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BLADE ELEMENT MOMENTUM THEORY
APPLIED TO HORIZONTAL AXIS WIND TURBINES

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ABSTRACT

Research efforts in the field of small wind turbines at Penn State has led to the need of an open source Blade Element Momentum Theory (BEMT) code for preliminary performance analysis. PSUWTA, a MATLAB code, has been developed in hopes of fulfilling this need. When checked against experimental wind turbine data and WT_Perf, the National Wind Technology Center’s non-open source BEMT code, the results of PSUWTA came to within engineering accuracy of both of these data sources. PSUWTA was then used to analyze Southwest Windpower’s Whisper 500 turbine, which Penn State currently uses, as well as to analyze the two and three-bladed versions of the Carolus turbine, an in-house design currently under construction. The Whisper 500 was found to have sub-par performance due to poor design while the Carolus turbine’s performance was found to be a substantial improvement. The source code for PSUWTA, as well as operating instructions, is also included.
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NOMENCLATURE

a = Axial Induction Ratio
a’ = Tangential Induction Ratio
c = Chord length of the blade element
\(C_d\) = Coefficient of Drag
\(C_l\) = Coefficient of Lift
\(C_n\) = Lift and drag coefficients combined and resolved in the direction normal to the rotor plane
\(C_p\) = Power Coefficient
\(C_T\) = Thrust Coefficient
\(C_t\) = Lift and drag coefficients combined and resolved in the direction tangential to the rotor plane
D = Drag Force
F = Combined Prandtl hub and tip loss factor
\(F_{\text{hub}}\) = Prandtl hub loss factor
\(F_{\text{tip}}\) = Prandtl tip loss factor
L = Lift Force
N = Number of blades on the turbine
R = Radius of the wind turbine
\(R_o\) = Hub Radius (Dimensional root cutout value)
r = Dimensional radial location of the blade element
\(Re\) = Reynolds Number
\(U_{\infty}\) = Wind speed
y = Non-dimensional radial location of the blade element
\(y_o\) = Non-dimensional root cutout value, defined as where the hub ends and blade begins
W = Local wind velocity relative to the blade element
\(\alpha\) = Local Angle of Attack
\(\beta\) = Local Pitch Angle, defined as the angle between the rotor plane and the chord of
the blade element

\( \delta r \) = Width of the blade element

\( \lambda \) = Tip Speed Ratio

\( \mu \) = Air Viscosity

\( \rho \) = Air Density

\( \sigma \) = Solidity of the annulus containing the blade element

\( \phi \) = Local Inflow Angle

\( \Omega \) = Rotational rate
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Chapter 1

Introduction

Looking towards the future, green energy sources, such as wind, solar, geothermal, and nuclear, are all being looked at to one day help alleviate our dependence on fossil fuels. In President Obama’s most recent “State of the Union” speech, he called for America to generate 80% of its electricity from clean sources such as these by the year 2035 (Obama 2011). Each of these energy resources will need to be harnessed in order to meet this goal.

Wind energy has already shown its worth in countries such as Denmark, where, as of 2009, wind power provides 19% of the country’s electricity (Walsh 2009). The majority of this power comes from wind farms, large tracts of land used for holding hundreds of massive wind turbines, among other uses. This is what most people tend to think of when they think of wind energy. However, there is another avenue through which the wind’s energy can be harvested. This lays in the usage of small scale wind turbines in isolated or distributed use for specific purposes. Rather than using a massive wind farm to power a whole town or city, small scale wind turbines can be used, for example, to supplement a home’s electrical needs and help lower electricity bills.

Using wind turbines in this sense seems to have been overshadowed since the easiest way to increase the power generated by wind turbines is to simply increase their overall size. However, for small wind turbines, where increasing the size is not an option, their performance must be maximized in other ways. From an aerodynamics perspective, this can be done by carefully designing the wind turbine blades. This is done by borrowing much theory from helicopters and propellers. In those cases, the goal of the designer is generally to use the minimum amount of power to achieve the maximum amount of thrust. However, for wind turbines, it nearly the opposite, with the goal being to achieve the maximum possible power generation with whatever wind conditions are present.
In order to design and analyze these small scale wind turbines, much theory has once again been borrowed from propeller and helicopter research and retooled. The two primary ways this is done is through either Computational Fluid Dynamics (CFD), which consist of numerical codes that can take days to run to simulate performance, and Blade Element Momentum Theory (BEMT), a much more basic iterative approach that can be run in only a few minutes. Both require computer resources to run.

The purpose of this thesis is to modify an already existing BEMT code written in MATLAB in order to be able to use it to analyze various small wind turbines as well as to have an in-house BEMT code at Penn State that can be easily edited and updated as needed. The two turbines being analyzed in this thesis are the Whisper 500, designed and built by Southwest Windpower, and a custom design by Dr. Thomas Carolus, a visiting professor from the Institute for Fluid Dynamics and Thermodynamics at the University of Siegen in Siegen, Germany. The goal is to prove the program, called PSUWTA, does indeed work properly by comparing it to WT_Perf, the current BEMT code used by NREL (National Renewable Energy Laboratory), as well as to experimental data gathered from the Whisper turbine. Once the code is verified, it will then be used to analyze the performance of both the Whisper 500 and the Carolus wind turbines.
Chapter 2

Blade Element Momentum Theory

Blade Element Momentum Theory (BEMT) is one of the most simple and commonly used methods to analyze wind turbine performance. It was developed by from the work of Albert Betz and Hermann Glauert and combines two basic theories: momentum theory and blade element theory (Moriarty 1993).

Momentum theory, as applied to wind turbines, assumes that the work done by the airflow on the wind turbine manifests itself solely as the pressure loss, also seen as momentum loss, in the airflow in the rotor plane. Using momentum theory, the induced velocities in the flow can be calculated in both the axial and tangential directions relative to the rotor. Using this theory, Albert Betz was able to derive a theoretical limit on the maximum amount of energy that a turbine can extract from the wind’s kinetic energy. That limit stands at 59.3% and is achieved at an axial induction factor of one third (Hansen 2008).

The other half of BEMT is Blade Element theory. This theory assumes that turbine blades can be radially divided into thin, parallel segments, also known as elements, which act independently of each other. From here, each element can be analyzed as a two-dimensional airfoil and the aerodynamic forces on each can be calculated. The forces on all of the elements are then summed in order to find the total force acting on the turbine. Since the induced velocities from momentum theory also affect the aerodynamic forces from blade element theory and vice-versa, the two theories become coupled to create the iterative process that defines BEMT.

Section 2.1: BEMT Overview

The BEMT process works by calculating the axial and tangential induction factors, angle of attack, coefficients of lift and drag, inflow angle, and local wind velocity of each element. Figure 2.1 shows how the turbine is divided into elements:
In this figure, \( r \) represents the distance from the hub to the blade; \( \delta r \) represents the width of the blade element; \( \Omega \), also labeled as \( \omega \) on occasion, represents the rotational rate of the rotor; \( U \), sometimes labeled as \( U_\infty \), represents the free-stream velocity as unaffected by the turbine; \( a \) represents the axial induction factor; and \( a' \) represents the tangential induction factor.

From here each blade element can be examined more closely. Figure 2.2 shows a much more detailed description of an individual blade element and the aerodynamic forces acting on it:
Along with the previously defined variables, \( \beta \) represents the local pitch angle of the blade with respect to the rotor plane; \( \alpha \) represents the angle of attack; \( W \) represents the total local relative wind velocity; \( \phi \) represents the inflow angle, which is the angle between the relative wind velocity and the rotor plane; \( L \) represents the lift force acting on the blade element; and \( D \) represents the drag force acting on the blade element.

With the turbine properly divided into blade elements defined in the terms of BEMT, it is now possible to derive the iterative process used to calculate the overall forces acting on the turbine, and therefore the power production of the wind turbine.

The process starts with a guess for the axial and tangential inductions factors, typically one and zero respectively, and an assumed rotational rate and wind speed under which the turbine is operating. It is also assumed that the blade geometry, defined as the chord distribution, local pitch angle distribution, and airfoil used, is known. From here equations 2.1, 2.2 and 2.3 can be used to calculate the local velocity of the wind and the angle of attack on the blade element:

\[
W = \sqrt{U_\infty^2(1 - a)^2 + \Omega^2 r^2(1 + a')^2} \tag{2.1}
\]

\[
\tan(\phi) = \frac{(1 - a)U_\infty}{(1 + a')\Omega r} \tag{2.2}
\]

\[
\alpha = \phi - \beta \tag{2.3}
\]
With the angle of attack known, the coefficients of lift and drag, $C_l$ and $C_d$, can be found by looking up the airfoil data. If these coefficients vary widely with Reynolds number, the local Reynolds number of the blade element, $Re$, can be calculated using the local chord length of the element, $c$, and the local relative velocity, $W$. Equation 2.4 defines the local Reynolds number:

$$Re = \frac{\rho W c}{\mu}$$

Here $\rho$ is the air density and $\mu$ is the viscosity of the air. Coefficients of lift and drag can then be looked up based on both Reynolds number and angle of attack if necessary.

From here, the lift and drag coefficients can be transformed into force coefficients normal and tangential to the plane of the rotor, $C_n$ and $C_t$ respectively. They are defined here in equations 2.5 and 2.6:

$$C_n = C_l \cos(\phi) + C_d \sin(\phi)$$

$$C_t = C_l \sin(\phi) - C_d \cos(\phi)$$

Next, the solidity, $\sigma$, of the blade element must be defined before the new induction factors can be calculated. Equation 2.7 shows the definition of this factor:

$$\sigma = \frac{N c}{2 \pi r}$$

In the above equation, $N$ is the number of blades on the turbine.

With these factors calculated, new values for the axial and tangential induction factors can be found using equations 2.8 and 2.9:
With the new values of the axial and tangential inductions factors calculated, the process then loops back to equation 2.1 until the change in the axial induction factor between loops is less than a specified tolerance. Once this happens, the values of all the factors calculated for that blade element can be stored and the process can reset and repeat for the next element. With all of the values calculated in this process, the power, thrust and torque can all be derived as both a function of the radius and as overall values for the turbine as a whole.

The process shown above is the simplest form of BEMT. Corrections have been derived for things such as hub and tip losses as well as highly loaded elements via Prandtl loss factors and the Glauert correction. These can vary between blade element codes though and so they are left out of the basic BEMT process.

Section 2.2: Limitations of BEMT

BEMT calculations are performed using a set RPM and wind speed. This means that the calculations are static and that it cannot be used to predict wind turbine performance under changing conditions, as so often happens in the real world. It also assumes purely two-dimensional axial and tangential flow. One of the basic assumptions of blade element theory is that span-wise, radial flow is negligible, and leaves these effects unaccounted for.

BEMT also only models the amount of power generated from the aerodynamic perspective of wind turbines. It in no way accounts for losses in the electrical generator. It only accounts for how much power is contained in the turning shaft of the turbine and not how much of that gets converted into electrical power.
Thirdly, BEMT does not account for structural effects such as twisting and bending of the turbine blades. Since the theory assumes that momentum is balanced in the plane of the rotor, any deflection will cause errors in the aerodynamic model of airflow around the turbine. The model presented in the previous section also does not account for hub and tip vortex losses or the possibility of a skewed inflow, meaning that the wind is not blowing normal to the plane of the rotor.

Corrections for some of these errors do exist and vary from code to code. One of the most common ones is the Prandtl hub and tip loss factors, which account for hub and tip vortex losses. Another important correction factor is the Glauert correction, which can account for highly loaded blade elements that would cause a significant span-wise pressure distribution, and therefore, span-wise flow. Models also exist to account for a skewed inflow, but are less common.

**Section 2.3: Advantages of BEMT**

BEMT is one of the simplest and easiest ways to model wind turbine performance. It has been tested and proven time and time again ever since its inception in 1935 (Moriarty 1993). It provides an excellent starting point for the analysis of wind turbines and can be used as a base line comparison for other models in both debugging and checking accuracies. BEMT is the first step in the process to modeling the performance of a wind turbine. Using data generated by BEMT, further analysis can be done in other areas such as structures and dynamics. It can also be used to compare the results of more advanced analysis codes. Without BEMT, it is difficult to understand and progress further in the field of wind turbine aerodynamics and performance.
Chapter 3

Wind Turbine Blade Geometries

The geometry of the blades of a wind turbine is obviously crucial to the performance of the turbine as a whole. The three primary factors that determine the geometry of a turbine blade are the types of airfoils used, chord length vs. radial position, and local pitch angle vs. radial position.

Section 3.1: Airfoil Selections

Both the two bladed and three bladed Carolus turbines as well as the Whisper turbine use a single airfoil along the whole length of the blade. The Whisper turbine is a two bladed turbine that uses a Wortmann FX 60-126 Airfoil, shown in figure 3.1 below.

![Wortmann FX60-126 Airfoil](image)

**Figure 3.1: The Wortmann FX 60-126 Airfoil**

This airfoil has a $C_{l,\text{max}}$ of about 1.7 and stalls around a 13° angle of attack, depending on the Reynolds number of the flow. It also has a maximum thickness of 12.6% and camber of 3.6% (Wortmann 2011). The Wortmann FX 60-126 airfoil has been around since the late 1960s and was originally designed to have fairly forgiving stall characteristics for sailplanes (Wortmann 2011). Figure 3.2 shows the lift coefficients of the Wortmann FX 60-126 airfoil for various Reynolds numbers:
As can be seen in Figure 3.2, the Wortmann FX60-126 airfoil stalls around 13° regardless of Reynolds number, and from there the lift coefficient trails off rather slowly with increasing angle of attack, hence the forgiving stall characteristics. It also has a maximum lift coefficient of about 1.6-1.7 depending on Reynolds number. Figure 3.3 shows the drag polar for the Wortmann airfoil:

Figure 3.2: $C_l$ vs. Angle of Attack for the Wortmann FX 60-126

As can be seen in Figure 3.2, the Wortmann FX60-126 airfoil stalls around 13° regardless of Reynolds number, and from there the lift coefficient trails off rather slowly with increasing angle of attack, hence the forgiving stall characteristics. It also has a maximum lift coefficient of about 1.6-1.7 depending on Reynolds number. Figure 3.3 shows the drag polar for the Wortmann airfoil:

Figure 3.3: Wortmann FX 60-126 Drag Polar
The FX60-126 has a rather wide drag bucket ranging from a lift coefficient of almost negative one all the way to close to 1.7 depending on Reynolds number. Increasing the Reynolds number at which this airfoil operates at significantly increases the size of the drag bucket in the range of lift coefficients greater than about 1.3.

Figure 3.4 below shows $C_l$ and $C_d$ data as a function of angle of attack and expanded to the full range of angles of attack from $-180^\circ$ to $180^\circ$ necessary for wind turbine analysis; however, the expansion method used goes beyond the scope of this thesis.

```
Figure 3.4: Expanded $C_l$ and $C_d$ vs. Angle of Attack for the Wortmann FX 60-126
```

With this range of angles of attack, it is difficult to discern any major differences in curve shapes between Reynolds numbers. However, figure 3.5, shows the coefficient of drag as a function of angle of attack for a limited range of angles to better illustrate the differences in the curves among Reynolds numbers:
As can be seen in the above figure, drag really begins to increase around an angle of attack of 10°. However, increasing the Reynolds number tends to lower the drag overall.

On the other hand, both of the two and three bladed Carolus turbines use an S822 airfoil, which was designed in the 1990s for the purpose of three to ten meter, “stall-regulated, horizontal-axis wind turbines” (Somers 1993). The shape of the S822 is shown below in figure 3.6.
Compared to the Wortmann FX 60-126, the S822 has a lower maximum $C_l$ of about 1.3 and a higher stall angle of about 15°. It is also a much thicker airfoil with a maximum thickness of 16% but much less camber (Somers 1993). Of the two airfoils, the S822 was specifically designed for small wind turbines and is therefore expected to perform better than the Wortmann FX 60-126 under similar conditions. Figure 3.7 shows the $C_l$ and $C_d$ data for the S822 airfoil at a various Reynolds numbers.

**Figure 3.6: The S822 Airfoil**

**Figure 3.7: $C_l$ vs. Angle of Attack for the S822**
As can be seen here, the S822 airfoil tends to stall around 15° regardless of Reynolds number and the performance of the airfoil improves greatly with Reynolds number. As designed, the stall characteristics are also rather forgiving given the shallow drop in $C_l$ past the stall angle (Somers 1993). Figure 3.8 shows the S822’s drag polar:

![Figure 3.8: S822 Drag Polar](image)

The S822 also has a wide drag bucket ranging from a lift coefficient of about negative one to 1.3 depending on Reynolds number. The drag bucket also drops significantly with Reynolds number.

Once again, the airfoil data needs to be expanded out all the way from $-180^\circ$ to $180^\circ$. Figure 3.9 shows this data here:
Once again, it is difficult to see the majority of the differences in lift and drag coefficients based on Reynolds number for this range of angles of attack. Figure 3.10 shows the drag coefficient as a function of angle of attack since the lift coefficient has already been presented in Figure 3.7:

**Figure 3.9: Expanded Cl and Cd vs. Angle of Attack for the S822**

**Figure 3.10: Cd vs. Angle of Attack for the S822**
As was the case with the Wortmann FX60-126 airfoil, drag decreases with increased Reynolds number. However, drag does not tend to increase drastically until an angle of attack of about 15° as compared to 10° for the Wortmann FX60-126 airfoil.

Section 3.2: Chord and Pitch Distributions

Aside from the airfoil design, which is constant along the whole blade for each turbine, the pitch angle vs. span-wise location is critical in determining how the blade performs, because at various RPMs and wind speeds, the turbine blade must be kept from stalling or producing too much drag. Figure 3.11 below shows the pitch distribution for the Whisper turbine blades.

![Figure 3.11: Whisper Blade Local Pitch Angle vs. Radial Location](image)

\[
y = -7.2222x + 16.25
\]

The Whisper blade uses a simple linear pitch distribution along the span of its blades. Only performance analysis of radial distributions of various factors will indicate the results of this. It would appear that this was done to make manufacturing simple and not necessarily to optimize performance; however, this claim remains unsubstantiated until a thorough analysis can be conducted. Meanwhile, Figure 3.12 below shows the span-wise pitch distribution for the Carolus turbine blade:
The program used to originally design the Carolus blade did so using fifteen separate elements, each optimized to maximize power output at a wind speed of 5 m/s and a tip-speed ratio of 8.0. The pitch at each of the fifteen element locations is shown by the blue diamonds and a best fit polynomial, shown as the black line, and was calculated using MATLAB to interpolate between the distinct radial locations and create a smooth design. For the three bladed Carolus turbine, the twist distribution was left unchanged but the overall pitch of each blade was increased by 6°, based on previous research about optimizing the three bladed version of this turbine done by a fellow honors Undergraduate at Penn State, Maureen Sneft.

Finally, the span-wise chord distribution completes the design of the turbine blade. Based on the measurements taken on the Whisper turbine blade, it was determined that a near piece-wise linear chord distribution was used as shown in figure 3.13 below.

Figure 3.12: Carolus Local Pitch Angle vs. Radial Location
On the other hand, the Carolus Turbine uses a non-linear chord distribution once again to maximize power output at the same wind speed and tip speed ratio listed above for the span-wise pitch distribution. Figure 3.14 shows this chord distribution:

Overall, it appears that the geometry of the Whisper turbine was picked on the basis of simplicity and not to specifically maximize performance for a given set of operating conditions. Of course, it will take both a mix of analysis and experimental data
to find out how much truth this statement bears. The same can be said for the Carolus turbine though since that design is currently under construction and has yet to be tested experimentally.
Chapter 4

PSUWTA

In order to continue Penn State’s in house wind turbine research, it is necessary to have a proper open source BEMT code. This was the goal behind developing PSUWTA. As stated previously, BEMT is the most basic form of wind turbine analysis and yields fairly accurate results for its simplicity. Currently, the only code available for use is WT_Perf, a BEMT code developed and used by the National Wind Technology Center (NWTC), the wind energy division of the National Renewable Energy Laboratory (NREL). The problem here is that WT_Perf is not an open source code. In other words, the user does not have access to the source code nor knows how the code runs, what assumptions and equations it uses, etc. Although some of this can be gleaned from the input file necessary to run WT_Perf, it is necessary to have an open source code that can be edited and updated so that the user knows exactly how the code works and what assumptions it uses.

Section 4.1: Code Specifics

The purpose of this section is to document what additions and corrections to Blade Element Momentum Theory are being used in our code, PSUWTA. The code uses both an axial and a tangential induction factor to calculate the induction ratio, Prandtl hub and tip loss factors, and the Glauert correction for highly loaded elements.

The code was originally written by Leo Albanese, a graduate student at Penn State, for large wind turbines and has since been modified to run for smaller wind turbines. PSUWTA begins by following the standard BEMT method presented in Chapter 2. The first of the corrections used in the code come during the calculation of the
induction ratios and are the Prandtl hub and tip loss factors. PSUWTA uses the following formulas for calculating the tip loss factor (Moriarty 1993):

\begin{align}
    f_{\text{tip}} &= \frac{N_b (1 - y)}{2 \ y \sin(\phi)} \\
    f_{t,\exp} &= \exp(-f_{\text{tip}}) \\
    F_{\text{tip}} &= \frac{2}{\pi} \tan^{-1}\left(\sqrt{1 - \frac{f_{t,\exp}^2}{f_{t,\exp}}\right)
\end{align}

In the above equations, $N_b$ is the number of blades on the turbine, $y$ is the non-dimensional radial location of the element and $\phi$ is the inflow angle. Similarly, the following equations are used in the calculation of the hub loss factor (Moriarty 1993):

\begin{align}
    f_{\text{hub}} &= \frac{N_b (y - y_o)}{2 \ y_o \sin(\phi)} \\
    f_{h,\exp} &= \exp(-f_{\text{hub}}) \\
    F_{\text{hub}} &= \frac{2}{\pi} \tan^{-1}\left(\sqrt{1 - \frac{f_{h,\exp}^2}{f_{h,\exp}}\right)
\end{align}

Here, $y_o$ is the non-dimensional radial location of the hub, sometimes called the root cutout value. In order to calculate the total loss factor, the hub and tip loss factors are simply multiplied together (Moriarty 1993):

\[ F = F_{\text{hub}} \ast F_{\text{tip}} \]

Once the local hub and tip loss factor $F$ is calculated, the code calculates the thrust coefficient for the blade element using equation 4.8 (Hansen 2008):

\[ C_T = \frac{\sigma(1 - a)^2 C_n}{\sin^2(\phi)} \]
With this calculated, a comparison is drawn to determine whether to apply the standard formula modified by the Prandtl hub and tip loss factors for the axial induction factor or to calculate the axial induction factor using the Glauert correction. If the thrust coefficient, \( C_T \), is less than \( 0.96*F \), then equation 4.9 is used to calculate the axial induction factor, replacing equation 2.8 from Chapter 2 (Moriarty 1993):

\[
a = \left(1 + \frac{4Fs \sin^2 \phi}{\sigma C_n} \right)^{-1}
\]  

(4.9)

However, if \( C_T \) is greater than \( 0.96*F \), then the element is considered highly loaded and the Glauert correction is applied to the calculation of the axial induction factor as shown in equation 4.10, once again replacing equation 2.8 from Chapter 2 (Moriarty 1993):

\[
a = \frac{18F - 20 - 3\sqrt{C_T(50 - 36F)} + 12F(3F - 4)}{36F - 50}
\]  

(4.10)

Once the axial induction factor is calculated using one of the previous two equations, the tangential induction factor is then calculated using equation 4.11, replacing equation 2.9 from Chapter 2 (Moriarty 1993):

\[
a' = \left[\frac{4Fs \sin(\phi) \cos(\phi)}{\sigma C_t} - 1\right]^{-1}
\]  

(4.11)

From here, the program follows the rest of the iterative process outlined in Chapter 2 to obtain all of the values necessary to calculate the performance of the wind turbine in various conditions.
Section 4.2: Code Verification

Considering WT_Perf’s credentials as product of NWTC, it can be used to help verify the validity and functionality of PSUWTA. As described in the previous section on blade geometry, the Whisper blades will be used so that both the WT_Perf and PSUWTA data can be compared to experimental data. The best place to start comparisons would be with the prediction of power output for various RPMs and wind speeds. Figure 4.1 shows a comparison between PSUWTA and WT_Perf for an RPM of 250:

![Figure 4.1: Overall Power Output at 250 RPM Comparison](image)

Based on this figure above, for an RPM of 250, PSUWTA is quite accurate when compared to WT_Perf up until a wind speed of about 9 m/s, from which point on WT_Perf predicts a higher power output. However, a wind turbine typically operates at a higher RPM when the wind speed increases. Figure 4.2 shows the same comparison except for a higher RPM of 350:
For an RPM of 350, PSUWTA stays reasonably accurate relative to WT_Perf up to a wind speed of about 12 m/s. Of course, all of these predictions mean very little if they can’t be verified against real world data.

Research has been conducted at Penn State on the Whisper blades and experimental data has been collected; however, since the turbine is free spinning in a turbulent flow field where wind speed is constantly changing, it is difficult to compare for a specific RPM and wind speed combination. Nonetheless, comparisons can still be drawn. Figure 4.3 shows the raw power produced by the wind turbine at various wind speeds:
The connection between the data contained in Figure 4.3 and the comparisons of predicted power output in Figures 4.1 and 4.2 lies in the correlation between wind speed and RPM. Figure 4.4 shows this correlation as measured experimentally:
With this in place, it should now be possible to draw comparison. For example, typically the Whisper turbine runs at 250 RPM for a wind speed of 4 m/s. As predicted by WT_Perf in Figure 4.1, the turbine should produce about 140 Watts; while according to PSUWTA, the turbine should produce about 175 Watts. Both of these predicted power outputs at 250 RPM fall well within the range of experimentally measured power outputs for the turbine at a wind speed of 4 m/s as shown in Figure 4.3.

To check another case, the Whisper turbine tends to run at an RPM of 350 for a wind speed of about 7 m/s. According to WT_Perf and PSUWTA in Figure 4.2, the turbine should produce 1.35 kW and 1.26 kW respectively. Both of these predicted power outputs fall well within the range of experimentally measured power outputs and land almost right on the Manufacturer’s line on Figure 4.3.

Beyond the total power output, the power coefficient makes for an excellent tool when measuring the aerodynamic efficiency of a wind turbine. According to the Betz limit, the theoretical maximum power coefficient for a wind turbine should be about...
0.593 (16/27 to be exact). Therefore, it is just as important for PSUWTA to match WT_Perf in its ability to predict the overall power coefficient as it is the overall power of the turbine if PSUWTA is to be used for designing and optimizing wind turbine performance. Typically, the power coefficient is plotted against the tip speed ratio at which the turbine is running. Figure 4.5 here shows the predictions of both WT_Perf and PSUWTA for an RPM of 250:

![Cp vs. Tip Speed Ratio](image)

**Figure 4.5: Overall Power Coefficient Comparison**

Both WT_Perf and PSUWTA predict a maximum power coefficient of around 0.38 at a tip speed ratio of about 10. WT_Perf appears to predict a slightly higher overall $C_p$ compared to PSUWTA but the difference is negligible considering the general accuracy of BEMT in the first place.

Once again, experimental data has been taken on the Whisper blades and can be used to verify the accuracy of PSUWTA. Figure 4.6 shows the combined plots of $C_p$ vs. tip speed ratio and wind speed vs. tip speed ratio:
The Whisper turbine generally runs at a rotational rate of 250 RPM for a wind speed of 4 m/s according to Figure 4.4. This corresponds to a tip speed ratio of about 14.5 and a power coefficient of about 0.29 according to Figure 4.6. For the same tip speed ratio, WT_Perf predicts a power coefficient of 0.25 while PSUWTA predicts a power coefficient of about 0.29.

Considering that BEMT calculates overall performance parameters essentially by summing the performance parameters of discretized blade elements, it is important to ensure that PSUWTA and WT_Perf predict similar distributions of these parameters along the length of each blade. Also, it is important to know how these parameters are distributed when it comes to modifying blade designs in order to optimize them.

Once again, one of the most important parameters to check is how much power is produced by each blade element. Figure 4.7 shows the radial distribution of power for an RPM of 250 and a wind speed of 8 m/s:
The radial distribution of power predicted by PSUWTA is nearly exact compared to that predicted by WT_Perf. The differences towards the tip of the blade are negligible when integrated to find the total power produced by the wind turbine under this combination of RPM and wind speed.

BEMT does not directly calculate $C_p$; rather, it iterates to find a set of core variables for each blade element, such as the inflow angle and induction ratios. It then uses these core variables to calculate things such as the thrust, power, and torque produced by each blade element. Of all the core variables, one of the most important is the axial induction factor. The reason for this is that it determines how much the wind slows while passing through the turbine and in essence, dictates the maximum amount of power the turbine can theoretically extract from the wind. Once again, according to momentum theory as applied to an actuator disk and the Betz limit, the theoretical maximum power coefficient of 0.593 occurs at an axial induction ratio of 1/3. In theory

![Power vs. Non-Dim. Radial Position](image)

**Figure 4.7: Comparison of Radial Power Distribution Comparison**
then, the radial distribution of induction factors should integrate to produce an overall value of 1/3 for an ideal wind turbine. BEMT has the capability to predict the radial distribution of axial induction factors. Figure 4.8 shows these distributions as predicted by both PSUWTA and WT_Perf:

![Induction Ratio vs. Non-Dim. Radial Position](image)

**Figure 4.8: Radial Distributions of the Axial Induction Factor Comparison**

As can be seen in Figure 4.8 above, both PSUWTA and WT_Perf predict almost identical distributions of the axial induction ratio. There is some discrepancy towards the hub of the blade, but these differences even out when integrated over the length of the blade.

Finally, there is reason to justify using airfoil data for eight different Reynolds numbers. Figure 4.9 shows the radial Reynolds Number distribution for an RPM of 250 and a wind speed of 8 m/s:
Both PSUWTA and WT_Perf predict Reynolds Numbers in the range of 100,000-300,000 along the span of the blade. At such low Reynolds Numbers, airfoil performance can change greatly. Now compare that range to that of a turbine running at 11 m/s and 450 RPM:

![Figure 4.9: Reynolds Number Distribution Condition 1 Comparison](image)
Here the Reynolds Numbers can range anywhere from 100,000 to over 500,000. This is why it is important to use airfoil data for various Reynolds Numbers, especially when they fall below 1,000,000. Figures 3.2 and 3.3 in the Blade Geometry section (Chapter 3) show the various lift and drag coefficients for the airfoil used in the Whisper Blades for further verification of this.

Overall, PSUWTA is quite accurate when compared to WT_Perf as well as experimental data. Yes there are discrepancies between the PSUWTA and WT_Perf, and it is difficult to fully understand why these differences are occurring since WT_Perf is not an open source code. However, with PSUWTA, it will be possible to modify and update it in the future to further increase its accuracy.

Figure 4.10: Reynolds Number Distribution Condition 2 Comparison
Chapter 5

Whisper Turbine Analysis

The Whisper turbine is currently Penn State’s primary source of experimental data on small wind turbines. Since PSUWTA has been verified as a working BEMT code, it will be used here to analyze the Whisper turbine in two important areas: power output and structural loads due to aerodynamic forces. All analysis here is based solely off of aerodynamics. No outside forces such as gravity, friction, or magnetic or electrical forces from the generator have been considered here.

Section 5.1: Power Output and Performance

For any practical wind turbine, one of the most important performance factors is how much power the wind turbine can produce at various wind speeds. Figure 5.1 here shows the power output as a function of both wind speed and rotational rate:
As can be seen in the above figure, the rotation rate that produces the most power varies with wind speed. For wind speeds less than 4 m/s, a rotation rate of 150 RPM produces the most power. From 4 m/s to 7 m/s, 250 RPM produces the most power; from 7 m/s to 8.5 m/s, 350 RPM produces the most power; from 8.5 m/s to 11 m/s, 450 RPM produces the most power, and so on. As will be shown in Figure 5.2, this is due to the fact that these rotational rates produce the highest power coefficients. Figure 5.2 shows the comparison of power coefficient to wind speed for various RPMs:
It is also predicted here that the maximum power coefficient for the Whisper blades should be around 0.4. However, in reality the turbine is free spinning and therefore might not be spinning at the optimal rotational rate for any given wind speed. Figure 5.3 here displays the experimentally measured correlation between RPM and wind speed for the whisper turbine and should help provide some insight as to where the turbine is actually operating.
For a wind speed of 4 m/s, the Whisper turbine is actually operating right around 240 RPM; however, PSUWTA shows that the optimal rotational rate for this wind speed would probably be about 200 RPM. For a wind speed of 7 m/s, the Whisper turbine is running at just under 350 RPM; however, based on the results of PSUWTA, it can be inferred that a rotational rate of 300 RPM would be ideal for maximum power production. Based upon this analysis, it would seem that the Whisper turbine is not running at the ideal settings for maximum power production.

The data presented in Figure 5.2 can be further non-dimensionalized into power coefficient versus tip speed ratio. Figure 5.4 shows the fully non-dimensionalized data:
Based on the above figure, for a range of rotational rates from 250 RPM to 350 RPM, the ideal tip speed ratio appears to be about ten. However according to Figure 5.5, which shows the experimentally measured power coefficients versus the tip speed ratio at which they were measured, the Whisper turbine appears to be running at higher tip speed ratios ranging from about 11.5 to 15.5. Regardless of rotational rate, these tip speed ratios appear to be too high compared to the ideal tip speed ratios predicted by PSUWTA in Figure 5.4.
Beyond appearing to not run at the optimal rotational rate for various wind speeds, the theoretical data produced by PSUWTA could easily be interpreted to suggest that blade geometry of the whisper turbine is far from ideal. First of all, the maximum theoretical power coefficient predicted by PSUWTA is about 0.4; while the Betz limit stands at 0.593. This would indicate an overall efficiency of about 67.5% when compared to the Betz limit and obviously 40% when compared to the overall energy available in the wind passing through the turbine.

Of course, to further analyze the Whisper blades, it would be advantageous to look at the radial distribution of various performance factors such as the power generated, power coefficient, induction ratio, and angle of attack. The radial power distribution is the best place to start since in BEMT this is simply summed to find overall power production of the turbine. Each data point represents the power produced by each blade element and as such, the more elements that are used, the less power each element

Figure 5.5: Experimentally Measured Power Coefficient vs. Tip Speed Ratio
produces. Figure 5.6 shows the radial power distribution of the whisper turbine for a wind speed of 8 m/s:

![Power vs. Non-Dim. Radial Position](image)

**Figure 5.6: Radial Power Distribution of the Whisper Turbine, Wind Speed = 8 m/s**

For every case of rotational rate, the outboard elements tend to produce more power than the inboard elements. This should come as no surprise since these elements are moving at a much faster velocity relative to the wind. In order to analyze each blade element, it is helpful to look at the power coefficient of each element to determine which elements are the most efficient and which are not. Figure 5.7 shows the radial distribution of power coefficients:
As can be seen here, the power coefficients remain fairly constant for much of the span of the turbine. Near the hub and the tip, these drop to zero due to hub and tip losses modeled as vortexes being shed. The rotational rates of 250 RPM to 450 RPM tend to produce the best overall distribution of power coefficients as they remain relatively high and constant for the whole span of the blade. When compared to Figure 5.2, it is easy to understand why these rotational rates generate the highest overall power coefficients for a wind speed of 8 m/s. For a rotational rate of 150 RPM, the turbine is simply not spinning fast enough to extract enough energy from the wind, hence the lower power coefficients. For rotational rates greater than 450 RPM, the turbine is spinning too fast and the forces generated by the wind on the turbine will not produce as much power as desired.

According to momentum theory, the axial induction factor is directly correlated to how much energy is extracted from the flow. Therefore, it is important to look at the radial distribution of this performance factor since it encompasses all of the aerodynamic

![Figure 5.7: Power Coefficient vs. Radial Location, Wind Speed = 8 m/s](image)
forces experienced by the each element and links this to the power produced by each element. Figure 5.8 shows the radial distribution of induction factors for the whisper turbine.

![Figure 5.8: Axial Induction Factor vs. Radial Location, Wind Speed = 8 m/s](image)

Ideally, the axial induction ratio should be about 1/3 (0.333) regardless of radial location since this corresponds to the Betz limit and should produce the maximum theoretical power coefficient of 0.593. This is not the case however for the Whisper turbine as can be seen above in Figure 5.8. Having too high or too low of an induction factor will result in a less than ideal power coefficient for any element.

Equation 5.1, shown below, has been derived from equations 2.3, 2.5, 2.7, and 2.8. This has been done to show the direct relationship of each aerodynamic factor to the axial induction factor:
Due to the complex relationship among all of the variables here, it is very difficult to directly understand how they will affect the induction ratio of the element, and therefore make analyzing the radial distribution of each of these factors very difficult to apply. However, there is one more variable worth looking at as radially distributed.

The angle of attack along the length of the blade is a good indication of blade design, as the blade should not be stalling under various combinations of rotational rate and wind speed. Figure 5.9 here shows this radial distribution:

\[
\alpha = \left[ \frac{8\pi r \sin^2(\alpha + \beta)}{Nc[C_t \cos(\alpha + \beta) + C_d \sin(\alpha + \beta)] + 1} \right]^{-1}
\]

Figure 5.9: Angle of Attack vs. Radial Location, Wind Speed = 8 m/s

Considering that the Wortmann FX 60-126 airfoil stalls at an angle of attack of about 13°, the inboard section of the blade is stalled for the slower rotational rates of 150,
250 and 350 RPM. In fact, at 150 rpm, only the outboard 40% of the blade is not stalled. At 250 RPM, the inboard 28% of the blade is stalled and at 350 RPM, the inboard 22% of the blade is stalled. This signifies poor blade design since the turbine tends to operate around 350 RPM for a wind speed of 8 m/s as shown on Figure 5.3.

Section 5.2: Structural Loads

Aside from the power production of the wind turbine, it is also important to look at the thrust force experienced by the turbine to ensure that it can structurally withstand its operating conditions. Figure 5.10 shows the overall thrust experienced by the wind turbine as a function of wind speed and RPM:

![Thrust vs. Windspeed](image)

**Figure 5.10: Thrust vs. Wind Speed and RPM**

The maximum thrust force experienced overall is about 1300 N (~300 lbs.) in the most extreme operating condition that can be reasonably expected. Considering the
Whisper turbine tends to operate in wind speeds ranging from 4 m/s to 8 m/s at Penn State, a range of about 100 N to 400 N (20-90lbs.) can be expected.

More importantly, the radial distribution of thrust force needs to be analyzed to ensure the root bending moment of the turbine is not too great. Figure 5.11 here shows the radial distribution of the thrust force for a wind speed of 8 m/s:

![Thrust per Length vs. Non-Dim. Radial Position](image)

Figure 5.11: Thrust Force vs. Radial Location, Wind Speed = 8 m/s

Overall, the majority of the force is concentrated towards the tip of the blade, but even so, assuming that all of the thrust force were concentrated at the tip, this would result in an overall bending moment of \(400\text{N} \times 2.25\text{m} = 900\text{ N-m} (~660\text{ ft-lbs})\) under normal operating conditions.

One last structural issue needs to be analyzed and that is the overall torque that the shaft must handle in order to allow the turbine to operate. Figure 5.12 shows the overall torque produced by the turbine for various wind speeds and rotational rates.
Overall, the torque experienced by the shaft would probably not exceed about 75 N·m under usual operating conditions (4 – 8 m/s, 150 – 350 RPM).

Of course, none of this structural analysis includes radial forces due to centrifugal forces caused by the rotation of the turbine, twisting or bending moments experienced by the blade, nor does it include dynamic analysis with respect to resonance frequencies and changing wind speeds and rotational rates. It is simply a baseline structural analysis that can easily be derived from BEMT.

Overall, the whisper turbine appears to have much room for improvement. Currently, as can be inferred by the data generated by PSUWTA, the turbine is not operating at the ideal rotational rate for any given wind speed. Furthermore, the blade design used by the whisper turbine leaves plenty of room for improvement with respect to power producing capabilities.
Chapter 6

Carolus Turbine Analysis – Two-Bladed

Using the blade geometries laid out in Chapter 3 for the Carolus turbine blades, an analysis of these blades in the two-bladed configuration was done using PSUWTA. The same methodology applied to the Whisper turbine will be applied here.

Section 6.1: Power Output and Performance

Once again, the most logical place to start is the overall power production. Figure 6.1 shows the power output for various rotational rates:

Figure 6.1: Power Output vs. RPM and Wind Speed
As with the Whisper blades, the Carolus blades exhibit the same pattern of various rotational rates producing the maximum power for certain wind speeds. From zero to five meters per second, a rotational rate of 150 RPM produces the maximum amount of power; from five to eight meters per second, a rotational rate of 250 RPM produces the maximum amount of power; from eight to eleven meters per second, a rotational rate of 350 RPM produces the maximum amount of power, and so on. In general, the Carolus blades appear to be producing more power than the Whisper blades given any combination of wind speed and rotational rate.

Once again, the overall power coefficient is an excellent gauge of how efficient the turbine really is. Figure 6.2 shows the overall power coefficient as a function of both wind speed and rotational rate:

![Cp vs. Windspeed](image)

Figure 6.2: Power Coefficient vs. Wind Speed and RPM

All of the power coefficients for the Carolus turbine are much higher than those of the Whisper Turbine. The maximum power coefficient for the Whisper turbine tended to
be around 0.38-0.4 for most rotational rates and dropped to about 0.32 for 150 RPM. Meanwhile, the Carolus turbine had maximum power coefficients ranging from 0.41 to 0.43 for all rotational rates. This is a huge advantage for the Carolus turbine, especially in the lower range of wind speeds which can be expected for small wind turbines.

By making Figure 6.2 fully non-dimensional, a comparison can be drawn between the power coefficient and tip speed ratio. Figure 6.3 shows this comparison for the Carolus turbine:

![Figure 6.3: Power Coefficient vs. Tip Speed Ratio](image)

Once again, all of the power coefficient curves from figure 6.2 appear to collapse nearly onto one curve when compared to tip speed ratio. As the rotational rate increases, the power coefficient tends to stay higher as tip speed ratio is increased. Unlike the whisper turbine, drop off in performance as tip speed ratio is increased is much more consistent among RPMs than with the Whisper blades. In Whisper turbine, the drop in performance at 150 RPM is quite drastic, while for 250RPM and above, the drop is very
shallow. At optimal tip speed ratios, the Carolus turbine is predicted to outperform the Whisper turbine; however, the Carolus blade is much more susceptible to worse performance at off design conditions than the Whisper turbine. In general, the Carolus turbine’s power coefficient drops much more rapidly with increasing tip speed ratio than does the power coefficient for the Whisper turbine. How this will affect overall power output in reality is impossible to tell from this analysis without experimental data. It is possible that in a turbulent flow field where the wind speed is constantly changing, the gains made by optimizing the Carolus turbine will be offset by the amount of time spent in off-design conditions.

Aside from overall performance, it is important to look at how the Carolus turbine blades perform along the length of the blade in order to identify which parts contribute the most and least to the overall performance and to see where possible improvements could be made. Figure 6.4 shows the radial power distribution produced by the Blades when run through PSUWTA:
Once again, the majority of the power produced by the Carolus blades comes from near the blade tip and drops off near the hub. As for where the power production becomes negative in some of the higher RPM cases, this due to the fact that the turbine actually requires energy to keep these elements moving at this rate rather than be driven by the wind. When compared to the Whisper turbine, the power production near the tip of the blade is actually slightly less. However, the Carolus Blade has the advantage in the middle and near the hub of the blade. In these areas, the power produced by each element in the Carolus turbine is greater than that of the Whisper Turbine, and in the end, this small advantage distributed over the majority of the blade causes the Carolus turbine to outperform the Whisper turbine in power production.

Looking at the radial distribution of power coefficients is once again useful for determining how efficient each blade element is. Figure 6.5 shows this distribution:

![Power Coefficient vs. Non-Dim. Radial Position](image-url)

Figure 6.5: Power Coefficient vs. Radial Location, Wind Speed = 8 m/s
For a wind speed of 8 m/s, the optimal rotational rate falls right between 250 and 350 RPM, hence the curves for these rotational rates having the highest values of power coefficient across the span of the blade. Outside of these rotational rates, the power coefficient values tend to fall off rather quickly, especially near the tip of the blade. Compared to the whisper turbine, around the optimal rotational rate, the Carolus blade has consistently higher $C_p$ values. However, as conditions move away from optimal, the Whisper blades begin to outperform the Carolus blades.

Beyond the power coefficient, the axial induction factor is a good indicator of how to attempt to modify the blade if need be since it shows whether the wind passing through the turbine slows down too much or too little. Once again, the optimal value for the axial induction factor is one third. Figure 6.6 shows the radial distribution of this factor:

![Figure 6.6: Axial Induction Factor vs. Radial Location, Wind Speed = 8 m/s](image)
The two optimal cases plotted, 250 and 350 RPM, straddle the optimal value of one third for the most part, meaning that the turbine slows the wind down too much at 350 RPM and not enough at 250 RPM. The rest of the cases fall much farther away from this optimal induction ratio value though.

Finally, it is important to make sure that the Carolus blades are not stalled, as this is a sign that the blade design is working as properly intended. Figure 6.7 shows this distribution:

![Figure 6.7: Angle of Attack vs. Radial Location, Wind Speed = 8 m/s](image)

Since the Carolus blades use an S822 airfoil, which stalls around and angle of attack of 15°, the only time the blade is stalled in this case is when it is operating at 150 RPM, which is not an optimal rotational rate for a wind speed of 8 m/s as shown. For the rest of the cases, the angle of attack is nearly constant along the length of the blade. This
is much better than the Whisper blades, where even at an optimal combination of RPM and wind speed at least the inboard 20% of the blade was stalled.

Once again, analyzing any other factors calculated as a function of radial location really does not help gain a direct insight into how well the Carolus turbine is actually performing. Equation 5.1 in the previous chapter shows how complicated it can become when trying to analyze the direct effect of each of these factors on the axial induction factor.

Section 6.2: Structural Loads

As was done with the Whisper blades, a brief structural analysis of the Carolus blades can be performed using PSUWTA, specifically looking at the thrust and torque due solely to aerodynamic forces calculated by PSUWTA experienced by the turbine. First of all, the overall thrust experienced by the turbine must be analyzed in order know how much thrust force will be applied to whatever the turbine is mounted on. Figure 6.8 shows the overall thrust force experienced by the Carolus turbine:
As would be expected, with increasing wind speed and rotational rate comes a higher thrust force. For every combination of wind speed and rotational rate shown here, the Carolus turbine experiences a higher thrust force than the Whisper turbine under the same condition. The thrust curves for both follow the same basic trend and shape overall.

Aside from just affecting what the turbine is mounted on, the thrust force can possibly bend the blades out of the rotor plane. In order to withstand this, it is necessary to understand how the thrust force is distributed along each blade. Figure 6.9 shows the thrust force per unit length as a function of radial location on the Carolus blades:

![Figure 6.8: Overall Thrust vs. Wind Speed and RPM](image-url)
Following the same trend as the overall thrust force, the incremental thrust force on the Carolus blade is higher for every combination of wind speed and rotational rate. And once again, the majority of the thrust force is concentrated around the blade tip, leading to higher root bending moments that must be accounted for when it comes time to decide how to construct the blades.

The last piece of structural information that can be easily obtained is the overall torque produced by the turbine that must be handled by the shaft connected to the electrical generator. The torques shown here are solely those resulting purely from aerodynamic forces and does not include things such as electrical forces, gravity, or friction. Figure 6.10 shows the overall torque experienced by the turbine:
Since power is simply the product of torque multiplied by rotational rate, it comes as no surprise that the torque experienced by the Carolus blade is higher than that experienced by the Whisper turbine. This applies only at the optimal combinations of wind speed and rotational rate that produce a maximum power coefficient. Outside of these optimum combinations though, the Whisper turbine may experience a higher torque since it sometimes will be producing more power in many cases. No matter what though, these torques must accounted for when designing the structural parts of the turbine.

Figure 6.10: Overall Torque vs. Wind Speed and RPM
Chapter 7

Carolus Turbine Analysis – Three-Bladed

A three-bladed version of the Carolus is also in the process of being constructed here at Penn State. It will use the same blades with the same chord and twist distributions; however, the entire blade will be pitched an extra $6^\circ$ in order to compensate for the increase in overall solidity caused by the addition of a third blade.

Section 7.1: Power Output and Performance

As in the previous two chapters, power output is the most important measurement of wind turbine performance and Figure 7.1 shows this for the three-bladed Carolus turbine:

![Figure 7.1: Power vs. Wind Speed and RPM](image-url)
Power output for each RPM appears to have increased slightly compared to its two-bladed counterpart, but more importantly, the curves have shifted. Before a rotational rate of 250 RPM was optimal for wind speeds of 5-8 m/s; however, now it is optimal for wind speeds of about 7-10 m/s. The same trend follows for the other rotational rates. This can be illustrated much more clearly by comparing power coefficients to wind speed as shown here in Figure 7.2:

![Figure 7.2: Power Coefficient vs. Wind Speed and RPM](image)

Once again, the increase in power output is reflected here in the higher maximum power coefficients of about 0.43-0.44. For the same rotational rates as the two-bladed version, the wind speeds at which these maximums occur has increased.

Perhaps the biggest surprise comes when wind speed is made fully non-dimensional and converted to tip speed ratio. Figure 7.3 shows the comparison of power coefficient to tip speed ratio:
Here, the optimal tip speed ratio appears to be about seven, while for the two-bladed version of the turbine, it was closer to nine. However, the biggest change is clearly what happens away from the optimal tip speed ratio. Operating the three-bladed Carolus turbine anywhere outside of tip speed ratios ranging from about five to ten results in a massive loss in performance and power output. This is a much smaller range than that for the two-bladed Carolus turbine or even the Whisper turbine.

As far as the radial distribution of performance parameters such as power output and power coefficient go, they followed nearly the exact same trends as with the two-bladed Carolus turbine with nothing really worthy of note to be shown. The same also happened with the radial distribution of axial induction ratios as well as angles of attack.

Figure 7.3: Power Coefficient vs. Tip Speed Ratio
Section 7.2: Structural Loads

For structural purposes, the overall thrust experienced by the turbine increased with the addition of a third blade. Even though the blades have been pitched by $6^\circ$ to keep the solidity the same, the fact there is now a third blade exposed to the wind increases the thrust experienced by the turbine regardless. As far as the radial thrust distribution goes, the majority of the thrust force is still concentrated at the tip. However, since the overall thrust force is now distributed over three blades instead of two, the root bending moment of each blade is less than that of the two-bladed Carolus turbine.

Finally, the overall torque increases drastically for the three bladed-Carolus turbine when compared to the two-bladed version. This comes as no surprise since with a three bladed setup, higher power outputs can be obtained from lower rotational rates. Since power is the product of rotational rate multiplied by torque, an increase in power, and a decrease in rotational rate, results in a much greater torque that the turbine will experience.
Chapter 8

Conclusion

PSUWTA, a Blade Element Momentum Theory code written in MATLAB, was developed in order to be used as a starting point for analyzing small wind turbines at Penn State. When compared to the output of WT_Perf, NWTC’s BEMT code, PSUWTA continually comes within engineering accuracy of WT_Perf’s results, all of which was checked against experimental data collected from the Whisper turbine used in both programs. This code can be used for preliminary analysis of new wind turbine designs as well as to verify the output of other more complicated wind turbine analysis codes.

PSUWTA was then used to analyze the Performance of Southwest Windpower’s Whisper 500 wind turbine as well as the Carolus wind turbine, an in-house design by Dr. Thomas Carolus, a visiting professor from the Institute for Fluid Dynamics and Thermodynamics at the University of Siegen in Siegen, Germany. The Carolus turbine comes in two versions, a two bladed or a three bladed turbine, both of which were analyzed. Both the Whisper and Carolus turbines are the same size, with their differences lying in airfoil selection, chord distribution, and twist distribution.

The results for the Whisper Turbine indicate that its design, which uses linear distributions for both the chord length and local pitch angle, was made with simplicity in mind and not for aerodynamic performance. Even at the optimal combinations of wind speed and rotational rate where the turbine is producing the maximum amount of power at a maximum power coefficient, the inboard 20% of the blade is stalled. Even worse, it’s overall power coefficient tends to only reach a maximum of about 0.39, which falls well short of the theoretical maximum of 0.593 set by the Betz limit. At lower wind speeds and rotational rates, this maximum falls as low as 0.32 in some cases. One redeeming quality though is that outside of optimal tip speed ratios, performance does degrade too quickly.
For the two-bladed version of the Carolus turbine, performance overall was much better than that of the Whisper turbine. Looking at any of the optimal cases for wind speed and rotational rate, the blade is not stalled anywhere along its length. The overall maximum power coefficient sits around 0.43, but most importantly, it retains this high maximum power coefficient even at low wind speeds and rotational rates, unlike the Whisper turbine. However, outside of optimal tip speed ratios, performance degrades quicker than that of the Whisper turbine. In very turbulent or gusty wind, the Carolus turbine’s response time to changes in wind speed will be crucial for it to outperform the Whisper turbine. Should it remain at these non-optimal tip speed ratios for too long, it is possible that power production could turn out to be even with that of the Whisper turbine under the same conditions. However, since PSUWTA does not have the capability to predict performance under turbulent or changing wind speeds, these claims remain unverified.

When the Carolus turbine is changed into its three-bladed version and an extra 6° of pitch is added to each blade to keep the solidity the same as that of the two-bladed version, it is predicted to produce slightly more power. The maximum power coefficients rise to about 0.44. More importantly, performance at lower wind speeds improves dramatically. It is able to run at lower rotational rates for higher wind speeds and able to generate more power because of this. However, performance degrades quickly as conditions move away from the optimal tip speed ratio, which is now lower than the two-bladed version. Once again, response time to changes in wind speed should be the key to better performance.

In general there, should be noticeable improvements in power production as testing moves from the Whisper turbine to the two-bladed Carolus turbine and eventually the three-bladed version. It will also be interesting to see how things such as generator efficiency and RPM or the loading on the turbine from the battery bank or the grid affect the performance of these wind turbines. Hopefully the new Carolus turbines, along with PSUWTA, will provide a solid foundation for preliminary wind turbine analysis and help Penn State to continue in its efforts to further the field of small wind turbines.
Appendix A

Works Cited


Appendix B

PSUWTA Code

Section B.1: Code Setup Instructions

PSUWTA, as it stands at the time of writing, is not as cleaned up as it should be. In order to run it, the user must have a good foundation with MATLAB since many things are hard coded. The following items are needed in order to fully define the turbine in the program:

1) The number of blades on the turbine
2) The radius of the turbine in meters
3) The radius of the hub in meters (also called the root cutout value)
4) The number of blade elements the user wishes to use
5) Airfoil Data covering the full spectrum of angles of attack from $-180^\circ$ to $180^\circ$
6) The local pitch angle in radians as a function of non-dimensional radial location $(r/R)$
7) The chord length in meters as a function of non-dimensional radial location $(r/R)$
8) WT_Perf Performance Data (Optional – Only if the user desires to use it for comparison)

Items 1-4 are simply be entered into lines 14-17 of PSUWTAOp as well as in lines 23 and 24 of PSUWTA. From here, these instructions will describe how to input the rest of this information into the code.

Section B.1.1: Airfoil Data

Entering the airfoil data is the most difficult part of running PSUWTA. First of all, the user must select the airfoil used by the wind turbine. Currently, the code only runs
using one airfoil for the entire span of the blade. The user can obtain the airfoil data for
various Reynolds numbers from any source such as experimental data or Xfoil. From
here, the data must be expanded to cover the whole spectrum of angles of attack from
-180° to 180°. This can be done using a Microsoft Excel spreadsheet called
AirfoilPrep_v2p2.xlsm. It can be found online here:

http://wind.nrel.gov/designcodes/preprocessors/airfoilprep/

Once this data has been obtained for however many Reynolds numbers the user
would like to use, it must be imported into the program. The easiest way to do this, at
least in the opinion of the author, is to create a function to store all of the data. An
example function used for the S822 airfoil is provided below:

```
function ren = S822data

storage(:,:,1) = [α1 C_l C_d
                 α2 C_l C_d
                 α3 C_l C_d];
storage(:,:,2) = [α1 C_l C_d
                 α2 C_l C_d
                 α3 C_l C_d];
storage(:,:,3) = [α1 C_l C_d
                 α2 C_l C_d
                 α3 C_l C_d];
ren = storage;
end
```

**Figure B.1: Airfoil Data Storage Function**

In this function, the variable `storage` is used to hold all of the airfoil data. It is a
three dimensional array, defined as `storage(x,y,z)`. Here, `x` selects which angle of
attack to extract data from. `y` can have values of 1, 2, or 3 where 1 corresponds to the
value of the angle of attack itself; 2 corresponds to the lift coefficient; and 3 corresponds
to the drag coefficient. Finally, `z` selects which Reynolds number to select data from. The
user can set this up to have as many data sets for as many Reynolds numbers as desired.
Since this function requires no input and simply returns all of the airfoil data, it
essentially acts as a global variable and can be simply called. The function is called in PSUWTAOp at line 19. The user simply inserts the name of the function as shown below at that line:

\[
\text{ren = Function Name;}
\]

**Figure B.2: Airfoil Data Function Call**

Now, that the airfoil data has been updated, it is now necessary for the user to update the Reynolds number data selection code. Open up the function PSUWTA and go to line 162. This is where the experience with MATLAB becomes necessary. An ‘if’ structure must be constructed for the function to select which airfoil data set to use based on Reynolds number and should look like this when complete:

\[
\begin{align*}
\text{if} & \quad \text{Re} \leq 200000 \\
\text{airfoil} & = \text{ren}(:,:,1) \\
\text{elseif} & \quad \text{Re} \leq 400000 \\
\text{airfoil} & = \text{ren}(:,:,2) \\
\text{elseif} & \quad \text{Re} \leq 600000 \\
\text{airfoil} & = \text{ren}(:,:,3) \\
\text{else} & \\
\text{airfoil} & = \text{ren}(:,:,4) \\
\end{align*}
\]

**Figure B.3: Airfoil Data Selection Code**

The variable names used in this ‘if’ structure should be very straightforward: \( \text{Re} \) represents Reynolds number, \( \text{ren}(:,:,z) \) is the variable containing all of the airfoil data with the \( z \) index indicating Reynolds number for the data set and \( \text{airfoil} \) is the variable that stores the airfoil data set for the Reynolds number that the current element is being analyzed at. The selection structure uses airfoil data for a specific Reynolds number for
elements whose Reynolds number is within a reasonable range of the Reynolds number of the airfoil data. In plainer terms, the structure, shown in Figure B.3, runs as so:

<table>
<thead>
<tr>
<th>Table B.1: Airfoil Data vs. Blade Element Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds Number of Selected Airfoil Data</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>100,000</td>
</tr>
<tr>
<td>300,000</td>
</tr>
<tr>
<td>500,000</td>
</tr>
<tr>
<td>700,000</td>
</tr>
</tbody>
</table>

Once this is done, the program should be set to run for the new user selected airfoil.

**Section B.1.2: Chord and Local Pitch Angle Distributions**

Both the chord and local pitch angle distributions are quite easy to enter into the code. First, the user must know these distributions as a function of non-dimensional radial location (r/R). Next, the user needs to open PSUWTA. The chord distribution, stored in the variable c, in meters, is entered at line 118 as a function of the variable y, the non-dimensional radial location. The local pitch angle distribution in radians, stored in the variable theta, is entered at line 114 also as a function of the variable y.

**Section B.1.3: Importing WT_Perf Data**

If the user would like to compare the output of PSUWTA to that of WT_Perf, the user must first obtain the “.bid” output file and store it in the folder entitled “Data” in the “PSUWTA” folder. Both WT_Perf and PSUWTA must be run for the same number of blade elements for any plot containing WT_Perf data to work.
Next, the user must un-comment lines 117 to line 146 in PSUWTAOp. Finally, the user must enter the name of the WT_Perf “.bid” file into line 119 as such:

```plaintext
filename = 'Data/File_name.bid';
```

**Figure B.4: WT_Perf File Name Entry**

Once this is all done, the program should be set to run and compare the data from PSUWTA and WT_Perf.

**Section B.1.4: Running PSUWTA**

When the user is ready to actually run the code, all he or she needs to do is simply run PSUWTAOp and follow the text instructions that should appear in the MATLAB command window.

First the program will ask for a wind speed to plot. This is used on figures where a parameter is plotted against radial location for either one or various rotational rates. Next, the program will ask for an RPM. This is only used for comparison figures of PSUWTA and WT_Perf. On these comparison figures, only one line from each program is plotted, hence the need for an RPM and possibly a wind speed in some cases.

Once the wind speed and RPM have been selected, the user will be prompted with three “yes or no” questions:

1) Do you wish to plot comparisons of PSUWTA and WT_Perf data? [Y/N] :
2) Do you wish to plot solely PSUWTA data for various rpms? [Y/N] :
3) Do you wish to plot solely WT_Perf data for various rpms? [Y/N]:

Under each of these questions lies the exact same subset of questions. They are listed here:

1) Do you wish to plot the core variables? [Y/N] :
2) Do you wish to plot the radial power, torque, and thrust? [Y/N] :
3) Do you wish to plot the overall power? [Y/N] :
4) Do you wish to plot the overall thrust? [Y/N] :
5) Do you wish to plot the overall torque? [Y/N] :

Question one will plot six figures: angle of attack, lift coefficient, drag coefficient, local velocity, local Reynolds number, axial induction ratio, and tangential induction ratio. Each of these variables will be on its own plot against non-dimensional radial location.

Question two will also plot six figures: power per unit length, thrust per unit length, torque per unit length, power coefficient, thrust coefficient, and torque coefficient. Once again, each will appear on its own plot against non-dimensional radial location.

Questions three through five each produce three figures a piece. Question number three plots power vs. wind speed, power coefficient vs. wind speed, and power coefficient vs. tip speed ratio. Each of these is on its own plot. Questions four and five produce the same plots except for the overall thrust or torque respectively.

Finally, the program asks the user if he or she would like to select a new RPM and wind speed and plot again. This plotting loop can be run as many times as the user desires without the program having to recalculate anything.
Section B.2: Block Diagram

1) Choose the input Parameters:
   - RPM values to analyze
   - Number of blade elements to use
   - Number of blades on the turbine
   - Range of wind speeds to analyze

2) Reads in and stores the Coefficients of Lift and Drag for the airfoil at various Reynold's numbers. Can also read in WT_Perf data here if provided.

3) Creates and zeros all the matrices needed to store, manage, and plot all the data

4) Starts a loop that updates the RPM value to be analyzed

5) Selects RPM Value

6) Sets the following input parameters:
   - Air Density
   - Blade Radius
   - Pre-Cone Angle
   - Tolerance for calculating inflow ratio
   - Root cut out value
   - Viscosity of air

7) Creates data matrix containing:
   - Wind Speed
   - RPM
   - Tip Speed Ratio
   - Collective Pitch (if any)

8) Creates and zeros matrices needed to store data for this run of the function

9) Begins loop to vary wind speed used in the analysis

10) Selects wind speed to use

9) Begins loop to vary which blade element is analyzed

12) Selects Blade element to use

13) Calculates chord and local pitch angle of the element based off of the blade geometry as well as the local solidity of the blade

14) Runs an iterative loop to simultaneously calculate:
   - C_l - Angle of attack
   - C_d - Local Velocity
   - a - Reynold's Number
   - a' - Includes Prandtl Hub and Tip losses as well as the Glauert correction if necessary

15) Uses values from step 14 to calculate incremental and total lift, drag, thrust, torque, and power as well as their coefficients

15) Stores all values from steps 14 and 15 in matrices to be passed to front running code


17) Updates wind speed. Runs steps 10 - 16 for the next wind speed.

18) Receives, consolidates, and stores all data for RPM used in steps 5 - 17.

19) Updates RPM value. Runs steps 5-18 for the next RPM value

20) Plots the data
Section B.3: PSUWTA Source Code

In the following subsections, the actual MATLAB source code for PSUWTA has been pasted in. In these copies, PSUWTA is set up to run an analysis on the two-bladed version of the Carolus turbine.

Section B.3.1: BEMT Function Code “PSUWTA_v7_B.m”

```
function [Clar dLa Cdar dDa Qty1 Qty2 dQ Cta Cpa P dP T dT Uinfo yar thetaa phia alphaa locvel locRe dCt dCp indrat tindrat dCq pn pt Q Cqa] = PSUWTA_v7_B(Nb,rpm,seg,ren,minwind,maxwind)

% Program: PSUWTA_v7_B.m
% Author: Leo Albanese, See performance.m for original version of code
% Note: performance.m is heavily based off a code called WT_Perf produced
% by NREL
% Modified by Thomas Purcell 12/8/09
% Modified by Jacob Marsh and David Faust Spring 2010
% Modified by Jacob Marsh Fall 2010
% Modified by Thomas Purcell Spring 2011
%
% About the Program:
% This function is designed to analyze the performance of a wind turbine
% using Blade Element Momentum Theory.
% Please note that if the turbine uses collective pitch that you must enter
% a function that defines collective pitch in degrees as a function of the
% variable 'wind' (the wind speed in m/s).
%
% Input
R=2.25;                % Assigns blade radius in meters
Ro = 0.137;            % Assigns root cut out value in m
a_tol=1e-6;            % Assigns the tolerance for inflow ratio convergence
mu = 1.814826290763033E-5;       % Viscosity of air at 60 deg F
rho=1.225;             % Assigns air density in kg/m^3
%
% Calculations
```
\[ yo = \frac{Ro}{R}; \quad \text{% Assigns root cutout value (non-dimensional radius)} \]
\[ yi = \frac{(1-yo)}{seg}; \quad \text{% Sets interval step value of y} \]
\[ ya = yo : yi : 1; \quad \text{% Creates array with dimensionless radius values} \]

\% Uinfo contains the Tip Speed Ratio and Collective Pitch (deg) settings
\% for each Wind Speed (m/s). This array is generated under the assumption
\% that the turbine runs at a constant RPM for all wind speeds

\[
\text{Uinfo} = \text{zeros}((\text{maxwind}-\text{minwind}+1),3); \quad \text{% Initializes Uinfo to be set to zero} \\
\]
\[
j = 1; \quad \text{% Index counter variable} \\
w = \text{minwind}; \quad \text{% Initial wind speed} \\
\text{while } w \leq \text{maxwind}, \quad \text{% Generates array for all speeds between minwind and maxwind} \\
\]
\[
\text{Uinfo}(j,4) = \text{rpm}; \quad \text{% stores rpm in Uinfo column 4} \\
\text{Uinfo}(j,1) = w; \quad \text{% Column 1 of Uinfo holds the wind speed in m/s} \\
\]
\[
w = \text{rpm} \times 2 \times \pi / 60; \quad \text{% Calculates angular velocity of blade in rad/s} \\
v_{\text{tip}} = w \times R; \quad \text{% Calculates tip speed in m/s} \\
tsr = v_{\text{tip}} / w; \quad \text{% Calculates tip speed ratio} \\
\text{Uinfo}(j,2) = tsr; \quad \text{% Column 2 of Uinfo contains the tip speed ratio} \\
\]
\[
coll_\text{p} = 0; \quad \text{% Calculates collective pitch in degrees as a function of wind speed in m/s. Leave as zero if turbine doesn't use collective pitch.} \\
\text{Uinfo}(j,3) = coll_\text{p}; \quad \text{% Column 3 of Uinfo contains collective pitch in degrees} \\
\]
\[
\text{wind} = \text{wind} + 1; \quad \text{% Update steps to continue running loop} \\
j = j + 1; \quad \text{end} \\
\]
\% Zeros and pre-allocates the size of all arrays used in loops in the program to decrease run time
\[
\text{thetaa} = \text{zeros}(\text{length}(\text{Uinfo}), (\text{length}(\text{ya})-1)); \\
\text{ca} = \text{zeros}(\text{length}(\text{ya})-1,1); \\
\text{indrat} = \text{zeros}(\text{length}(\text{Uinfo}), (\text{length}(\text{ya})-1)); \\
\text{tindrat} = \text{zeros}(\text{length}(\text{Uinfo}), (\text{length}(\text{ya})-1)); \\
\text{phia} = \text{zeros}(\text{length}(\text{Uinfo}), (\text{length}(\text{ya})-1)); \\
\]
alphaa = zeros(length(Uinfo), (length(ya)-1));
C1ar = zeros(length(Uinfo), (length(ya)-1));
dLa = zeros(length(Uinfo), (length(ya)-1));
Cd1r = zeros(length(Uinfo), (length(ya)-1));
dDa = zeros(length(Uinfo), (length(ya)-1));
Qty1 = zeros(length(Uinfo), (length(ya)-1));
Qty2 = zeros(length(Uinfo), (length(ya)-1));
dQ = zeros(length(Uinfo), (length(ya)-1));
pt = zeros(length(Uinfo), (length(ya)-1));
pn = zeros(length(Uinfo), (length(ya)-1));
dCt = zeros(length(Uinfo), (length(ya)-1));
dCp = zeros(length(Uinfo), (length(ya)-1));
dCq = zeros(length(Uinfo), (length(ya)-1));
dP = zeros(length(Uinfo), (length(ya)-1));
dT = zeros(length(Uinfo), (length(ya)-1));
Cta = zeros(length(Uinfo), 1);
Cpa = zeros(length(Uinfo), 1);
Cqa = zeros(length(Uinfo), 1);
Q = zeros(length(Uinfo), 1);
P = zeros(length(Uinfo), 1);
T = zeros(length(Uinfo), 1);
locvel = zeros(length(Uinfo), (length(ya)-1));
locRe = zeros(length(Uinfo), (length(ya)-1));

q=0; % step indicating wind speed
while q<length(Uinfo) % Windspeed Steps
    q=q+1; % Update Step
    V=Uinfo(q,1); % Extracts the wind speed
    X=Uinfo(q,2); % Extracts the tip speed ratio
    %coll=Uinfo(q,3); % Extracts the collective pitch
    % each step is an increase in the analysed wind speed

    i=1;
    while i<(length(ya)-1) % Radial Station Steps % Calculates the induction ratio, and therefore % inflow angle (phi) and AoA ratio at each radial % position
        i=i+1;
        y=ya(i); % Selects value of radial position to use in this iteration

        % Calculates pitch angle at this radial position
        theta = (545.15*y*y*y*y*y*y - 2111*y*y*y*y*y + 3347.7*y*y*y*y - 2815.1*y*y*y + 1361.4*y*y - 384.02*y + 54.604)*(pi/180);
        % note: theta here is actually a misnomer and should be gamma, the % pitch angle
        c = -5.2033*y*y*y*y*y + 18.535*y*y*y*y*y - 25.472*y*y*y*y + 16.261*y*y*y - 3.8983*y*y - 0.6849*y + 0.5695;
ca(q,i) = c;

\theta_a(q,i) = \theta \times \frac{180}{\pi}; \quad \% \text{Stores } \theta \text{ value into a global array}

ca(i) = c; \quad \% \text{Stores chord value into a global array}

\text{sig} = Nb \times c / \left(2 \times \pi \times y \times R\right); \quad \% \text{Calculates solidity at this radial position}

\% \text{Calculates induction factor}
\begin{align*}
a &= 0.0; \quad \% \text{Initial value of axial induction factor}
del_a &= 0.0; \quad \% \text{Stores previous } a \\
a_{\text{step}} &= 0.25; \quad \% \text{Iteration step size of } a \\
del_a_{\text{test}} &= 1; \quad \% \text{The delta } a \text{ that is tested against}
\end{align*}

aprime = 0.0; \quad \% \text{Initial Tangential Induction Factor}

\text{ItSLSC} = 0; \quad \% \text{Stores Iterations Since Last Sign Change of } a
\text{iter} = 1;
\text{while} \; \text{iter} < 5000 \; \&\& \; \text{abs(del_a_{\text{test}}) >= a_{\text{tol}}} \; \% \text{Stops performing loop when iterations}
\begin{align*}
\text{Vi}_{\text{tan}} &= X \times V \times y \times (1+\text{aprime}); \quad \% \text{get too high or the del}_a \text{ is below the tolerance}
\text{Vi}_{\text{norm}} &= V \times (1-a); \quad \% \text{specified velocity}
\text{Re} &= \rho \times \text{Vi} \times c / \mu; \quad \% \text{Calculates Local Reynolds Number}
\phi &= \text{atan} \left( \text{Vi}_{\text{norm}} / \text{Vi}_{\text{tan}} \right); \quad \% \text{Calculates inflow angle}
\phi &= \alpha = (\phi - \theta) \times \frac{180}{\pi}; \quad \% \text{Calculates angle of attack } \alpha
\end{align*}

\% \text{Calculates Prandtl Losses at hub and tip}
\text{fhub} = (Nb / 2) \times \left( \frac{(y-yo)}{(yo \times \sin(\phi))} \right);
\text{Fhexp} = \exp(-\text{fhub});
\text{Fhub} = (2 / \pi) \times \text{atan} \left( \sqrt{1-\text{Fhexp}^2} / \text{Fhexp} \right);
\text{fftip} = (Nb / 2) \times \left( \frac{(1-y)}{(y \times \sin(\phi))} \right);
\text{Fftexp} = \exp(-\text{fttip});
\text{Ftip} = (2 / \pi) \times \text{atan} \left( \sqrt{1-\text{Fftexp}^2} / \text{Fftexp} \right);
P = \text{Fhub} \times \text{Ftip};

k = 1; \quad \% \text{Counter variable for interpolating } Cl \text{ and } Cd
Cl = 0; \quad \% \text{Initializing } Cl \text{ and } Cd
Cd = 0;
if ((alpha < -180) || (alpha > 180))
    alpha=-10;
end

if Re <= 200000
    airfoil = ren(:,:,1);
elseif Re <= 400000
    airfoil = ren(:,:,2);
elseif Re <= 600000
    airfoil = ren(:,:,3);
else
    airfoil = ren(:,:,4);
end

% Loop to interpolate Cl and Cd
while (Cd==0)
    if ((airfoil(k,1)<=alpha) && (airfoil(k+1,1)>=alpha))
        Cl=airfoil(k,2)+(alpha-airfoil(k,1))*(airfoil(k+1,2)-airfoil(k,2))/(airfoil(k+1,1)-airfoil(k,1));
        Cd=airfoil(k,3)+(alpha-airfoil(k,1))*(airfoil(k+1,3)-airfoil(k,3))/(airfoil(k+1,1)-airfoil(k,1));
    else
        k=k+1;
    end
end

Cn = Cl*cos(phi)+Cd*sin(phi); % Calculates Cn to be used below

Ct = Cl*sin(phi)-Cd*cos(phi);

CT = sig*((1-a)^2)*Cn/(sin(phi))^2;

CT = min(max(CT,-2),2);

if CT > 0.96*F,
    if CT*(50-36*F)+12*F*(3*F-4) < 0,
        a_new = 0;
    else
        a_new = (18*F-20-3*sqrt(CT*(50-36*F)+12*F*(3*F-4)))/(36*F-50);
    end
else
    a_new = 1/(4*F*(sin(phi))^2/(sig*Cn)+1);
end

aprime = 1/((4*F*sin(phi)*cos(phi)/(sig*Ct))-1);
del_a = a_new-a;
if ((del_a_O ~= 0.0) && (del_a/del_a_O < 0.0)) % Changes
    a_step=0.5*a_step; % of
    ItSLSC=0; % accordingly
elseif (ItSLSC == 10)
    a_step=2.0*a_step;
    ItSLSC=0;
else
    ItSLSC=ItSLSC+1;
end
del_a_test=a_step*del_a;
a=a+del_a_test;
del_a_O=del_a_test;
iter=iter+1;
end

indrat(q,i)=a; % Stores value of a into a global
array

tindrat(q,i)=aprim; % Stores value of a' into a global
array

phia(q,i)=phi*180/pi; % Stores phi value into a global array
alphaa(q,i)=alpha; % Stores angle of attack in a global
array

locvel(q,i)=Vi; % Stores local velocity in a global
array

locRe(q,i) = Re; % Stores Local Reynolds number into a
global array

Clar(q,i)=Cl; % Stores Cl in global array
Cdar(q,i)=Cd; % Stores Cd in global array

\[ dL = \frac{1}{2} \rho (V_i^2) c C_l; \]
\[ dL = \text{incremental lift} \]

\[ dL(a,q,i) = dL; \]
\[ dL = \frac{1}{2} \rho (V_i^2) c C_l; \]
\[ dL = \text{incremental lift} \]

\[ dD = \frac{1}{2} \rho (V_i^2) c C_d; \]
\[ dD = \text{incremental drag} \]

\[ dD(a,q,i) = dD; \]
\[ dD = \text{incremental drag} \]

\[ Q_{ty1}(q,i) = dL \sin(\phi); \]
\[ Q_{ty1} = \text{incremental tangential lift} \]

\[ Q_{ty2}(q,i) = dD \cos(\phi); \]
\[ Q_{ty2} = \text{incremental tangential drag} \]

\[ p_t(q,i) = Q_{ty1}(q,i) - Q_{ty2}(q,i); \]
\[ p_t = \text{incremental tangential force} \]

\[ p_n(q,i) = dL \cos(\phi) + dD \sin(\phi); \]
\[ p_n = \text{incremental normal force} \]

\[ A = \frac{(p_t(q,i)-p_t(q,i-1))}{(R*yit)}; \]
\[ B = \frac{p_t(q,i-1)*R*y-p_t(q,i)*R*(y-yit))}{(R*yit)}; \]
\[ dM = \frac{(1/3)*A*((R*y)^3-(R*(y-yit))^3)+(1/2)*B*((R*y)^2-(R*(y-yit))^2)}{2}; \]
\[ dQ_{act} = Nb*dM; \]
\[
dQ(q, i-1) = \frac{dQ\text{act}}{(y_{it}*R*Nb)}; \\
dCq(q, i-1) = \frac{dQ\text{act}}{(1/2*\rho*V^2*pi*R^2*(y^2-(y_{it})^2)*y*R)}; \\
dCt(q, i-1) = (1-a)^2*\sigma*Cn/(\sin(\phi)^2); \\
dT(q, i-1) = (1/2*\rho*V^2*pi*R^2*(y^2-(y_{it})^2)*dCt(q, i-1))/(Nb*R*y_{it}); \\
dP(q, i-1) = w*dQ\text{act}; \\
dCp(q, i-1) = dP(q, i-1)/(1/2*\rho*V^3*pi*R^2*(y^2-(y_{it})^2));
\]

\text{end}

\text{m = 1;}
\text{while m < (length(ya)-1),}
    \text{Q(q) = Q(q) + dQ(q, m)*y_{it}*R*Nb;}
    \text{T(q) = T(q) + dT(q, m)*y_{it}*R*Nb;}
    \text{P(q) = P(q) + dP(q, m);}
    \text{m = m + 1;}
\text{end}

\text{CtA(q) = T(q)/(0.5*\rho*(V^2)*pi*(R^2));}
\text{CqA(q) = Q(q)/(1/2*\rho*V^2*pi*R^3);}
\text{CpA(q) = P(q)/(1/2*\rho*V^3*pi*R^2);}
\text{end}

\text{yar=ya(2:length(ya)); \% Array used for plotting dimensionless radius}
\text{\% End of the function}
Section B.3.2: Operating Code “PSUWTAOp_v4_D.m”

% This code is to be an operator of PSUWTA, a Blade Element Momentum Theory function.
% It stores values from each run into a global array and plots all of the data as selected by the user.
% It can also import Data from the output file of WT_Perf in order to run comparisons between the two codes.

% Authors: Jacob Marsh and Thomas Purcell

close all
clear
clc

seg = 15;  % Number of Segments analyzed over the length of the blade
Nb = 2;    % Number of Blades
rho = 1.225;  % Assigns air density in kg/m^3
Ro = 0.137;  % Assigns root cut out value in m
R = 2.25;   % Assigns blade radius in meters

ren = S822data;

segwidth = R*(1-Ro/R)/(seg);  % Width of each blade element in m

RPMval = [150;250;350;450;550;650];  % Set RPM values the code will run for
RPMcount = size(RPMval);
maxi = RPMcount(1);  % Number of RPM values to calculate it over

minwindspeed = 2;  % Minimum Windspeed to be used (m/s) MUST BE AN INTIGER
maxwindspeed = 15;  % Maximum Windspeed to be used (m/s) MUST BE AN INTIGER
numwin = maxwindspeed - minwindspeed + 1;

% Creation of Empty Global Matricies

PSUWTA_CL = zeros (numwin,seg,maxi);  % PSUWTA Coefficient of Lift
PSUWTA_dL = zeros (numwin,seg,maxi);  % PSUWTA incremental lift
PSUWTA_CD = zeros (numwin,seg,maxi);  % PSUWTA Coefficient of Drag
PSUWTA_dD = zeros (numwin,seg,maxi);  % PSUWTA incremental Drag
PSUWTA_Qty1 = zeros (numwin,seg,maxi);  % PSUWTA incremental tangential lift
PSUWTA_Qty2 = zeros (numwin,seg,maxi);  % PSUWTA incremental tangential drag
PSUWTA_dQ = zeros (numwin,seg,maxi);  % PSUWTA incremental torque (N-m)
PSUWTA_Ct = zeros (numwin, maxi); %PSUWTA Total Thrust Coefficient
PSUWTA_dCt = zeros (numwin, seg, maxi); %PSUWTA Incremental Thrust Coefficient
PSUWTA_T = zeros (numwin, maxi); %PSUWTA Total Thrust in Newtons
PSUWTA_Cq = zeros (numwin, maxi); %PSUWTA Total Torque Coefficient
PSUWTA_dCq = zeros (numwin, seg, maxi); %PSUWTA Incremental Torque Coefficient
PSUWTA_T = zeros (numwin, maxi); %PSUWTA Total Thrust in Newtons
PSUWTA_Cp = zeros (numwin, maxi); %PSUWTA Total Power Coefficient
PSUWTA_dCp = zeros (numwin, seg, maxi); %PSUWTA Incremental Power Coefficient
PSUWTA_P = zeros (numwin, maxi); %PSUWTA Total Power in watts
PSUWTA_Uinfo = zeros (numwin, 4, maxi); %page 1 = wind speed (m/s)
%page 2 = tip speed ratio
%page 3 = collective pitch (deg)
%page 4 = RPM
PSUWTA_TSR = zeros (numwin, maxi); %PSUWTA Tip Speed Ratio Matrix,
%row= wind speed, column = RPM
PSUWTA_yar = zeros (maxi, seg); %Global array for plotting dimensionless radius
PSUWTA_Theta = zeros (numwin, seg, maxi); %PSUWTA theta
PSUWTA_Phia = zeros (numwin, seg, maxi); %PSUWTA phi
PSUWTA_AoA = zeros (numwin, seg, maxi); %PSUWTA angle of attack
PSUWTA_LocVel = zeros (numwin, seg, maxi); %PSUWTA Local Velocity
PSUWTA_LocRe = zeros (numwin, seg, maxi); %PSUWTA Reynolds Number
PSUWTA_dT = zeros (numwin, seg, maxi); %PSUWTA Radial Thrust
PSUWTA_dP = zeros (numwin, seg, maxi); %PSUWTA Radial Power
PSUWTA_indrat = zeros (numwin, seg, maxi); %PSUWTA Induction Ratio
(a)
PSUWTA_tindrat = zeros (numwin, seg, maxi); %PSUWTA Tangential Induction Ratio (a')
PSUWTA_pn = zeros (numwin, seg, maxi); %PSUWTA Normal Force per length at each radial station
PSUWTA_pt = zeros (numwin, seg, maxi); %PSUWTA Tangential Force per length at each radial station
WTPerf_totP = zeros (67, 19); %WT_Perf initialization
WTPerf_totCp = zeros (67, 19); %WT_Perf initialization
WTPerf_totT = zeros (67, 19); %WT_Perf initialization
WTPerf_totCt = zeros (67, 19); %WT_Perf initialization
WTPerf_totQ = zeros (67, 19); %WT_Perf initialization
WTPerf_totCq = zeros (67, 19); %WT_Perf initialization
WTPerf_TSR = zeros (67, 19); %WT_Perf initialization
i = 1; % each i count is another RPM value run
while i <= maxi

    [PSUWTA_C1(:,:,i) ... 
    PSUWTA_dL(:,:,i) ... 
    PSUWTA_Cd(:,:,i) ... 
    PSUWTA_dD(:,:,i) ... 
    PSUWTA_Qty1(:,:,i) ... 
    PSUWTA_Ct(:,i) ... 
    PSUWTA_Cp(:,i) ... 
    PSUWTA_dP(:,:,i) ... 
    PSUWTA_T(:,i) ... 
    PSUWTA_yar(i,:) ... 
    PSUWTA_Theta(:,:,i) ... 
    PSUWTA_Phia(:,:,i) ... 
    PSUWTA_AoA(:,:,i) ... 
    PSUWTA_LocVel(:,:,i) ... 
    PSUWTA_LocRe(:,:,i) ... 
    PSUWTA_dCt(:,:,i) ... 
    PSUWTA_dCp(:,:,i) ... 
    PSUWTA_indrat(:,:,i) ... 
    PSUWTA_tindrat(:,:,i) ... 
    PSUWTA_dCq(:,:,i) ... 
    PSUWTA_Q(:,i)] = PSUWTA_v7_B_Carolus(Nb,RPMval(i),seg,ren,minwindspeed,maxwindspeed);

    PSUWTA_TSR(:,i) = PSUWTA_Uinfo(:,2,i);
    i = i + 1;
end

%% Read in WT_Perf data
filename = 'Data/Test06_SWWT_ManuBlades_15.bid';
[WTPerf_windspeed WTPerf_RPM WTPerf_LocVel WTPerf_Re WTPerf_Loss WTPerf_AxialInd WTPerf_TangInd WTPerf_AoA WTPerf_AlfaD WTPerf_C1 WTPerf_Cd WTPerf_Ct WTPerf_Cq WTPerf_Cp WTPerf_ThrustLen WTPerf_TorqueLen WTPerf_Power] = WTPerfLoad(filename);

i = 1;
while i <= 67;
    y = 1;
    while y <= 19;
        ...
        ...
        ...
        ...
    end
    i = i + 1;
end
WTPerf_totP(i,y) = sum(WTPerf_Power(:,i,y));
WTPerf_totCp(i,y) = WTPerf_totP(i,y)/(0.5*rho*(WTPerf_windspeed(1,i)^3)*pi*R^2);
WTPerf_totT(i,y) = sum(WTPerf_ThrustLen(:,i,y)*(segwidth*Nb));
WTPerf_totCt(i,y) = WTPerf_totT(i,y)/(0.5*rho*(WTPerf_windspeed(1,i)^2)*pi*R^2);
WTPerf_totQ(i,y) = sum(WTPerf_TorqueLen(:,i,y)*(segwidth*Nb));
WTPerf_totCq(i,y) = WTPerf_totQ(i,y)/(0.5*rho*(WTPerf_windspeed(1,i)^2)*pi*R^3);

w = WTPerf_RPM(y)*2*pi/60;          % Calculates angular velocity
of blade in rad/s
vtip=w*R;
WTPerf_TSR(i,y) = vtip/WTPerf_windspeed(i);

y = y + 1;
end

i = i + 1;
end

WTPerf_Re = WTPerf_Re*1.0e+06 ;      %Makes WT_Perf and PSUWTA have the
%same units
%
Plotagain = 'y';
while Plotagain == 'y' || Plotagain == 'Y';

close all
clc
plotted = 0;

%Prompt for Windspeed and RPM for graphs
wspd = input('Input desired Windspeed for graphs (>=2,<=15):  ');
wspdval = (2:15);
while wspd == all(wspdval)
    wspd = input('Windspeed entered not valid, please enter one of the
following (>=2,<=15 INTEGERS ONLY):  ');
end

rpmselect = input('Input desired RPM for graphs
(150,250,350,450,550,650):  ');
while rpmselect == all(RPMval)
    rpmselect = input('RPM entered not valid, please enter one of the
following (150,250,350,450,550,650):  ');
end

%Calculations for what value to call when looking for desired RPM or
%Windspeed value in PSUWTA_PSU and WT_Perf
PSUWTA_rpm = ((rpmselect-150)/100)+1;
WTPerf_rpm = (rpmselect-50)/50;
PSUWTA_wind = wspd - 1;
WTPerf_wind = (wspd-1.5)*2;
yar = PSUWTA_yar(1,:);

%Table Properties for ALL plots
whitebg('w') %Sets all figures to a while color scheme
set(0,'DefaultAxesColorOrder',[0 0 0],...
    'DefaultLineMarkerSize',7,...
    'DefaultAxesLineStyleOrder',('-o','--+'))
set(0,'DefaultAxesFontWeight','bold')

LABEL(2) = {'Carolus Blades'};
LABEL(3) = {'4 Reynolds Numbers - 15 Segments'};
LABEL(4) = cellstr([{'Windspeed = ',num2str(wspd)},' m/s   RPM = ',num2str(rpmselect)]);

legendlab = {'PSUWTA','WT\_Perf'};

close

ques1 = input('Do you wish to plot comparisons of PSUWTA and WT_Perf data? [Y/N] : ','s');
if isempty(ques1)
    ques1 = 'N';
end
if ques1 == 'N' || ques1 == 'n' %Does nothing and skipps plots 8-15
else
    ques1a = input('Do you wish to plot the core variables? [Y/N] : ','s');
    if isempty(ques1a)
        ques1a = 'N';
    end
    if ques1a == 'N' || ques1a == 'n' %Does nothing and skipps plots 1-7
else
    %Executes the Plot functions
    plotted = 1;
    % Angle of Attack vs Radial Position
    figure(1)
    p = plot(yar,PSUWTA_AoA(PSUWTA_wind,:),PSUWTA_rpm),yar,WTPerf_AoA(:,WTPerf_wind,WTPerf_rpm),'LineWidth',2);
    set(p,'LineWidth',2')
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Angle of Attack (Degrees)', 'FontWeight', 'bold')
LABEL(1) = {'Angle of Attack vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend(legendlab, 'Location', 'Best')
grid on
saveas(gcf, 'Output_v3D/AoAvsNDR.jpg')
saveas(gcf, 'Output_v3D/AoAvsNDR.fig')

% Cl vs Radial Position
figure(2)
plot(yar, PSUWTA_Cl(PSUWTA_wind,:,PSUWTA_rpm), yar, WTPerf_Cl(:,WTPerf_wind,WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Cl', 'FontWeight', 'bold')
LABEL(1) = {'Cl vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend(legendlab, 'Location', 'Best')
grid on
saveas(gcf, 'Output_v3D/ClvsNDR.jpg')
saveas(gcf, 'Output_v3D/ClvsNDR.fig')

% Cd vs Radial Position
figure(3)
plot(yar, PSUWTA_Cd(PSUWTA_wind,:,PSUWTA_rpm), yar, WTPerf_Cd(:,WTPerf_wind,WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Cd', 'FontWeight', 'bold')
LABEL(1) = {'Cd vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend(legendlab, 'Location', 'Best')
grid on
saveas(gcf, 'Output_v3D/CdvsNDR.jpg')
saveas(gcf, 'Output_v3D/CdvsNDR.fig')

% Displays a graph of Radial Station Local Velocity
figure(4)
plot(yar, PSUWTA_LocVel(PSUWTA_wind,:,PSUWTA_rpm), yar, WTPerf_LocVel(:,WTPerf_wind,WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Local Velocity (m/s)', 'FontWeight', 'bold')
LABEL(1) = {'Loc. Velocity vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend(legendlab, 'Location', 'Best')
grid on
saveas(gcf, 'Output_v3D/locvelvsNDR.jpg')
saveas(gcf, 'Output_v3D/locvelvsNDR.fig')

% Displays a graph of Radial Station Rn #
figure(5)
plot(yar, PSUWTA_LocRe(PSUWTA_wind,:,PSUWTA_rpm), yar, WTPerf_Re(:,WTPerf_wind,WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Local Reynolds Number', 'FontWeight', 'bold')
LABEL(1) = {'Loc. Reynolds # vs. Non-Dim. Radial Position'};
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
grid on
saveas(gcf,'Output_v3D/locRevsNDR.jpg')
saveas(gcf,'Output_v3D/locRevsNDR.fig')

%Displays a graph of Radial Station Induction Ratio (a)
figure(6)
plot(yar,PSUWTA_indrat(PSUWTA_wind,:,PSUWTA_rpm),yar,WTPerf_AxialInd(:,WTPerf_wind,WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight','bold')
ylabel('Induction Ratio (a)', 'FontWeight','bold')
LABEL(1) =( 'Induction Ratio vs. Non-Dim. Radial Position');
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
grid on
saveas(gcf,'Output_v3D/avsNDR.jpg')
saveas(gcf,'Output_v3D/avsNDR.fig')

%Displays a graph of Radial Station Tangential Induction Ratio (a')
figure(7)
plot(yar,PSUWTA_tindrat(PSUWTA_wind,:,PSUWTA_rpm),yar,WTPerf_TangInd(:,WTPerf_wind,WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight','bold')
ylabel('Tangential Induction Ratio (a prime)', 'FontWeight','bold')
LABEL(1) =( 'Tangential Induction Ratio vs. Non-Dim. Radial Position');
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
grid on
saveas(gcf,'Output_v3D/aprimevsNDR.jpg')
saveas(gcf,'Output_v3D/aprimevsNDR.fig')

end

ques1b = input('Do you wish to plot the radial power, torque, and thrust? [Y/N] : ', 's');
if isempty(ques1b)
    ques1b = 'N';
end

if ques1b == 'N' || ques1b == 'n' %Does nothing and skipps plots 8-15
else
    %Executes the Plot functions
    plotted = 1;

    %Displays a graph of Coefficient of Thrust (Ct)
    figure(8)
    plot(yar,PSUWTA_dCt(PSUWTA_wind,:,PSUWTA_rpm),yar,WTPerf_Ct(:,WTPerf_wind,WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight','bold')
ylabel('Thrust Coefficient (Ct)', 'FontWeight','bold')
LABEL(1) = {'Thrust Coefficient vs. Non-Dim. Radial Position'};
title (LABEL, 'FontWeight', 'bold');
legend(legendlab, 'Location', 'Best');
grid on
saveas(gcf, 'Output_v3D/CtvsNDR.jpg');
saveas(gcf, 'Output_v3D/CtvsNDR.fig');

%Displays a graph of Torque Coefficient (Cq)
figure(9)
plot(yar, PSUWTA_dCq(PSUWTA_wind, :, PSUWTA_rpm), yar, WTPerf_Cq(:, WTPerf_wind, WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Torque Coefficient (Ct)', 'FontWeight', 'bold')
LABEL(1) = {'Torque Coefficient vs. Non-Dim. Radial Position'};
title (LABEL, 'FontWeight', 'bold');
legend(legendlab, 'Location', 'Best');
grid on
saveas(gcf, 'Output_v3D/CqvsNDR.jpg');
saveas(gcf, 'Output_v3D/CqvsNDR.fig');

%Displays a graph of Power Coefficient (Cp)
figure(10)
plot(yar, PSUWTA_dCp(PSUWTA_wind, :, PSUWTA_rpm), yar, WTPerf_Cp(:, WTPerf_wind, WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Power Coefficient (Cp)', 'FontWeight', 'bold')
LABEL(1) = {'Power Coefficient vs. Non-Dim. Radial Position'};
title (LABEL, 'FontWeight', 'bold');
legend(legendlab, 'Location', 'Best');
grid on
saveas(gcf, 'Output_v3D/CpvsNDR.jpg');
saveas(gcf, 'Output_v3D/CpvsNDR.fig');

%Displays a graph of Power (W)
figure(11)
plot(yar, PSUWTA_dP(PSUWTA_wind, :, PSUWTA_rpm), yar, WTPerf_Power(:, WTPerf_wind, WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Power (W)', 'FontWeight', 'bold')
LABEL(1) = {'Power vs. Non-Dim. Radial Position'};
title (LABEL, 'FontWeight', 'bold');
legend(legendlab, 'Location', 'Best');
grid on
saveas(gcf, 'Output_v3D/PowervsNDR.jpg');
saveas(gcf, 'Output_v3D/PowervsNDR.fig');

%Displays a graph of Thrust per Length (T)
figure(12)
plot(yar, PSUWTA_dT(PSUWTA_wind, :, PSUWTA_rpm), yar, WTPerf_ThrustLen(:, WTPerf_wind, WTPerf_rpm)', 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Thrust per Length (N/m)', 'FontWeight', 'bold')
LABEL(1) = {'Thrust per Length vs. Non-Dim. Radial Position'};
title (LABEL, 'FontWeight', 'bold')
legend(legendlab,'Location','Best');
grid on
saveas(gcf,'Output_v3D/ThrustvsNDR.jpg')
saveas(gcf,'Output_v3D/ThrustvsNDR.fig')

%Displays a graph of Torque per Length (Q)
figure(13)
plot(yar,PSUWTA_dQ(PSUWTA_wind,:),PSUWTA_rpm),yar,WTPerf_TorqueLen(:,WTPerf_wind,:,:),','LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Torque per Length (N-m/m)','FontWeight','bold')
LABEL(1) =('Torque per Length vs. Non-Dim. Radial Position');
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
grid on
saveas(gcf,'Output_v3D/TorquevsNDR.jpg')
saveas(gcf,'Output_v3D/TorquevsNDR.fig')
end

ques1c = input('Do you wish to plot the overall power? [Y/N] : ','s');
if isempty(ques1c)
    ques1c = 'N';
end

if ques1c =='N' || ques1c =='n'
    %Does nothing and skipps plots 8-15
else
    %Executes the Plot functions

    plotted = 1;

    LABEL(4) = cellstr([,'RPM = ',num2str(rpmselect)]);

    %Displays a graph of Power vs. Wind
    figure(14)
    plot(wspdval,PSUWTA_P(:,PSUWTA_rpm),WTPerf_windspeed,WTPerf_totP(:,WTPerf_rpm),','LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Power (W)','FontWeight','bold')
LABEL(1) =('Power vs. Windspeed');
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Southeast');
%,'Location','Best'
grid on
xlim([2 15])
saveas(gcf,'Output_v3D/PowervsWind.jpg')
saveas(gcf,'Output_v3D/PowervsWind.fig')

    %Displays a graph of Cp vs. Wind
    figure(15)
    plot(wspdval,PSUWTA_Cp(:,PSUWTA_rpm),WTPerf_windspeed,WTPerf_totCp(:,WTPerf_rpm),','LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Cp','FontWeight','bold')
LABEL(1) =('Cp vs. Windspeed');
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
xlim([2 15])
ylim([0 0.5])
grid on
saveas(gcf,'Output_v3D/CpvsWind.jpg')
saveas(gcf,'Output_v3D/CpvsWind.fig')

%Displays a graph of Cp vs. Tip Speed Ratio
figure(16)
plot(PSUWTA_TSR(:,PSUWTA_rpm),PSUWTA_Cp(:,PSUWTA_rpm),WTPerf_TSR(:,WTPerf_rpm),WTPerf_totCp(:,WTPerf_rpm),'LineWidth',2)
xlabel('Tip Speed Ratio','FontWeight','bold')
ylabel('Cp','FontWeight','bold')
LABEL(1) =('Cp vs. Tip Speed Ratio');
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','South');
xlim([0 20])
grid on
saveas(gcf,'Output_v3D/CpvsTSR.jpg')
saveas(gcf,'Output_v3D/CpvsTSR.fig')

end
ques1d = input('Do you wish to plot the overall thrust? [Y/N] : ','s');
if isempty(ques1d)
    ques1d = 'N';
end
if ques1d =='N' || ques1d =='n' %Does nothing and skips plots 8-15
else
    %Executes the Plot functions
    plotted = 1;
    LABEL(4) = cellstr(['RPM = ',num2str(rpmselect)]);
    %Displays a graph of Thrust vs. Windspeed
    figure(17)
    plot(wspdval,PSUWTA_T(:,PSUWTA_rpm),WTPerf_windspeed,WTPerf_totT(:,WTPerf_rpm),'LineWidth',2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Thrust (N)','FontWeight','bold')
LABEL(1) =('Thrust vs. Windspeed');
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
xlim([2 15])
grid on
saveas(gcf,'Output_v3D/ThrustvsWind.jpg')
saveas(gcf,'Output_v3D/ThrustvsWind.fig')

%Displays a graph of Ct vs. Wind Speed
figure(18)
plot(wspdval,PSUWTA_Ct(:,PSUWTA_rpm),WTPerf_windspeed,WTPerf_totCt(:,WTPerf_rpm), 'LineWidth', 2)
xlabel('Windspeed (m/s)', 'FontWeight', 'bold')
ylabel('Ct', 'FontWeight', 'bold')
LABEL(1) = {'Ct vs. Windspeed'};
title (LABEL, 'FontWeight', 'bold')
legend(legendlab, 'Location', 'Best');
xlim([2 15])
grid on
saveas(gcf,'Output_v3D/CtvsWind.jpg')
saveas(gcf,'Output_v3D/CtvsWind.fig')

%Displays a graph of Ct vs. Tip Speed Ratio
figure(19)
plot(PSUWTA_TSR(:,PSUWTA_rpm),PSUWTA_Ct(:,PSUWTA_rpm),WTPerf_TSR(:,WTPerf_rpm),WTPerf_totCt(:,WTPerf_rpm), 'LineWidth', 2)
xlabel('Tip Speed Ratio', 'FontWeight', 'bold')
ylabel('Ct', 'FontWeight', 'bold')
LABEL(1) = {'Ct vs. Tip Speed Ratio'};
title (LABEL, 'FontWeight', 'bold')
legend(legendlab, 'Location', 'Best');
xlim([0 20])
grid on
saveas(gcf,'Output_v3D/CtvsTSR.jpg')
saveas(gcf,'Output_v3D/CtvsTSR.fig')

end
ques1e = input('Do you wish to plot the overall torque? [Y/N] : ', 's');
if isempty(ques1e)
    ques1e = 'N';
end
if ques1e == 'N' || ques1e == 'n' %Does nothing and skipps plots 8-15
else

    %Executes the Plot functions

    plotted = 1;

    LABEL(4) = cellstr(['RPM = ',num2str(rpmselect)]);

    %Displays a graph of Torque vs. Wind Speed
    figure(20)
    plot(wspdval,PSUWTA_Q(:,PSUWTA_rpm),WTPerf_windspeed,WTPerf_totQ(:,WTPerf_rpm), 'LineWidth', 2)
xlabel('Windspeed (m/s)', 'FontWeight', 'bold')
ylabel('Torque (N-m)', 'FontWeight', 'bold')
LABEL(1) ={'Torque vs. Windspeed'};
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
xlim([2 15])
ylim([0 300])
grid on
saveas(gcf,'Output_v3D/TorquevsWind.jpg')
saveas(gcf,'Output_v3D/TorquevsWind.fig')

%Displays a graph of Cq vs. Windspeed
figure(21)
plot(wspdval,PSUWTA_Cq(:,PSUWTA_rpm),WTPerf_windspeed,WTPerf_totCq(:,WTPerf_rpm),'LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Cq','FontWeight','bold')
LABEL(1) ={'Cq vs. Windspeed'};
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
xlim([0 15])
ylim([0 0.06])
grid on
saveas(gcf,'Output_v3D/CqvsWind.jpg')
saveas(gcf,'Output_v3D/CqvsWind.fig')

%Displays a graph of Cq vs. Tip Speed Ratio
figure(22)
plot(PSUWTA_TSR(:,PSUWTA_rpm),PSUWTA_Cq(:,PSUWTA_rpm),WTPerf_TSR(:,WTPerf_rpm),WTPerf_totCq(:,WTPerf_rpm),'LineWidth', 2)
xlabel('Tip Speed Ratio','FontWeight','bold')
ylabel('Cq','FontWeight','bold')
LABEL(1) ={'Cq vs. Tip Speed Ratio'};
title (LABEL,'FontWeight','bold')
legend(legendlab,'Location','Best');
xlim([0 20])
ylim([0 0.06])
grid on
saveas(gcf,'Output_v3D/CqvsTSR.jpg')
saveas(gcf,'Output_v3D/CqvsTSR.fig')
end
end

ques2 = input('Do you wish to plot solely PSUWTA data for various rpms? [Y/N] : ','s');
if isempty(ques2)
    ques2 = 'N';
end

if ques2 == 'N' || ques2 =='n'
else
LABEL(2) = {'PSUWTA.m'}; %Label for each plot
LABEL(3) = {'Carolus Blades'};
LABEL(4) = {'4 Reynolds Numbers - 15 Segments'};

% Table Properties for ALL plots
whitebg('w') % Sets all figures to a white color scheme
set(0,'DefaultAxesColorOrder',[0 0 0],...
    'DefaultLineMarkerSize',7,...
    'DefaultAxesLineStyleOrder',{-o','s','-+','-d',':^','--h'})

if plotted == 0;
    close
end

ques2a = input('Do you wish to plot the core variables? [Y/N] : ','s');
if isempty(ques2a)
    ques2a = 'N';
end

if ques2a == 'N' || ques2a == 'n' % Does nothing and skips plots 8-15
else

    LABEL(5) = cellstr([Windspeed = ',num2str(wspd),' m/s]);

    plotted = 1;

    % Alpha vs Radial Position
    figure(23)
    plot(yar,PSUWTA_AoA(PSUWTA_wind,:,1),yar,PSUWTA_AoA(PSUWTA_wind,:,2),yar,
        PSUWTA_AoA(PSUWTA_wind,:,3),yar,PSUWTA_AoA(PSUWTA_wind,:,4),yar,PSUWTA_AoA(PSUWTA_wind,:,5),yar,PSUWTA_AoA(PSUWTA_wind,:,6),'LineWidth', 2)
    xlabel('Non-Dim. Radial Position','FontWeight','bold')
    ylabel('Angle of Attack (Degrees)','FontWeight','bold')
    LABEL(1) = {'Angle of Attack vs. Non-Dim. Radial Position'};
    title(LABEL,'FontWeight','bold')
    legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best')
    grid on

    % Cl vs Radial Position
    figure(24)
    plot(yar,PSUWTA_Cl(PSUWTA_wind,:,1),yar,PSUWTA_Cl(PSUWTA_wind,:,2),yar,
        PSUWTA_Cl(PSUWTA_wind,:,3),yar,PSUWTA_Cl(PSUWTA_wind,:,4),yar,PSUWTA_Cl(PSUWTA_wind,:,5),yar,PSUWTA_Cl(PSUWTA_wind,:,6),'LineWidth', 2)
    xlabel('Non-Dim. Radial Position','FontWeight','bold')
    ylabel('Cl','FontWeight','bold')
    LABEL(1) = {'Cl vs. Non-Dim. Radial Position'};
    title(LABEL,'FontWeight','bold')
    legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best')
    grid on

end
% Cd vs Radial Position
figure(25)
plot(yar,PSUWTA_Cd(PSUWTA_wind,:,1),yar,PSUWTA_Cd(PSUWTA_wind,:,2),yar,
PSUWTA_Cd(PSUWTA_wind,:,3),yar,PSUWTA_Cd(PSUWTA_wind,:,4),yar,PSUWTA_Cd
(PSUWTA_wind,:,5),yar,PSUWTA_Cd(PSUWTA_wind,:,6),yar,PSUWTA_Cd(PSUWTA_wind,:,7),
'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Cd','FontWeight','bold')
LABEL(1) ={'Cd vs. Non-Dim. Radial Position'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best')
grid on

%Displays a graph of Radial Station Local Velocity
figure(26)
plot(yar,PSUWTA_LocVel(PSUWTA_wind,:,1),yar,PSUWTA_LocVel(PSUWTA_wind,:,2),yar,
PSUWTA_LocVel(PSUWTA_wind,:,3),yar,PSUWTA_LocVel(PSUWTA_wind,:,4),yar,PSUWTA_LocVel
(PSUWTA_wind,:,5),yar,PSUWTA_LocVel(PSUWTA_wind,:,6),yar,PSUWTA_LocVel(PSUWTA_wind,:,7),
'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Local Velocity (m/s)','FontWeight','bold')
LABEL(1) ={'Loc. Velocity vs. Non-Dim. Radial Position'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best')
grid on

%Displays a graph of Radial Station Rn #
figure(27)
plot(yar,PSUWTA_LocRe(PSUWTA_wind,:,1),yar,PSUWTA_LocRe(PSUWTA_wind,:,2),yar,
PSUWTA_LocRe(PSUWTA_wind,:,3),yar,PSUWTA_LocRe(PSUWTA_wind,:,4),yar,PSUWTA_LocRe
(PSUWTA_wind,:,5),yar,PSUWTA_LocRe(PSUWTA_wind,:,6),yar,PSUWTA_LocRe(PSUWTA_wind,:,7),
'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Local Reynolds Number','FontWeight','bold')
LABEL(1) ={'Loc. Reynolds # vs. Non-Dim. Radial Position'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best')
grid on

%Displays a graph of Radial Station Induction Ratio (a)
figure(28)
plot(yar,PSUWTA_indrat(PSUWTA_wind,:,1),yar,PSUWTA_indrat(PSUWTA_wind,:,2),yar,
PSUWTA_indrat(PSUWTA_wind,:,3),yar,PSUWTA_indrat(PSUWTA_wind,:,4),yar,PSUWTA_indrat
(PSUWTA_wind,:,5),yar,PSUWTA_indrat(PSUWTA_wind,:,6),yar,PSUWTA_indrat(PSUWTA_wind,:,7),
'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Induction Ratio (a)','FontWeight','bold')
LABEL(1) ={'Induction Ratio vs. Non-Dim. Radial Position'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best')
grid on
% Displays a graph of Radial Station Tangential Induction Ratio (a')
figure(29)
plot(yar,PSUWTA_tindrat(PSUWTA_wind, :, 1), yar, PSUWTA_tindrat(PSUWTA_wind, :, 2), yar, PSUWTA_tindrat(PSUWTA_wind, :, 3), yar, PSUWTA_tindrat(PSUWTA_wind, :, 4), yar, PSUWTA_tindrat(PSUWTA_wind, :, 5), yar, PSUWTA_tindrat(PSUWTA_wind, :, 6), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Tangential Induction Ratio (a prime)', 'FontWeight', 'bold')
LABEL(1) = {'Tangential Induction Ratio vs. Non-Dim. Radial Position'};
title (LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
grid on
end

ques2b = input('Do you wish to plot the radial power, torque, and thrust? [Y/N] : ', 's');
if isempty(ques2b)
    ques2b = 'N';
end

if ques2b == 'N' || ques2b == 'n'
% Does nothing and skips plots 8-15
else
    % Executes the Plot functions

    LABEL(5) = cellstr({'Windspeed = ', num2str(wspd), ' m/s'});
    plotted = 1;

    % Displays a graph of Coefficient of Thrust (Ct)
    figure(30)
    plot(yar, PSUWTA_dCt(PSUWTA_wind, :, 1), yar, PSUWTA_dCt(PSUWTA_wind, :, 2), yar, PSUWTA_dCt(PSUWTA_wind, :, 3), yar, PSUWTA_dCt(PSUWTA_wind, :, 4), yar, PSUWTA_dCt(PSUWTA_wind, :, 5), yar, PSUWTA_dCt(PSUWTA_wind, :, 6), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Thrust Coefficient (Ct)', 'FontWeight', 'bold')
LABEL(1) = {'Thrust Coefficient vs. Non-Dim. Radial Position'};
title (LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
grid on

    % Displays a graph of Torque Coefficient (Cq)
    figure(31)
    plot(yar, PSUWTA_dCq(PSUWTA_wind, :, 1), yar, PSUWTA_dCq(PSUWTA_wind, :, 2), yar, PSUWTA_dCq(PSUWTA_wind, :, 3), yar, PSUWTA_dCq(PSUWTA_wind, :, 4), yar, PSUWTA_dCq(PSUWTA_wind, :, 5), yar, PSUWTA_dCq(PSUWTA_wind, :, 6), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Torque Coefficient (Cq)', 'FontWeight', 'bold')
LABEL(1) = {'Torque Coefficient vs. Non-Dim. Radial Position'};
%Displays a graph of Power Coefficient (Cp)
figure(32)
plot(yar,PSUWTA_dCp(PSUWTA_wind,:,1),yar,PSUWTA_dCp(PSUWTA_wind,:,2),yar,PSUWTA_dCp(PSUWTA_wind,:,3),yar,PSUWTA_dCp(PSUWTA_wind,:,4),yar,PSUWTA_dCp(PSUWTA_wind,:,5),yar,PSUWTA_dCp(PSUWTA_wind,:,6), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Power Coefficient (Cp)', 'FontWeight', 'bold')
LABEL(1) = {'Power Coefficient vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
grid on

%Displays a graph of Power (W)
figure(33)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Power (W)', 'FontWeight', 'bold')
LABEL(1) = {'Power vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
ylim([0 250])
grid on

%Displays a graph of Thrust per Length (T)
figure(34)
plot(yar,PSUWTA_dT(PSUWTA_wind,:,1),yar,PSUWTA_dT(PSUWTA_wind,:,2),yar,PSUWTA_dT(PSUWTA_wind,:,3),yar,PSUWTA_dT(PSUWTA_wind,:,4),yar,PSUWTA_dT(PSUWTA_wind,:,5),yar,PSUWTA_dT(PSUWTA_wind,:,6), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Thrust per Length (N/m)', 'FontWeight', 'bold')
LABEL(1) = {'Thrust per Length vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
ylim([0 0.6])
grid on

%Displays a graph of Torque per Length (Q)
figure(35)
plot(yar,PSUWTA_dQ(PSUWTA_wind,:,1),yar,PSUWTA_dQ(PSUWTA_wind,:,2),yar,PSUWTA_dQ(PSUWTA_wind,:,3),yar,PSUWTA_dQ(PSUWTA_wind,:,4),yar,PSUWTA_dQ(PSUWTA_wind,:,5),yar,PSUWTA_dQ(PSUWTA_wind,:,6), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Torque per Length (N-m/m)', 'FontWeight', 'bold')
LABEL(1) = {'Torque per Length vs. Non-Dim. Radial Position'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
grid on

end

ques2c = input('Do you wish to plot the overall power? [Y/N] : ', 's');
if isempty(ques2c)
    ques2c = 'N';
end
if ques2c == 'N' || ques2c == 'n' %Does nothing and skipps plots 8-15
else
    %Executes the Plot functions
    plotted = 1;

    %Displays a graph of Power vs. Wind
    figure(36)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Power (W)','FontWeight','bold')
LABEL(1) =('Power vs. Windspeed');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
grid on
xlim([2 15])

%Displays a graph of Cp vs. Wind
figure(37)
LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Cp','FontWeight','bold')
LABEL(1) =('Cp vs. Windspeed');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([2 15])
ylim([0 0.5])
grid on

%Displays a graph of Cp vs. Tip Speed Ratio
figure(38)
LineWidth', 2)
xlabel('Tip Speed Ratio','FontWeight','bold')
ylabel('Cp','FontWeight','bold')
LABEL(1) =('Cp vs. Tip Speed Ratio');
title (LABEL, 'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([0 20])
ylim([.5*.1 .5])
grid on

end

ques2d = input('Do you wish to plot the overall thrust? [Y/N] : ','s');
if isempty(ques2d)
    ques2d = 'N';
end

if ques2d =='N' || ques2d =='n' %Does nothing and skips plots 8-15
else
    %Executes the Plot functions
    plotted = 1;

%Displays a graph of Thrust vs. Windspeed
figure(39)
plot(wspdval,PSUWTA_T(:,1),wspdval,PSUWTA_T(:,2),wspdval,PSUWTA_T(:,3),
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Thrust (N)','FontWeight','bold')
LABEL(1) =('Thrust vs. Windspeed');
title (LABEL, 'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([2 15])
grid on

%Displays a graph of Ct vs. Wind Speed
figure(40)
plot(wspdval,PSUWTA_Ct(:,1),wspdval,PSUWTA_Ct(:,2),wspdval,PSUWTA_Ct(:,3),
wspdval,PSUWTA_Ct(:,4),wspdval,PSUWTA_Ct(:,5),wspdval,PSUWTA_Ct(:,6),'LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Ct','FontWeight','bold')
LABEL(1) =('Ct vs. Windspeed');
title (LABEL, 'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([2 15])
grid on
%Displays a graph of Ct vs. Tip Speed Ratio
figure(41)
plot(PSUWTA_TSR(:,1),PSUWTA_Ct(:,1),PSUWTA_TSR(:,2),PSUWTA_Ct(:,2),PSUWTA_TSR(:,3),PSUWTA_Ct(:,3),PSUWTA_TSR(:,4),PSUWTA_Ct(:,4),PSUWTA_TSR(:,5),PSUWTA_Ct(:,5),PSUWTA_TSR(:,6),PSUWTA_Ct(:,6),'LineWidth', 2)
xlabel('Tip Speed Ratio','FontWeight','bold')
ylabel('Ct','FontWeight','bold')
LABEL(1) ={'Ct vs. Tip Speed Ratio'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([0 25])
grid on
end

ques2e = input('Do you wish to plot the overall torque? [Y/N] : ','s');
if isempty(ques2e)
    ques2e = 'N';
end

if ques2e =='N' || ques2e =='n' %Does nothing and skipps plots 8-15
else
    %Executes the Plot functions
    plotted = 1;

    %Displays a graph of Torque vs. Wind Speed
    figure(42)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Torque (N-m)','FontWeight','bold')
LABEL(1) ={'Torque vs. Windspeed'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([2 15])
ylim([0 300])
grid on
end

%Displays a graph of Cq vs. Windspeed
figure(43)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Cq','FontWeight','bold')
LABEL(1) ={'Cq vs. Windspeed'};
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([2 15])
ylim([0 0.06])
grid on

%Displays a graph of Cq vs. Tip Speed Ratio
figure(44)
plot(PSUWTA_TSR(:,1),PSUWTA_Cq(:,1),PSUWTA_TSR(:,2),PSUWTA_Cq(:,2),PSUWTA_TSR(:,3),PSUWTA_Cq(:,3),PSUWTA_TSR(:,4),PSUWTA_Cq(:,4),PSUWTA_TSR(:,5),PSUWTA_Cq(:,5),PSUWTA_TSR(:,6),PSUWTA_Cq(:,6), 'LineWidth', 2)
xlabel('Tip Speed Ratio', 'FontWeight', 'bold')
ylabel('Cq', 'FontWeight', 'bold')
LABEL(1) = {'Cq vs. Tip Speed Ratio'};
title(LABEL, 'FontWeight', 'bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([0 20])
ylim([0 0.06])
grid on
end

ques3 = input('Do you wish to plot solely WT_Perf data for various rpms? [Y/N] : ','s');
if isempty(ques3)
    ques3 = 'N';
end
if ques3 == 'N' || ques3 == 'n'
else
    LABEL(2) = {'WT_Perf'}; %Label for each plot
    LABEL(3) = {'Carolus Blades'};
    LABEL(4) = {'4 Reynolds Numbers - 15 Segments'};
end

%Table Properties for ALL plots
whitebg('w') %Sets all figures to a while color scheme
set(0,'DefaultAxesColorOrder',[0 0 0],...    'DefaultLineMarkerSize',7,...    'DefaultAxesLineStyleOrder',('-o',':s','--+','-d',':^','--h'))

if plotted == 0;
    close
end

ques3a = input('Do you wish to plot the core variables? [Y/N] : ','s');
if isempty(ques3a)
    ques3a = 'N';
end
if ques3a == 'N' || ques3a == 'n'  %Does nothing and skips plots 1-7
else

LABEL(5) = cellstr(['Windspeed = ',num2str(wspd), ' m/s']);

% Angle of Attack vs Radial Position
figure(45)
plot(yar,WTPerf_AoA(:,WTPerf_wind,2),yar,WTPerf_AoA(:,WTPerf_wind,4),yar,WTPerf_AoA(:,WTPerf_wind,6),yar,WTPerf_AoA(:,WTPerf_wind,8),yar,WTPerf_AoA(:,WTPerf_wind,10),yar,WTPerf_AoA(:,WTPerf_wind,12), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Angle of Attack (Degrees)', 'FontWeight', 'bold')
LABEL(1) = {'Angle of Attack vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
grid on

% Cl vs Radial Position
figure(46)
plot(yar,WTPerf_Cl(:,WTPerf_wind,2),yar,WTPerf_Cl(:,WTPerf_wind,4),yar,WTPerf_Cl(:,WTPerf_wind,6),yar,WTPerf_Cl(:,WTPerf_wind,8),yar,WTPerf_Cl(:,WTPerf_wind,10),yar,WTPerf_Cl(:,WTPerf_wind,12), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Cl', 'FontWeight', 'bold')
LABEL(1) = {'Cl vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
grid on

% Cd vs Radial Position
figure(47)
plot(yar,WTPerf_Cd(:,WTPerf_wind,2),yar,WTPerf_Cd(:,WTPerf_wind,4),yar,WTPerf_Cd(:,WTPerf_wind,6),yar,WTPerf_Cd(:,WTPerf_wind,8),yar,WTPerf_Cd(:,WTPerf_wind,10),yar,WTPerf_Cd(:,WTPerf_wind,12), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
ylabel('Cd', 'FontWeight', 'bold')
LABEL(1) = {'Cd vs. Non-Dim. Radial Position'};
title(LABEL, 'FontWeight', 'bold')
legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
grid on

%Displays a graph of Radial Station Local Velocity
figure(48)
plot(yar,WTPerf_LocVel(:,WTPerf_wind,2),yar,WTPerf_LocVel(:,WTPerf_wind,4),yar,WTPerf_LocVel(:,WTPerf_wind,6),yar,WTPerf_LocVel(:,WTPerf_wind,8),yar,WTPerf_LocVel(:,WTPerf_wind,10),yar,WTPerf_LocVel(:,WTPerf_wind,12), 'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Local Velocity (m/s)','FontWeight','bold')
LABEL(1) =('Loc. Velocity vs. Non-Dim. Radial Position');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
grid on

%Displays a graph of Radial Station Rn #
figure(49)
plot(yar,WTPerf_Re(:,WTPerf_wind,2),yar,WTPerf_Re(:,WTPerf_wind,4),yar,WTPerf_Re(:,WTPerf_wind,6),yar,WTPerf_Re(:,WTPerf_wind,8),yar,WTPerf_Re(:,WTPerf_wind,10),yar,WTPerf_Re(:,WTPerf_wind,12),'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Local Reynolds Number','FontWeight','bold')
LABEL(1) =('Loc. Reynolds # vs. Non-Dim. Radial Position');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
grid on

%Displays a graph of Radial Station Induction Ratio (a)
figure(50)
plot(yar,WTPerf_AxialInd(:,WTPerf_wind,2),yar,WTPerf_AxialInd(:,WTPerf_wind,4),yar,WTPerf_AxialInd(:,WTPerf_wind,6),yar,WTPerf_AxialInd(:,WTPerf_wind,8),yar,WTPerf_AxialInd(:,WTPerf_wind,10),yar,WTPerf_AxialInd(:,WTPerf_wind,12),'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Induction Ratio (a)','FontWeight','bold')
LABEL(1) =('Induction Ratio vs. Non-Dim. Radial Position');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
grid on

%Displays a graph of Radial Station Tangential Induction Ratio (a')
figure(51)
plot(yar,WTPerf_TangInd(:,WTPerf_wind,2),yar,WTPerf_TangInd(:,WTPerf_wind,4),yar,WTPerf_TangInd(:,WTPerf_wind,6),yar,WTPerf_TangInd(:,WTPerf_wind,8),yar,WTPerf_TangInd(:,WTPerf_wind,10),yar,WTPerf_TangInd(:,WTPerf_wind,12),'LineWidth', 2)
xlabel('Non-Dim. Radial Position','FontWeight','bold')
ylabel('Tangential Induction Ratio (a prime)','FontWeight','bold')
LABEL(1) =('Tangential Induction Ratio vs. Non-Dim. Radial Position');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
grid on

end

ques3b = input('Do you wish to plot the radial power, torque, and thrust? [Y/N] : ','s');
if isempty(ques3b)
ques3b = 'N';

if ques3b == 'N' || ques3b == 'n'
  %Does nothing and skips plots 8-15
else
  %Executes the Plot functions

  LABEL(5) = cellstr([ 'Windspeed = ', num2str(wspd), ' m/s' ]);  

  %Displays a graph of Coefficient of Thrust (Ct)
  figure(52)
  plot(yar,WTPerf_Ct(:,WTPerf_wind,2),yar,WTPerf_Ct(:,WTPerf_wind,4),yar,
        WTPerf_Ct(:,WTPerf_wind,6),yar,WTPerf_Ct(:,WTPerf_wind,8),yar,WTPerf_Ct
          (:,WTPerf_wind,10),yar,WTPerf_Ct(:,WTPerf_wind,12), 'LineWidth', 2)
  xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
  ylabel('Thrust Coefficient (Ct)', 'FontWeight', 'bold')
  LABEL(1) = { 'Thrust Coefficient vs. Non-Dim. Radial Position' };
  title (LABEL, 'FontWeight', 'bold')
  legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
  grid on

  %Displays a graph of Torque Coefficient (Cq)
  figure(53)
  plot(yar,WTPerf_Cq(:,WTPerf_wind,2),yar,WTPerf_Cq(:,WTPerf_wind,4),yar,
        WTPerf_Cq(:,WTPerf_wind,6),yar,WTPerf_Cq(:,WTPerf_wind,8),yar,WTPerf_Cq
          (:,WTPerf_wind,10),yar,WTPerf_Cq(:,WTPerf_wind,12), 'LineWidth', 2)
  xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
  ylabel('Torque Coefficient (Ct)', 'FontWeight', 'bold')
  LABEL(1) = { 'Torque Coefficient vs. Non-Dim. Radial Position' };
  title (LABEL, 'FontWeight', 'bold')
  legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
  grid on

  %Displays a graph of Power Coefficient (Cp)
  figure(54)
  plot(yar,WTPerf_Cp(:,WTPerf_wind,2),yar,WTPerf_Cp(:,WTPerf_wind,4),yar,
        WTPerf_Cp(:,WTPerf_wind,6),yar,WTPerf_Cp(:,WTPerf_wind,8),yar,WTPerf_Cp
          (:,WTPerf_wind,10),yar,WTPerf_Cp(:,WTPerf_wind,12), 'LineWidth', 2)
  xlabel('Non-Dim. Radial Position', 'FontWeight', 'bold')
  ylabel('Power Coefficient (Cp)', 'FontWeight', 'bold')
  LABEL(1) = { 'Power Coefficient vs. Non-Dim. Radial Position' };
  title (LABEL, 'FontWeight', 'bold')
  legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
  grid on

  %Displays a graph of Power (W)
  figure(55)
  plot(yar,WTPerf_Power(:,WTPerf_wind,2),yar,WTPerf_Power(:,WTPerf_wind,4)
        ),yar,WTPerf_Power(:,WTPerf_wind,6),yar,WTPerf_Power(:,WTPerf_wind,8),y
end

ques3c = input('Do you wish to plot the overall power? [Y/N] : ', 's');
if isempty(ques3c)
    ques3c = 'N';
end

if ques3c == 'N' || ques3c == 'n' %Does nothing and skipps plots 8-15
else
    %Executes the Plot functions

    %Displays a graph of Power vs. Wind
    figure(58)
plot(WTPerf_windspeed,WTPerf_totP(:,2),WTPerf_windspeed,WTPerf_totP(:,4),WTPerf_windspeed,WTPerf_totP(:,6),WTPerf_windspeed,WTPerf_totP(:,8),WTPerf_windspeed,WTPerf_totP(:,10),WTPerf_windspeed,WTPerf_totP(:,12),'LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Power (W)','FontWeight','bold')
LABEL(1) ={['Power vs. Windspeed']};
title (LABEL,'FontWeight','bold')
legend([150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best']);
grid on
xlim([2 15])

figure(59)
plot(WTPerf_windspeed,WTPerf_totCp(:,2),WTPerf_windspeed,WTPerf_totCp(:,4),WTPerf_windspeed,WTPerf_totCp(:,6),WTPerf_windspeed,WTPerf_totCp(:,8),WTPerf_windspeed,WTPerf_totCp(:,10),WTPerf_windspeed,WTPerf_totCp(:,12),'LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Cp','FontWeight','bold')
LABEL(1) ={['Cp vs. Windspeed']};
title (LABEL,'FontWeight','bold')
legend([150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best']);
xlim([2 15])
ylim([0 0.5])
grid on

figure(60)
plot(WTPerf_TSR(:,2),WTPerf_totCp(:,2),WTPerf_TSR(:,4),WTPerf_totCp(:,4),WTPerf_TSR(:,6),WTPerf_totCp(:,6),WTPerf_TSR(:,8),WTPerf_totCp(:,8),WTPerf_TSR(:,10),WTPerf_totCp(:,10),WTPerf_TSR(:,12),WTPerf_totCp(:,12),'LineWidth', 2)
xlabel('Tip Speed Ratio','FontWeight','bold')
ylabel('Cp','FontWeight','bold')
LABEL(1) ={['Cp vs. Tip Speed Ratio']};
title (LABEL,'FontWeight','bold')
legend([150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best']);
xlim([0 20])
grid on

end
ques3d = input('Do you wish to plot the overall thrust? [Y/N] : ','s');
if isempty(ques3d)
    ques3d = 'N';
end

if ques3d =='N' || ques3d =='n' %Does nothing and skipps plots 8-15
    else
%Executes the Plot functions

%Displays a graph of Thrust vs. Windspeed
figure(61)
plot(WTPerf_windspeed,WTPerf_totT(:,2),WTPerf_windspeed,WTPerf_totT(:,4),WTPerf_windspeed,WTPerf_totT(:,6),WTPerf_windspeed,WTPerf_totT(:,8),WTPerf_windspeed,WTPerf_totT(:,10),WTPerf_windspeed,WTPerf_totT(:,12),'LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Thrust (N)','FontWeight','bold')
LABEL(1) =('Thrust vs. Windspeed');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([2 15])
grid on

%Displays a graph of Ct vs. Wind Speed
figure(62)
plot(WTPerf_windspeed,WTPerf_totCt(:,2),WTPerf_windspeed,WTPerf_totCt(:,4),WTPerf_windspeed,WTPerf_totCt(:,6),WTPerf_windspeed,WTPerf_totCt(:,8),WTPerf_windspeed,WTPerf_totCt(:,10),WTPerf_windspeed,WTPerf_totCt(:,12),'LineWidth', 2)
xlabel('Windspeed (m/s)','FontWeight','bold')
ylabel('Ct','FontWeight','bold')
LABEL(1) =('Ct vs. Windspeed');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([2 15])
grid on

%Displays a graph of Ct vs. Tip Speed Ratio
figure(63)
plot(WTPerf_TSR(:,2),WTPerf_totCt(:,2),WTPerf_TSR(:,4),WTPerf_totCt(:,4),WTPerf_TSR(:,6),WTPerf_totCt(:,6),WTPerf_TSR(:,8),WTPerf_totCt(:,8),WTPerf_TSR(:,10),WTPerf_totCt(:,10),WTPerf_TSR(:,12),WTPerf_totCt(:,12),'LineWidth', 2)
xlabel('Tip Speed Ratio','FontWeight','bold')
ylabel('Ct','FontWeight','bold')
LABEL(1) =('Ct vs. Tip Speed Ratio');
title (LABEL,'FontWeight','bold')
legend('150 RPM','250 RPM','350 RPM','450 RPM','550 RPM','650 RPM','Location','Best');
xlim([0 20])
grid on

end
ques3e = input('Do you wish to plot the overall torque? [Y/N] : ', 's');
if isempty(ques3e)
    ques3e = 'N';
end
if ques3e == 'N' || ques3e == 'n'
  %Does nothing and skips plots 8-15
else
  %Executes the Plot functions

  %Displays a graph of Torque vs. Wind Speed
  figure(64)
  plot(WTPerf_windspeed,WTPerf_totQ(:,2),WTPerf_windspeed,WTPerf_totQ(:,4),
       WTPerf_windspeed,WTPerf_totQ(:,6),WTPerf_windspeed,WTPerf_totQ(:,8),
       WTPerf_windspeed,WTPerf_totQ(:,10),WTPerf_windspeed,WTPerf_totQ(:,12),'
LineWidth', 2)
  xlabel('Windspeed (m/s)', 'FontSize', 14, 'FontWeight', 'bold')
  ylabel('Torque', 'FontSize', 14, 'FontWeight', 'bold')
  LABEL(1) = {'Torque vs. Windspeed'};
  title (LABEL, 'FontSize', 16, 'FontWeight', 'bold')
  legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
  xlim([2 15])
  ylim([0 300])
  grid on

  %Displays a graph of Cq vs. Windspeed
  figure(65)
  plot(WTPerf_windspeed,WTPerf_totCq(:,2),WTPerf_windspeed,WTPerf_totCq(:,4),
       WTPerf_windspeed,WTPerf_totCq(:,6),WTPerf_windspeed,WTPerf_totCq(:,8),
       WTPerf_windspeed,WTPerf_totCq(:,10),WTPerf_windspeed,WTPerf_totCq(:,12),'
LineWidth', 2)
  xlabel('Windspeed (m/s)', 'FontSize', 14, 'FontWeight', 'bold')
  ylabel('Cq', 'FontSize', 14, 'FontWeight', 'bold')
  LABEL(1) = {'Cq vs. Windspeed'};
  title (LABEL, 'FontSize', 16, 'FontWeight', 'bold')
  legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
  xlim([2 15])
  ylim([0 0.06])
  grid on

  %Displays a graph of Cq vs. Tip Speed Ratio
  figure(66)
  plot(WTPerf_TSR(:,2),WTPerf_totCq(:,2),WTPerf_TSR(:,4),WTPerf_totCq(:,4),
       WTPerf_TSR(:,6),WTPerf_totCq(:,6),WTPerf_TSR(:,8),WTPerf_totCq(:,8),
       WTPerf_TSR(:,10),WTPerf_totCq(:,10),WTPerf_TSR(:,12),WTPerf_totCq(:,12),'
LineWidth', 2)
  xlabel('Tip Speed Ratio', 'FontSize', 14, 'FontWeight', 'bold')
  ylabel('Cq', 'FontSize', 14, 'FontWeight', 'bold')
  LABEL(1) = {'Cq vs. Tip Speed Ratio'};
  title (LABEL, 'FontSize', 16, 'FontWeight', 'bold')
  legend('150 RPM', '250 RPM', '350 RPM', '450 RPM', '550 RPM', '650 RPM', 'Location', 'Best');
  xlim([0 20])
  ylim([0 0.06])
  grid on
end
end

Plotagain = input('Do you wish to select a new wind speed or RPM and plot again? [Y/N] : ', 's');
if isempty(Plotagain)
    Plotagain = 'N';
end
end

set(0,'DefaultAxesLineStyleOrder','remove')
set(0,'DefaultAxesColorOrder','remove')
Section B.3.3: WT_Perf Read-In Function “WTPerfLoad.m”

```matlab

%filename = 'Data/Test06_SWT_ManuBlades_15.bed'; %for testing
function
fid = fopen(filename,'r');

Segments = 15; %Number of Segments in WTPerf Output
NumWind = 67; %Number of Windspeeds in WTPerf Output
NumRPM = 19; %Number of RPMs in WTPerf Output

%Initialize all values
LocVel = zeros(Segments,NumWind,NumRPM);  
Re = zeros(Segments,NumWind,NumRPM);  
Loss = zeros(Segments,NumWind,NumRPM);  
AxialInd = zeros(Segments,NumWind,NumRPM);  
TangInd = zeros(Segments,NumWind,NumRPM); 
AirflowAng = zeros(Segments,NumWind,NumRPM);  
AlfaD = zeros(Segments,NumWind,NumRPM);  
Cl = zeros(Segments,NumWind,NumRPM);  
Cd = zeros(Segments,NumWind,NumRPM);  
ThrustCo = zeros(Segments,NumWind,NumRPM); 
TorqueCo = zeros(Segments,NumWind,NumRPM);  
PowerCo = zeros(Segments,NumWind,NumRPM);  
ThrustLen = zeros(Segments,NumWind,NumRPM);  
TorqueLen = zeros(Segments,NumWind,NumRPM);  
Power = zeros(Segments,NumWind,NumRPM);  
windspeed = zeros(1,NumWind);  
RPM = zeros(1,NumRPM);  
fseek(fid,0,-1);

RPMcount = 1;  
while RPMcount <= NumRPM 
    windcount = 1;  
    while windcount <= NumWind 
        if RPMcount == 1 && windcount == 1
            dataset = textscan(fid,'%*s %*s %*s %*s %f %*s %*s %*s %*s %*s %*s %f %*s %*s %*s %*s %*s %*s %*s %f %*[\n]', 'headerlines',6);  
        else 
            dataset = textscan(fid,'%*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %f %*s %*s %*s %*s %*s %*s %*s %*s %*s %f %*[\n]');  
        end 
        fseek(fid, 2, 0);
        A = 
        textscan(fid,'%*f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f', 'HeaderLines',2);  
        %Elements = A {1,1};
```
LocVel(:,windcount,RPMcount) = A{1,1};
Re(:,windcount,RPMcount) = A{1,2};
Loss(:,windcount,RPMcount) = A{1,3};
AxialInd(:,windcount,RPMcount) = A{1,4};
TangInd(:,windcount,RPMcount) = A{1,5};
AirflowAng(:,windcount,RPMcount) = A{1,6};
AlfaD(:,windcount,RPMcount) = A{1,7};
Cl(:,windcount,RPMcount) = A{1,8};
Cd(:,windcount,RPMcount) = A{1,9};
ThrustCo(:,windcount,RPMcount) = A{1,10};
TorqueCo(:,windcount,RPMcount) = A{1,11};
PowerCo(:,windcount,RPMcount) = A{1,12};
ThrustLen(:,windcount,RPMcount) = A{1,13};
TorqueLen(:,windcount,RPMcount) = A{1,14};
Power(:,windcount,RPMcount) = A{1,15};

fseek(fid, 2, 0); %Skip to next set of data
if RPMcount == 1
    windspeed (windcount) = dataset{1,2};
end

windcount = windcount + 1;
end

RPM(RPMcount) = dataset{1,1};
RPMcount = RPMcount + 1;
end

fclose(fid);
Appendix C

Airfoil Data

C.1: Wortmann FX 60-126 Airfoil Data

<table>
<thead>
<tr>
<th>Angle of Attack (degrees)</th>
<th>Cl</th>
<th>Cd</th>
<th>Angle of Attack (degrees)</th>
<th>Cl</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>-180</td>
<td>0.962</td>
<td>0.0047</td>
<td>3</td>
<td>0.862</td>
<td>0.011</td>
</tr>
<tr>
<td>-170</td>
<td>0.835</td>
<td>0.0435</td>
<td>4</td>
<td>0.972</td>
<td>0.0113</td>
</tr>
<tr>
<td>-160</td>
<td>0.708</td>
<td>0.1553</td>
<td>5</td>
<td>1.075</td>
<td>0.0113</td>
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<tr>
<td>-150</td>
<td>0.637</td>
<td>0.3265</td>
<td>6</td>
<td>1.184</td>
<td>0.0127</td>
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<td>0.5366</td>
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<td>1.284</td>
<td>0.0151</td>
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<td>-130</td>
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<td>0.9698</td>
<td>8</td>
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<td>0.0192</td>
</tr>
<tr>
<td>-120</td>
<td>0.316</td>
<td>1.1407</td>
<td>9</td>
<td>1.443</td>
<td>0.0254</td>
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<td>0.161</td>
<td>1.2519</td>
<td>10</td>
<td>1.513</td>
<td>0.0343</td>
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<td>0.0447</td>
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<tr>
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<td>-0.452</td>
<td>1.1407</td>
<td>30</td>
<td>1.011</td>
<td>0.3265</td>
</tr>
<tr>
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<td>40</td>
<td>0.91</td>
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<td>0.798</td>
<td>0.76</td>
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<td>0.646</td>
<td>0.9698</td>
</tr>
<tr>
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<td>1.1407</td>
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<td>90</td>
<td>0</td>
<td>1.29</td>
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<td>1.2519</td>
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<td>0.5366</td>
</tr>
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<td>150</td>
<td>-0.708</td>
<td>0.3265</td>
</tr>
<tr>
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<td>0.0106</td>
<td>160</td>
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### C.2: S822 Airfoil Data

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VITA

Thomas Russell Purcell

Thomas R. Purcell
1191 Old Jordan Road
Holland, PA, 18966
trp5030@psu.edu

Education:

Bachelor of Science Degree in Aerospace Engineering, Penn State University, Spring 2011
Honors in Aerospace Engineering
Thesis Title: Blade Element Momentum Theory Applied to Horizontal Axis Wind Turbines
Thesis Supervisor: Dr. Dennis K. McLaughlin
Commissioned as an Ensign in the U.S. Navy via Penn State Naval ROTC, Spring 2011

Awards:

Tweedale Scholarship
Alumni Memorial Scholarship
Richard W. Leonhard Scholarship
National Defense Service Medal
National Sojourner’s Award
President’s Freshman Award
Eagle Scout
Dean’s List
National Honors Society

Activities:

Penn State Naval ROTC
Phi Mu Alpha Sinfonia Fraternity of America
NROTC SpecWar Club
NROTC Run/Swim Club
NROTC Quarterdeck Society
Ski/Snowboard Club