0.0000%	0.0103%	
4.26	0.775	5.74	42.53	5.74	42.53	0.0000	0.0049	0.0000%	0.0115%	
4.43	0.805	5.29	41.50	5.29	41.50	0.0000	0.0053	0.0000%	0.0128%	
4.59	0.835	4.82	40.53	4.82	40.52	0.0000	0.0057	0.0000%	0.0141%	
4.76	0.865	4.31	39.60	4.31	39.59	0.0000	0.0062	0.0000%	0.0157%	
4.92	0.895	3.76	38.71	3.76	38.70	0.0000	0.0066	0.0000%	0.0171%	
5.09	0.925	3.14	37.87	3.14	37.86	0.0000	0.0070	0.0000%	0.0185%	
5.25	0.955	2.41	37.06	2.41	37.05	0.0000	0.0075	0.0000%	0.0202%	
5.42	0.985	1.38	36.29	1.38	36.28	0.0000	0.0080	0.0000%	0.0220%	
5.50	1.000	0.75	35.92	0.75	35.91	0.0000	0.0083	0.0000%	0.0231%	
						Max:	0.0004	0.0083	0.0016%	0.0231%
						Sum:	0.0004	0.0889	0.0016%	0.2169%

Run PV4 - Diameter:11" - RPM:4000 - V:50 - Blades:2										
Radial Position		QMIL Stand Alone		PROPDES		Difference		Percent Difference		
r (in)	r/R	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord	Beta	
0.63	0.115	7.13	79.79	7.13	79.79	0.0004	0.0005	0.0055%	0.0006%	
0.80	0.145	6.35	78.57	6.35	78.57	0.0000	0.0007	0.0000%	0.0009%	
0.96	0.175	7.43	76.20	7.43	76.20	0.0000	0.0007	0.0000%	0.0009%	
1.13	0.205	8.88	73.65	8.88	73.65	0.0000	0.0007	0.0000%	0.0010%	
1.29	0.235	9.61	71.47	9.61	71.47	0.0000	0.0008	0.0000%	0.0011%	
1.46	0.265	10.76	69.12	10.76	69.12	0.0000	0.0008	0.0000%	0.0012%	
1.62	0.295	11.14	67.10	11.14	67.10	0.0000	0.0009	0.0000%	0.0013%	
1.79	0.325	12.87	64.64	12.87	64.64	0.0000	0.0008	0.0000%	0.0012%	
1.95	0.355	13.36	62.63	13.36	62.63	0.0000	0.0009	0.0000%	0.0014%	
2.12	0.385	12.53	61.07	12.53	61.07	0.0000	0.0010	0.0000%	0.0016%	
2.28	0.415	11.91	59.51	11.91	59.51	0.0000	0.0012	0.0000%	0.0020%	
2.45	0.445	10.96	58.16	10.96	58.16	0.0000	0.0014	0.0000%	0.0024%	
2.61	0.475	11.39	56.27	11.39	56.26	0.0000	0.0015	0.0000%	0.0027%	
2.78	0.505	11.05	54.75	11.05	54.74	0.0000	0.0016	0.0000%	0.0029%	
2.94	0.535	9.97	53.65	9.97	53.64	0.0000	0.0020	0.0000%	0.0037%	
3.11	0.565	8.52	52.96	8.52	52.96	0.0000	0.0023	0.0000%	0.0043%	
3.27	0.595	7.02	52.70	7.02	52.69	0.0000	0.0031	0.0000%	0.0059%	
3.44	0.625	5.68	52.84	5.68	52.84	0.0000	0.0038	0.0000%	0.0072%	
3.60	0.655	4.55	53.39	4.55	53.39	0.0000	0.0050	0.0000%	0.0094%	
3.77	0.685	4.34	52.20	4.34	52.19	0.0000	0.0054	0.0000%	0.0103%	
3.93	0.715	4.16	50.96	4.16	50.96	0.0000	0.0058	0.0000%	0.0114%	
4.10	0.745	3.95	49.78	3.95	49.77	0.0000	0.0061	0.0000%	0.0123%	
4.26	0.775	3.72	48.65	3.72	48.64	0.0000	0.0065	0.0000%	0.0134%	
4.43	0.805	3.47	47.56	3.47	47.56	0.0000	0.0069	0.0000%	0.0145%	
4.59	0.835	3.19	46.52	3.19	46.52	0.0000	0.0073	0.0000%	0.0157%	
4.76	0.865	2.89	45.53	2.89	45.52	0.0000	0.0078	0.0000%	0.0171%	
4.92	0.895	2.54	44.57	2.54	44.56	0.0000	0.0082	0.0000%	0.0184%	
5.09	0.925	2.14	43.66	2.14	43.65	0.0000	0.0087	0.0000%	0.0199%	
5.25	0.955	1.66	42.78	1.66	42.77	0.0000	0.0092	0.0000%	0.0215%	
5.42	0.985	0.95	41.93	0.95	41.92	0.0000	0.0097	0.0000%	0.0231%	
5.50	1.000	0.52	41.52	0.52	41.51	0.0000	0.0099	0.0000%	0.0238%	
						Max:	0.0004	0.0099	0.0055%	0.0238%
						Sum:	0.0004	0.1212	0.0055%	0.2533%

Run PV5 - Diameter:18 - RPM:4500 - V:45 - Blades:2										
Radial Position		QMIL Stand Alone		PROPDES		Difference		Percent Difference		
r (in)	r/R	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord	Beta	
1.03	0.115	3.54	65.20	3.54	65.20	0.0000	0.0006	0.0000%	0.0009%	
1.30	0.145	3.15	60.96	3.15	60.96	0.0000	0.0008	0.0000%	0.0013%	
1.57	0.175	3.35	56.30	3.35	56.30	0.0000	0.0009	0.0000%	0.0016%	
1.84	0.205	3.69	51.79	3.69	51.79	0.0000	0.0011	0.0000%	0.0021%	
2.11	0.235	3.88	47.84	3.88	47.84	0.0000	0.0012	0.0000%	0.0025%	
2.38	0.265	3.92	44.40	3.92	44.40	0.0000	0.0014	0.0010%	0.0032%	
2.65	0.295	3.99	41.25	3.99	41.25	0.0000	0.0015	0.0000%	0.0036%	
2.92	0.325	3.56	39.02	3.56	39.01	0.0000	0.0020	0.0000%	0.0051%	
3.19	0.355	3.18	37.06	3.18	37.06	0.0000	0.0024	0.0000%	0.0065%	
3.46	0.385	3.16	34.77	3.16	34.76	0.0000	0.0027	0.0000%	0.0078%	
3.73	0.415	3.06	32.82	3.06	32.82	0.0000	0.0030	0.0000%	0.0091%	
4.01	0.445	2.96	31.04	2.96	31.04	0.0000	0.0034	0.0000%	0.0110%	
4.28	0.475	2.85	29.44	2.85	29.44	0.0000	0.0038	0.0000%	0.0129%	
4.54	0.505	2.75	27.98	2.75	27.97	0.0000	0.0042	0.0000%	0.0150%	
4.81	0.535	2.64	26.64	2.64	26.63	0.0000	0.0046	0.0000%	0.0173%	
5.09	0.565	2.54	25.41	2.54	25.40	0.0000	0.0050	0.0000%	0.0197%	
5.36	0.595	2.44	24.27	2.44	24.26	0.0000	0.0055	0.0016%	0.0227%	
5.63	0.625	2.34	23.21	2.34	23.20	0.0000	0.0059	0.0000%	0.0254%	
5.89	0.655	2.24	22.22	2.24	22.22	0.0000	0.0064	0.0018%	0.0288%	
6.16	0.685	2.14	21.30	2.14	21.30	0.0000	0.0068	0.0000%	0.0319%	
6.44	0.715	2.05	20.44	2.05	20.43	0.0000	0.0073	0.0000%	0.0357%	
6.71	0.745	1.95	19.62	1.95	19.61	0.0000	0.0078	0.0000%	0.0398%	
6.98	0.775	1.84	18.85	1.84	18.84	0.0000	0.0082	0.0000%	0.0435%	
7.24	0.805	1.73	18.11	1.73	18.10	0.0000	0.0087	0.0023%	0.0480%	
7.51	0.835	1.61	17.41	1.61	17.40	0.0000	0.0091	0.0000%	0.0523%	
7.79	0.865	1.48	16.75	1.48	16.74	0.0000	0.0096	0.0000%	0.0573%	
8.06	0.895	1.33	16.11	1.33	16.10	0.0000	0.0100	0.0030%	0.0621%	
8.33	0.925	1.15	15.49	1.15	15.48	0.0000	0.0104	0.0000%	0.0672%	
8.59	0.955	0.91	14.90	0.91	14.89	0.0000	0.0107	0.0000%	0.0719%	
8.86	0.985	0.54	14.32	0.54	14.31	0.0000	0.0110	0.0000%	0.0768%	
9.00	1.000	0.31	14.04	0.31	14.03	0.0000	0.0112	0.0013%	0.0798%	
						Max:	0.0000	0.0112	0.0030%	0.0798%
						Sum:	0.0002	0.1672	0.0109%	0.8628%

Run PV6 - Diameter:19" - RPM:3000 - V:40 - Blades:2										
Radial Position		QMIL Stand Alone		PROPDES		Difference		Percent Difference		
r (in)	r/R	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord (in)	Beta (deg)	Chord	Beta	
1.09	0.115	4.70	71.47	4.70	71.47	0.0000	0.0005	0.0000%	0.0007%	
1.38	0.145	5.34	67.29	5.34	67.29	0.0000	0.0005	0.0000%	0.0007%	
1.66	0.175	6.32	62.99	6.32	62.99	0.0000	0.0006	0.0000%	0.0010%	
1.95	0.205	6.36	59.52	6.36	59.51	0.0000	0.0007	0.0000%	0.0012%	
2.23	0.235	6.27	56.32	6.27	56.32	0.0000	0.0008	0.0000%	0.0014%	
2.52	0.265	6.78	52.86	6.78	52.86	0.0000	0.0009	0.0000%	0.0017%	
2.80	0.295	7.03	49.79	7.03	49.79	0.0000	0.0009	0.0000%	0.0018%	
3.09	0.325	7.20	46.96	7.20	46.96	0.0000	0.0011	0.0000%	0.0023%	
3.37	0.355	7.15	44.46	7.15	44.46	0.0000	0.0012	0.0000%	0.0027%	
3.66	0.385	7.24	42.04	7.24	42.04	0.0000	0.0013	0.0000%	0.0031%	
3.94	0.415	6.42	40.42	6.42	40.42	0.0000	0.0016	0.0000%	0.0040%	
4.23	0.445	5.72	38.96	5.72	38.96	0.0000	0.0019	0.0000%	0.0049%	
4.51	0.475	5.72	37.02	5.72	37.02	0.0000	0.0021	0.0000%	0.0057%	
4.80	0.505	5.37	35.54	5.37	35.54	0.0000	0.0023	0.0000%	0.0065%	
5.08	0.535	4.73	34.55	4.73	34.55	0.0000	0.0028	0.0000%	0.0081%	
5.37	0.565	3.97	34.03	3.97	34.03	0.0000	0.0035	0.0000%	0.0103%	
5.65	0.595	3.22	33.97	3.22	33.97	0.0000	0.0045	0.0000%	0.0132%	
5.94	0.625	2.57	34.37	2.57	34.36	0.0000	0.0058	0.0000%	0.0169%	
6.22	0.655	2.16	34.50	2.16	34.50	0.0000	0.0072	0.0000%	0.0209%	
6.51	0.685	2.05	33.46	2.05	33.45	0.0000	0.0078	0.0000%	0.0233%	
6.79	0.715	1.93	32.48	1.93	32.48	0.0000	0.0083	0.0000%	0.0256%	
7.08	0.745	1.81	31.57	1.81	31.57	0.0000	0.0090	0.0000%	0.0285%	
7.36	0.775	1.68	30.72	1.68	30.71	0.0000	0.0096	0.0000%	0.0313%	
7.65	0.805	1.55	29.92	1.55	29.91	0.0000	0.0104	0.0000%	0.0348%	
7.93	0.835	1.41	29.17	1.41	29.16	0.0000	0.0111	0.0000%	0.0381%	
8.22	0.865	1.26	28.46	1.26	28.45	0.0000	0.0118	0.0000%	0.0415%	
8.50	0.895	1.10	27.79	1.10	27.78	0.0000	0.0127	0.0000%	0.0457%	
8.79	0.925	0.92	27.16	0.92	27.14	0.0000	0.0134	0.0000%	0.0494%	
9.07	0.955	0.71	26.56	0.71	26.54	0.0000	0.0143	0.0000%	0.0539%	
9.36	0.985	0.41	25.99	0.41	25.97	0.0000	0.0151	0.0000%	0.0581%	
9.50	1.000	0.22	25.72	0.22	25.70	0.0000	0.0156	0.0000%	0.0607%	
						Max:	0.0000	0.0156	0.0000%	0.0607%
						Sum:	0.0000	0.1793	0.0000%	0.5977%



## PV5 Propeller File

Blades: 2      Radius: 9. inches    RPM: 4500

```

2          ! Nblades

0.3856  5.7868      ! CL0      CL_a
-0.3000  1.1253      ! CLmin    CLmax

0.00724  0.01250  0.01250  0.4650      ! CD0      CD2u  CD2l
CLCD0
578257.0  -0.500          ! RRef    RExp

1.0000  1.0000  1.0000      ! Rfac    Cfac    Bfac
0.0000  0.0000  0.0000      ! Radd    Cadd    Badd

#          r          c          beta
0.26289E-01  0.89826E-01  65.2020
0.33147E-01  0.79914E-01  60.9571
0.40005E-01  0.85026E-01  56.2976
0.46863E-01  0.93656E-01  51.7873
0.53721E-01  0.98483E-01  47.8377
0.60579E-01  0.99680E-01  44.3991
0.67437E-01  0.10147          41.2471
0.74295E-01  0.90389E-01  39.0133
0.81153E-01  0.80795E-01  37.0595
0.88011E-01  0.80363E-01  34.7627
0.94869E-01  0.77626E-01  32.8219
0.10173          0.75204E-01  31.0393
0.10859          0.72502E-01  29.4358
0.11544          0.69801E-01  27.9739
0.12230          0.67137E-01  26.6343
0.12916          0.64524E-01  25.4015
0.13602          0.61961E-01  24.2619
0.14288          0.59441E-01  23.2041
0.14973          0.56951E-01  22.2182
0.15659          0.54473E-01  21.2956
0.16345          0.51978E-01  20.4289
0.17031          0.49435E-01  19.6117
0.17717          0.46799E-01  18.8385
0.18402          0.44017E-01  18.1042
0.19088          0.41010E-01  17.4048
0.19774          0.37670E-01  16.7363
0.20460          0.33829E-01  16.0956
0.21146          0.29197E-01  15.4797
0.21831          0.23164E-01  14.8861
0.22517          0.13741E-01  14.3124
0.22860          0.77584E-02  14.0330

```

## PV6 Propeller File

Blades: 2      Radius: 9.5 inches      RPM: 3000

```

2          ! Nblades

0.3856  5.7868      ! CL0      CL_a
-0.3000  1.1253      ! CLmin    CLmax

0.00724  0.01250  0.01250  0.4650      ! CD0      CD2u  CD2l
CLCD0
578257.0  -0.500          ! RRef    RExp

1.0000  1.0000  1.0000      ! Rfac    Cfac    Bfac
0.0000  0.0000  0.0000      ! Radd    Cadd    Badd

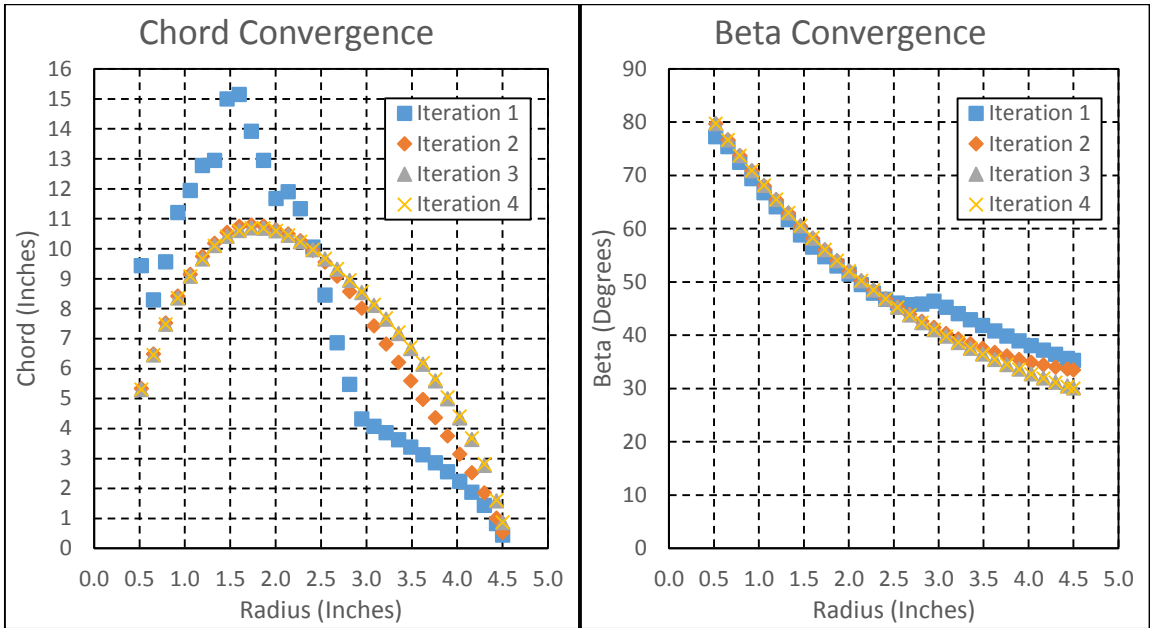
#          r          c          beta
0.27750E-01  0.11936      71.4679
0.34989E-01  0.13576      67.2868
0.42228E-01  0.16049      62.9922
0.49467E-01  0.16148      59.5148
0.56706E-01  0.15926      56.3175
0.63945E-01  0.17215      52.8599
0.71184E-01  0.17847      49.7897
0.78423E-01  0.18285      46.9627
0.85662E-01  0.18166      44.4604
0.92901E-01  0.18398      42.0418
0.10014      0.16313      40.4154
0.10738      0.14523      38.9623
0.11462      0.14520      37.0224
0.12186      0.13643      35.5406
0.12910      0.12020      34.5468
0.13633      0.10080      34.0273
0.14357      0.81856E-01  33.9695
0.15081      0.65301E-01  34.3620
0.15805      0.54978E-01  34.4956
0.16529      0.52027E-01  33.4512
0.17253      0.49000E-01  32.4765
0.17977      0.45889E-01  31.5650
0.18701      0.42677E-01  30.7110
0.19425      0.39339E-01  29.9093
0.20149      0.35835E-01  29.1555
0.20872      0.32105E-01  28.4454
0.21596      0.28050E-01  27.7752
0.22320      0.23491E-01  27.1419
0.23044      0.18034E-01  26.5422
0.23768      0.10322E-01  25.9737
0.24130      0.56204E-02  25.7011

```

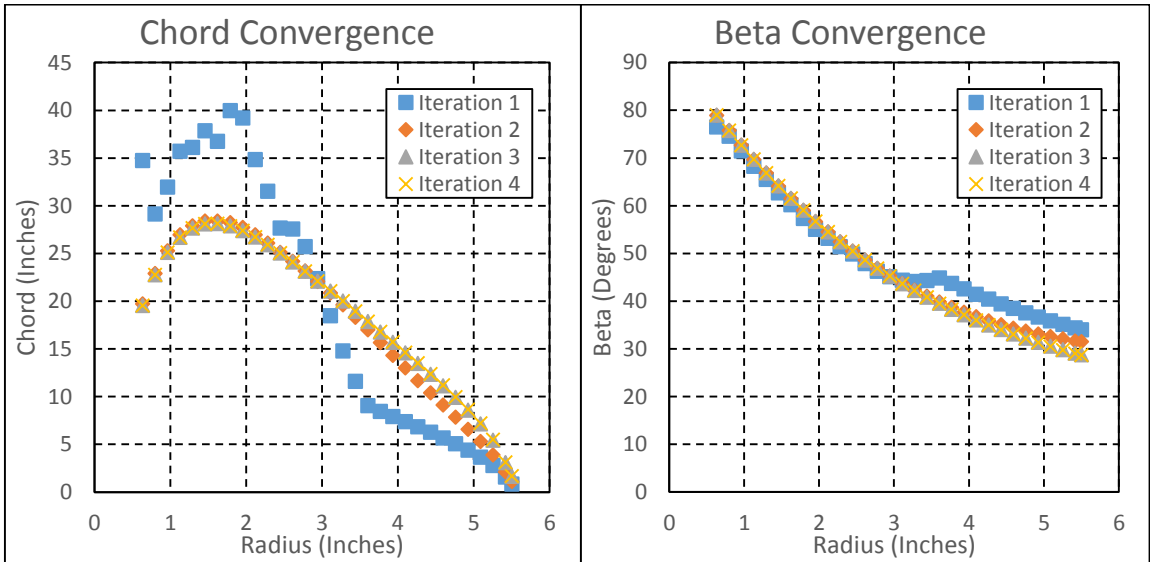
## APPENDIX F CONVERGENCE CHARTS

The convergence charts contained in this appendix show how the PV test cases converged for the design case. These charts support the discussion in Paragraph 6.3

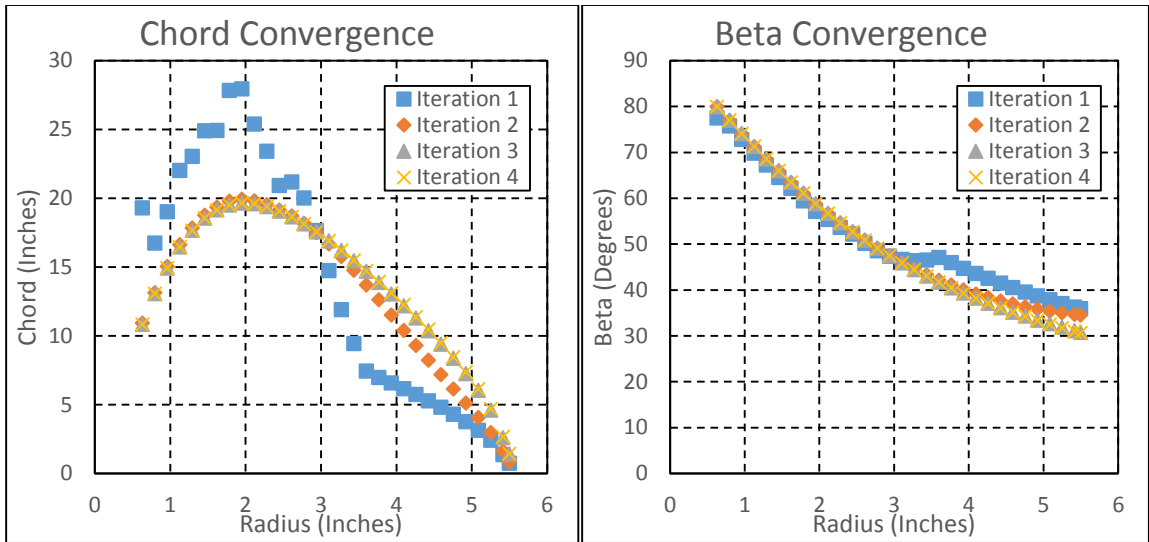
## PV – Convergence Charts



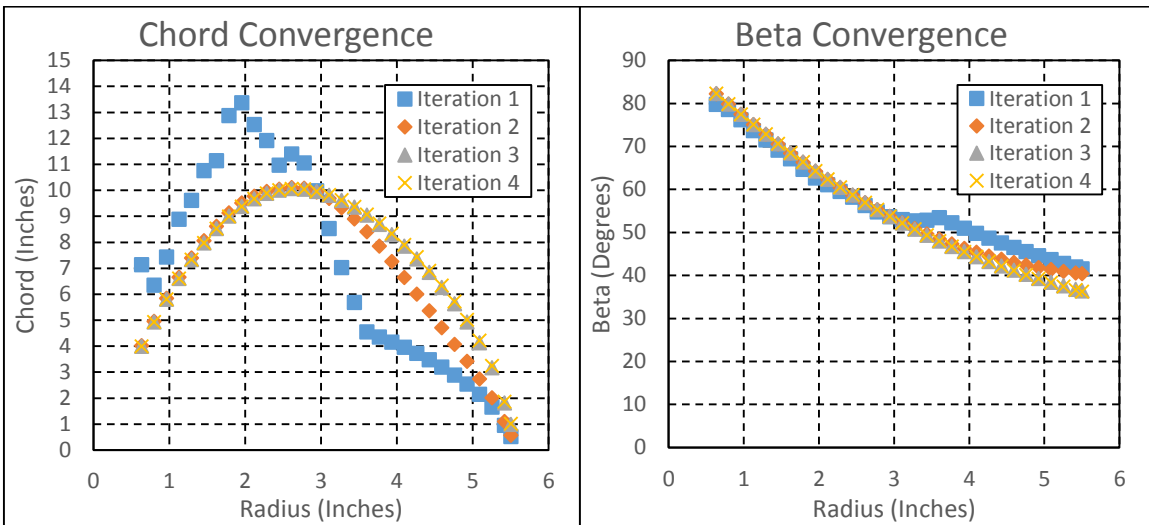
Appendix Figure 13: PV1 - Convergence Charts



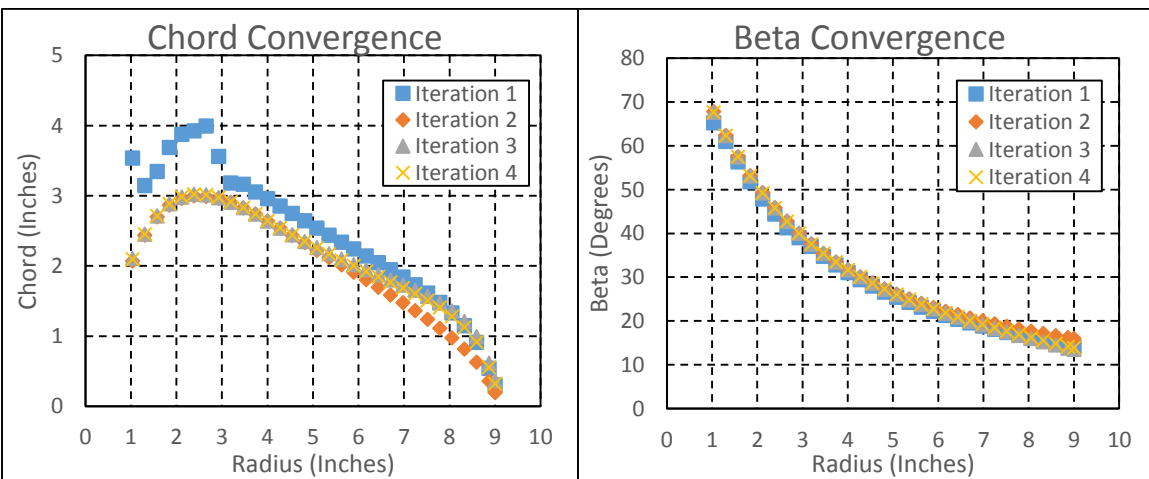
Appendix Figure 14: PV2 - Convergence Charts



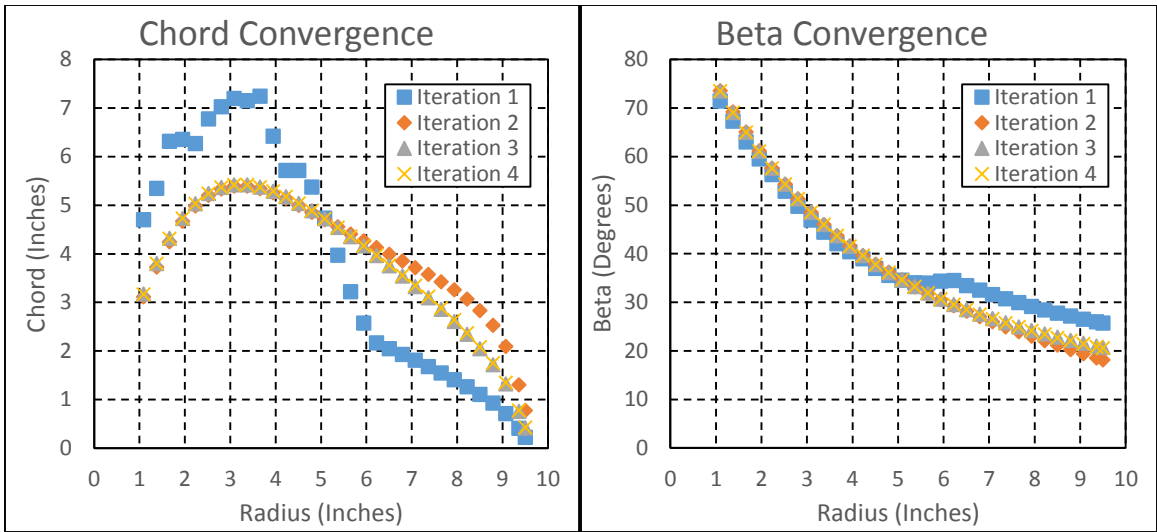
Appendix Figure 15: PV3 - Convergence Charts



Appendix Figure 16: PV4 - Convergence Charts

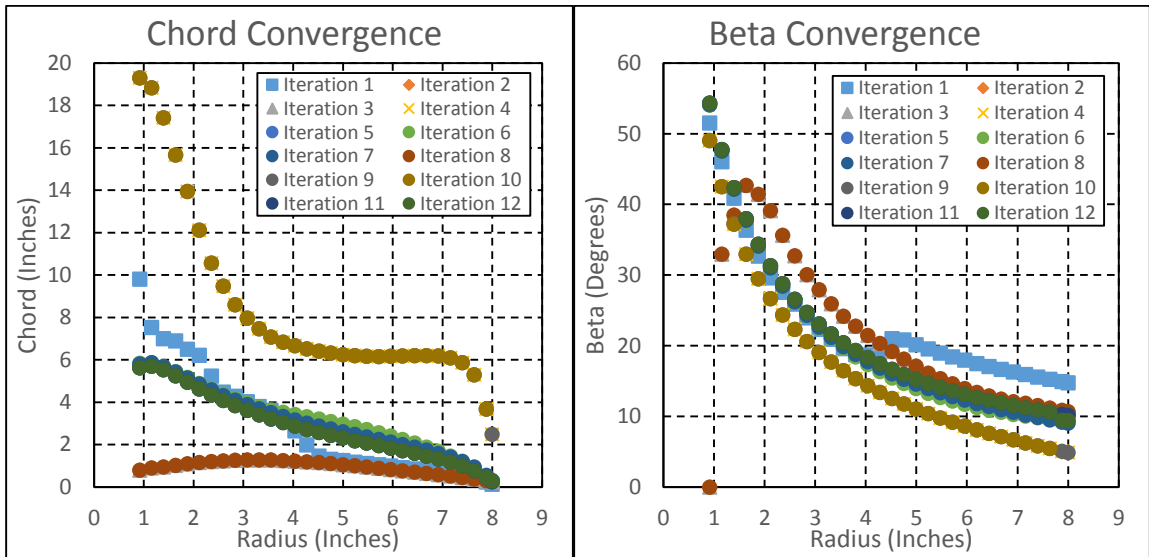


Appendix Figure 17: PV5 - Convergence Charts

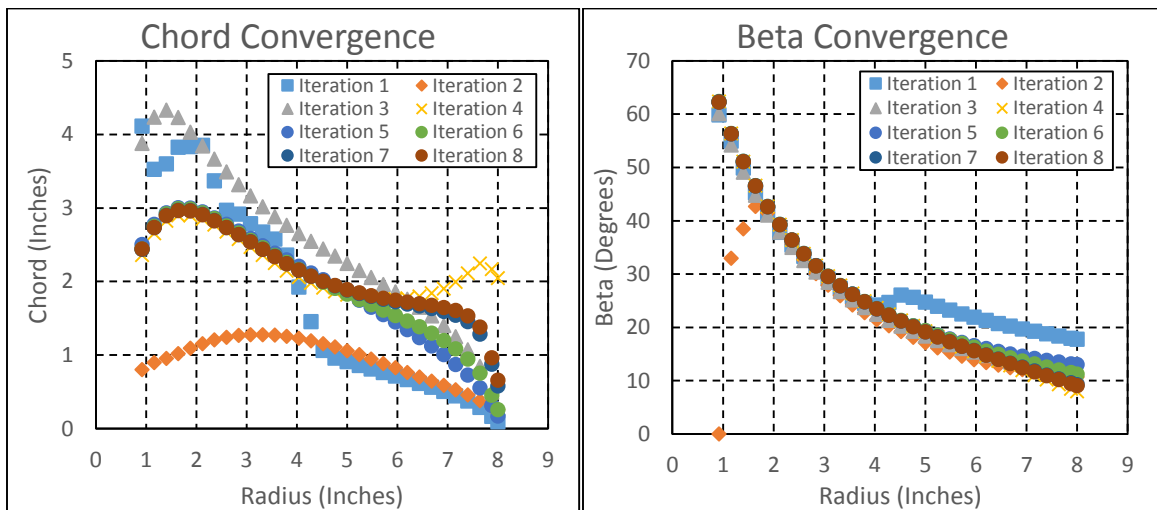


Appendix Figure 18: PV6 - Convergence Charts

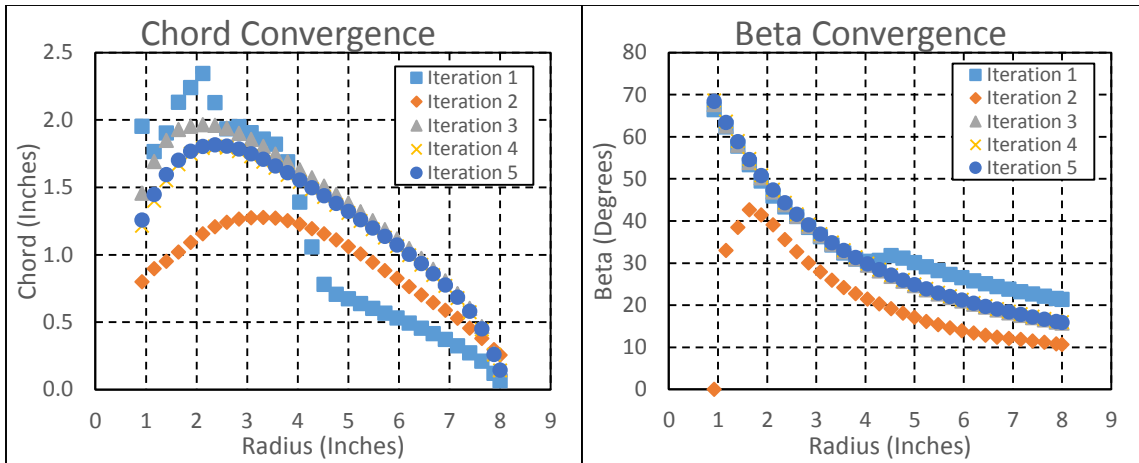
## Further Testing Convergence Charts



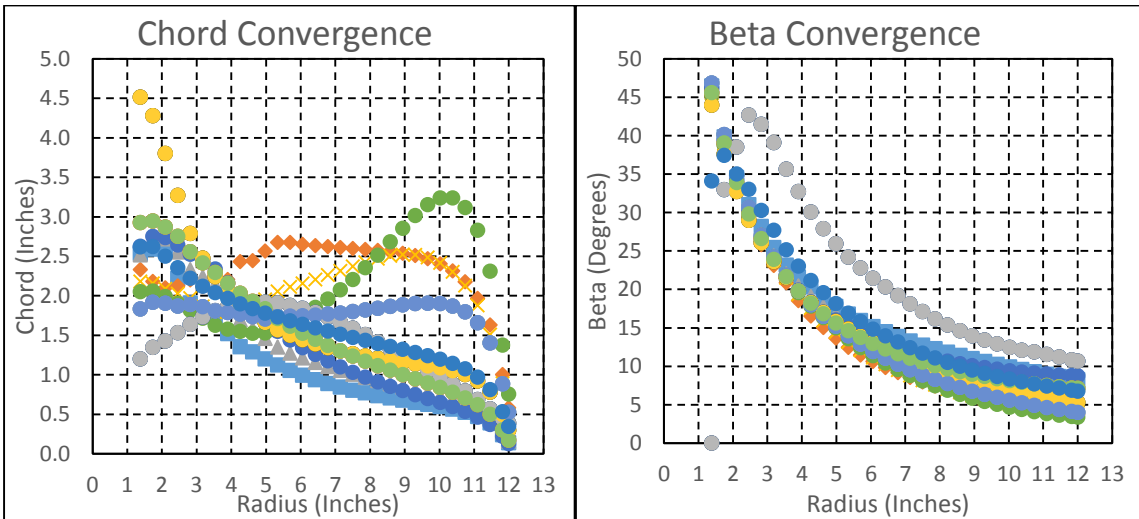
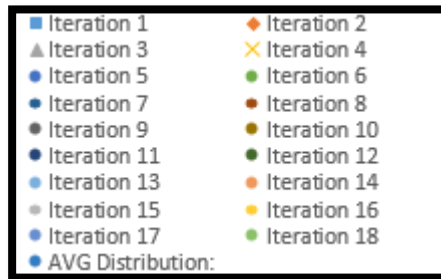
**Appendix Figure 19: Further Testing Case #8 - Convergence Charts**



**Appendix Figure 20: Further Testing Case #17 - Convergence Charts**



Appendix Figure 21: Further Testing Case #26 - Convergence Charts



Appendix Figure 22: Further Testing Case #37 - Convergence Charts



## APPENDIX G FULL-SCALE TEST DETAILS

Appendix G contains the files necessary for running PROPDES for the Full Scale propeller as discussed in Paragraph 6.5 as well as the detailed results of the full scale test. Specifically, the propeller file for the 10 foot diameter, 3 blade, Clark Y section, 5868-9 propeller as discussed in McCormick's textbook and described further in NACA Report 640 is provided followed by the table of results and the test data sheet for this single RPM test case.

## 5868-9.txt – PRODES/QPROP Propeller File

Three Bladed 5868-9 Clark Y 10-ft Propeller 35 deg ! McCormick/NACA Report 640

```

3                ! Nblades      [R]

0.3856  7.162    ! CL0          CL_a  ALL CL and CD data based on CLARK-Y @ RE=1000000
-1       1.5     ! CLmin        CLmax

0.0010  0.0250  0.0120  0.5    ! CD0  CD2u  CD2l  CLCD0
1000000-0.5          ! Reref REexp (Drela recommends REexp = -0.5 unless large prop)

1.0      1.0      1.0    ! Rfac  Cfac  Bfac
0.        0.        0.    ! Radd  Cadd  Badd

#  r/R   c/R    beta
0.08324 0.11666 79.82
0.11228 0.12322 76.76
0.13045 0.12716 75.13
0.15458 0.13329 72.98
0.17147 0.13752 71.69
0.18794 0.14182 70.52
0.20442 0.14605 69.41
0.22089 0.15035 68.38
0.23694 0.15472 67.42
0.25341 0.15903 66.45
0.26905 0.16340 65.58
0.28425 0.16792 64.76
0.29987 0.17244 63.95
0.34761 0.18549 60.86
0.35768 0.18790 60.53
0.38159 0.19584 59.11
0.39768 0.19993 58.46
0.41957 0.20394 57.02
0.45052 0.21182 55.43
0.47079 0.21554 54.46
0.48937 0.21955 53.59
0.50879 0.22334 52.70
0.53116 0.22677 51.68
0.55651 0.22955 50.56
0.58403 0.23146 49.40
0.61289 0.23241 48.27
0.64269 0.23250 47.19
0.67218 0.23171 46.20
0.70090 0.23041 45.31
0.72926 0.22868 44.38
0.75643 0.22643 43.54
0.78115 0.22390 42.89
0.80787 0.22202 42.13
0.83303 0.21926 41.55
0.85823 0.21621 41.01
0.88301 0.21317 40.48
0.90781 0.21005 39.95
0.93056 0.20664 39.58
0.99413 0.19764 38.08
1.01860 0.19372 37.68

```

1.04135	0.19038	37.34
1.06412	0.18682	37.02
1.08568	0.18304	36.73
1.10644	0.17898	36.47
1.13005	0.17535	36.16
1.17111	0.16765	35.46
1.19144	0.16372	35.09
1.21096	0.15973	34.92
1.23047	0.15573	34.73
1.25039	0.15174	34.54
1.28941	0.14382	33.98
1.30852	0.13975	33.85
1.32762	0.13568	33.72
1.36502	0.12740	33.21
1.38579	0.12333	32.97
1.41729	0.11592	32.53
1.44879	0.10851	32.11
1.48030	0.10110	31.70
1.51180	0.09369	31.30
1.52400	0.09632	31.18

## Full Scale Test Result Table

Run Full Scale Propeller - 5868-9 - Diameter: 10 Foot - Pitch: 35 Deg- Blades: 3 - NACA Report 640																
RPM	Experimental Data				PROPDES Data				Difference				Percent Difference			
RPM	J	CT	CP	Eta	J	CT	CP	Eta	J	CT	CP	Eta	J	CT	CP	Eta
800	0.175499	#N/A	#N/A	0.114289	0.189784	0.163403	0.178746	0.1735	0.01428504	#N/A	#N/A	0.059211	8.14%	#N/A	#N/A	51.81%
800	0.231339	#N/A	#N/A	0.153733	0.253055	0.165729	0.180694	0.2321	0.02171626	#N/A	#N/A	0.078367	9.39%	#N/A	#N/A	50.98%
800	0.287179	0.165544	0.239702	0.193176	0.316327	0.168364	0.183494	0.2902	0.02914748	0.00282	0.056208	0.097024	10.15%	1.70%	23.45%	50.23%
800	0.374929	0.164346	0.237501	0.256297	0.379567	0.171232	0.187147	0.3474	0.00463845	0.006886	0.050354	0.091103	1.24%	4.19%	21.20%	35.55%
800	0.426781	0.162749	0.233099	0.295768	0.442839	0.174333	0.191652	0.4028	0.01605825	0.011584	0.041447	0.107032	3.76%	7.12%	17.78%	36.19%
800	0.502564	0.161551	0.228706	0.351006	0.506111	0.17755	0.197132	0.4558	0.00354647	0.015998	0.031574	0.104794	0.71%	9.90%	13.81%	29.86%
800	0.566382	0.159552	0.225041	0.398361	0.569351	0.180922	0.203585	0.5059	0.00296905	0.02137	0.021456	0.107539	0.52%	13.39%	9.53%	27.00%
800	0.598291	0.157155	0.218447	0.418054	0.632623	0.184332	0.211012	0.5526	0.03433192	0.027177	0.007434	0.134546	5.74%	17.29%	3.40%	32.18%
800	0.698006	0.155956	0.21478	0.493042	0.695894	0.187782	0.219414	0.5955	0.00211153	0.031826	0.004634	0.102458	0.30%	20.41%	2.16%	20.78%
800	0.745869	0.154759	0.211844	0.524574	0.759134	0.191076	0.228668	0.6344	0.01326551	0.036317	0.016824	0.109826	1.78%	23.47%	7.94%	20.94%
800	0.837607	0.153561	0.208909	0.595635	0.822406	0.194099	0.238165	0.6703	0.01520073	0.040539	0.029257	0.074665	1.81%	26.40%	14.00%	12.54%
800	0.897436	0.151968	0.203767	0.643018	0.885678	0.195533	0.245714	0.7047	0.01175814	0.043565	0.041948	0.061682	1.31%	28.67%	20.59%	9.59%
800	0.973219	0.149164	0.200834	0.698255	0.94895	0.194061	0.248393	0.7414	0.02426987	0.044897	0.047559	0.043145	2.49%	30.10%	23.68%	6.18%
800	0.997151	0.144752	0.197169	0.718005	1.01219	0.188441	0.247663	0.7702	0.0150387	0.043688	0.050493	0.052195	1.51%	30.18%	25.61%	7.27%
800	1.092877	0.139137	0.192776	0.773101	1.075461	0.179565	0.238043	0.8114	0.01741605	0.040429	0.045267	0.038299	1.59%	29.06%	23.48%	4.95%
800	1.160684	0.133118	0.181805	0.796523	1.138733	0.165922	0.226841	0.833	0.02195067	0.032805	0.045036	0.036477	1.89%	24.64%	24.77%	4.58%
800	1.196581	0.117064	0.174496	0.80822	1.201973	0.152008	0.214178	0.8528	0.00539218	0.034944	0.039683	0.044458	0.45%	29.85%	22.74%	5.52%
800	1.296296	0.109438	0.158422	0.827431	1.265245	0.137745	0.200176	0.8707	0.03105127	0.028307	0.041754	0.043269	2.40%	25.87%	26.36%	5.23%
800	1.396011	0.093383	0.148928	0.842658	1.328517	0.12325	0.18459	0.8868	0.06749471	0.029867	0.035662	0.044142	4.83%	31.98%	23.95%	5.24%
800	1.396011	0.080539	0.138703	0.842658	1.391788	0.108406	0.167544	0.9009	0.00422306	0.027867	0.028841	0.058242	0.30%	34.60%	20.79%	6.91%

**Run Full Scale Propeller - 5868-9 - Diameter: 10 Foot - Pitch: 35 Deg- Blades: 3 - NACA Report 640**

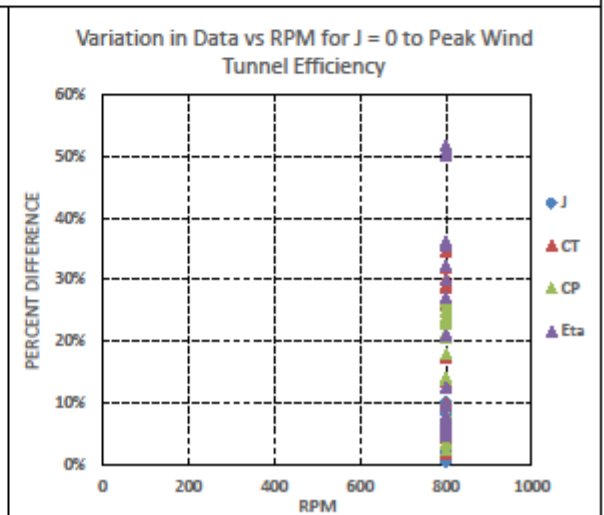
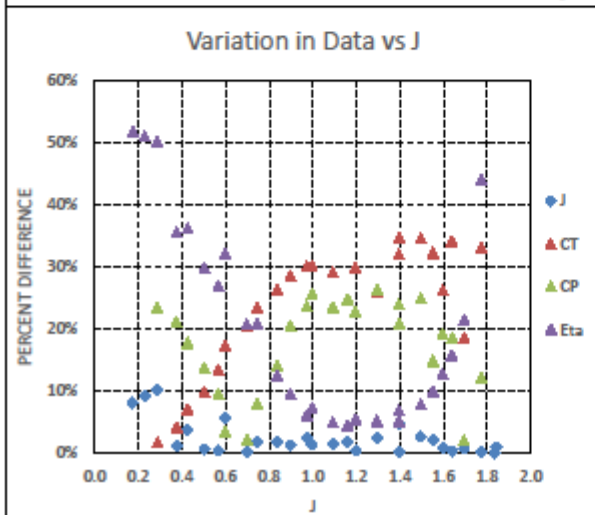
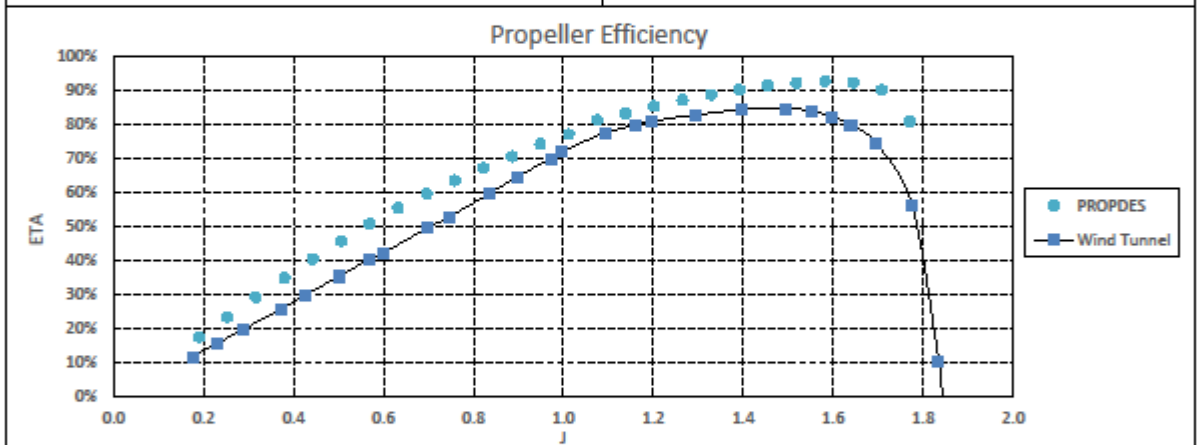
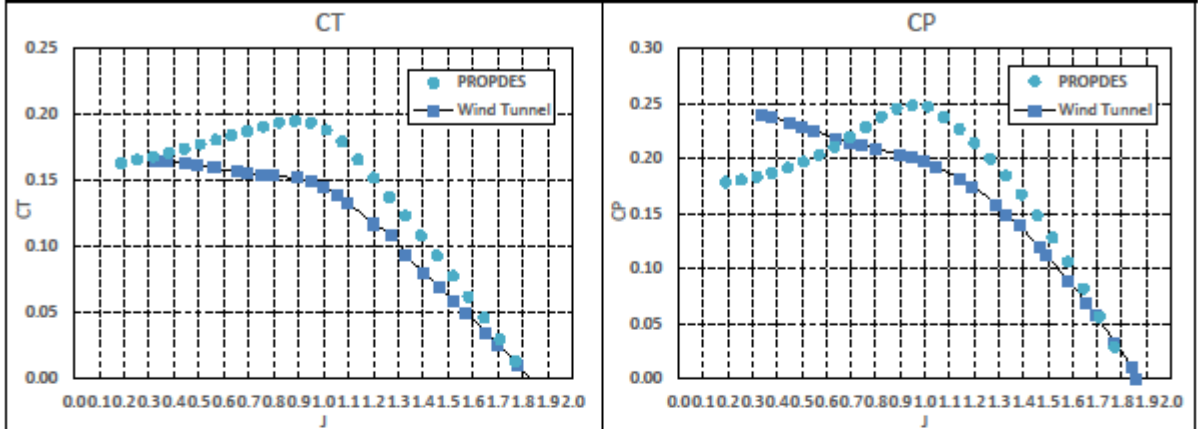
<b>RPM</b>	<b>Experimental Data</b>				<b>PROPDES Data</b>				<b>Difference</b>				<b>Percent Difference</b>			
RPM	J	CT	CP	Eta	J	CT	CP	Eta	J	CT	CP	Eta	J	CT	CP	Eta
800	1.495726	0.069301	0.11899	0.845933	1.455029	0.09329	0.148671	0.9126	0.04069788	0.023989	0.029681	0.066667	2.72%	34.62%	24.94%	7.88%
800	1.551567	0.058865	0.111689	0.837567	1.5183	0.077865	0.128336	0.9214	0.03326668	0.018999	0.016648	0.083833	2.14%	32.28%	14.91%	10.01%
800	1.595442	0.049232	0.089057	0.821319	1.581572	0.062129	0.106164	0.9259	0.01386958	0.012897	0.017107	0.104581	0.87%	26.20%	19.21%	12.73%
800	1.639316	0.034381	0.069347	0.797102	1.644812	0.046122	0.082238	0.9225	0.00549597	0.011741	0.012891	0.125398	0.34%	34.15%	18.59%	15.73%
800	1.695157	0.025149	0.057669	0.740928	1.708084	0.029801	0.056497	0.9009	0.01292717	0.004652	0.001172	0.159972	0.76%	18.50%	2.03%	21.59%
800	1.774929	0.009896	0.032853	0.561078	1.771356	0.01317	0.028894	0.8075	0.00357326	0.003274	0.003959	0.246422	0.20%	33.08%	12.05%	43.92%
800	1.834758	-0.00014	0.010229	0.102485	1.834627	#N/A	#N/A	#N/A	0.00013048	#N/A	#N/A	#N/A	0.01%	#N/A	#N/A	#N/A
800	1.842735	#N/A	1.54E-05	-0.00116	1.86	#N/A	#N/A	#N/A	0.01726496	#N/A	#N/A	#N/A	0.94%	#N/A	#N/A	#N/A

<b>Averages:</b>	<b>2.44%</b>	<b>23.65%</b>	<b>17.37%</b>	<b>20.59%</b>
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Full Scale Test Data Sheet

# Full Scale Propeller Test Data Sheet

Propeller	Model	Blades	Diameter (In)	Pitch	P/D	RPMs	Velocity Range (KIAS)	Wind Tunnel Data Source
5868-9	Clark Y Airfoil	3	120	35 Deg 608.5"	5.07	800	0-145	NACA Report 640



## VITA

Trevor Edwin Lowe

Candidate for the Degree of

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DESIGN AND ANALYSIS TOOL

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1 year of experience with DoD Defense Contract Management Agency providing oversight of contractor quality processes and facilities related to FAA type certificated VIP-SAM Military Commercial Derivative Aircraft (MCDA).

5 years of experience with the United States Air Force in Acquisition and Sustainment Engineering on platforms including VIP-SAM aircraft, tankers, and bombers.