DEVELOPMENT AND VALIDATION OF A WIND GENERATOR
FIELD TESTING METHODOLOGY

A Thesis in
Aerospace Engineering

by

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of the Requirements
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ABSTRACT

The purpose of this study was to develop a wind turbine field testing system with the capability of performing comprehensive power production and rotor aerodynamics studies. Testing was conducted on a 3 kW rated Southwest Windpower Whisper 500 wind turbine located at the Center for Sustainability at Penn State. Measurements include high resolution data acquisition of power and meteorological parameters. Performance of the wind turbine is resolved to 1 second data resolution with comparable results to measurements made at 10 and 60 second blocked averaging intervals. A biasing correction is applied to account for the delay between the wind speed anemometer response and the response of the wind turbine. Experimental performance data are compared to the extensively validated WT_PERF code developed by the National Renewable Energy Laboratory (NREL). WT_Perf computational results predict higher coefficient of power levels than are being shown by experimental data analysis. This discrepancy demonstrates the need to include a more comprehensive electro-mechanical performance model in the computational routine. Experimental results were also compared with the published specifications for the Whisper 500 available on Southwest Windpower’s website. This comparison does show good agreement which validate the power measurement elements of the field testing methodology presented.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF FIGURES</th>
<th>vii</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>xii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xiv</td>
</tr>
</tbody>
</table>

Chapter 1 Introduction ............................................................................. 1
  1.1 Wind Energy Overview ....................................................................... 1
    1.1.1 Wind Energy Growth ..................................................................... 1
    1.1.2 Small Wind Energy Systems ......................................................... 3
  1.2 Project Background ........................................................................... 4
  1.3 Research Scope .................................................................................. 5
  1.4 Research Objectives .......................................................................... 6

Chapter 2 Facilities and Instrumentation .................................................... 8
  2.1 System Overview ................................................................................ 8
  2.2 Wind Turbine .................................................................................... 11
  2.3 Tower Systems .................................................................................. 13
  2.4 Test Site Evaluation ......................................................................... 17
    2.4.1 General Description ................................................................. 17
    2.4.2 Evaluation of Obstructions ......................................................... 20
  2.5 Electrical Systems ............................................................................ 23
    2.5.1 Controller ................................................................................ 24
    2.5.2 Diversion Load (Dump Load) ..................................................... 27
    2.5.3 Battery Bank ............................................................................ 29
    2.5.4 Brake (Emergency Shutdown) ..................................................... 29
    2.5.5 Inverter .................................................................................. 29
  2.6 Data Acquisition Systems .................................................................. 31
    2.6.1 General Overview ................................................................. 31
    2.6.2 NI DAQPad-6020E ................................................................ 31
    2.6.3 Power Measurement System (Voltage and Current Transducer’s) .... 32
    2.6.4 Meteorological Measurement System ....................................... 36
    2.6.5 LabVIEW Program (“Wind_Turbine_Acquisition.vi”) ............... 37

Chapter 3 Experimental Methods and Calculations .................................... 40
  3.1 Experimentation Overview ............................................................. 40
  3.2 Electrical System Measurement .................................................... 41
    3.2.1 Turbine Voltage and Current .................................................. 42
    3.2.2 Three Phase Circuits and Turbine Power .................................. 43
    3.2.3 Turbine RPM ........................................................................ 45
    3.2.4 Turbine Thrust and Torque ..................................................... 47
  3.3 Meteorological Measurements ....................................................... 49
Appendix A  Full Schematic of the Data Acquisition System .......................................................... 133
Appendix B  CAD Drawing of the Whisper 5009 Blade ................................................................. 134
Appendix C  Tower Information: Loads and Procedures ................................................................. 135
Appendix D  Inverter User Instructions ........................................................................................... 139
Appendix E  Voltage Transducer Wiring Diagram ........................................................................... 144
Appendix F  LabVIEW Codes .......................................................................................................... 145
  Wind_Turbine_Acquisition.vi ........................................................................................................... 145
  Wind_Turbine Calculations.vi .......................................................................................................... 147
Appendix G  Wind Direction Vane Specifications and Algorithm ..................................................... 148
Appendix H  Example Weather Data Input File ................................................................................. 150
Appendix I  MATLAB Codes ............................................................................................................ 151
  WT_realtimproc.m ...................................................................................................................... 151
  vane2angle.m ............................................................................................................................ 161
  WT_processing_7.m ................................................................................................................... 162
Appendix J  Wortmann Airfoil Information ....................................................................................... 170
Appendix K  WT_Perf Simulation Input Parameters ......................................................................... 173
LIST OF FIGURES

Figure 1-1. Non-US and US Capacity with Proportion of Annual Wind Energy Growth Since 1982.................................................................2

Figure 1-2. U.S. Department of Energy 20% by 2030 Wind Energy Scenario ...............3

Figure 2-1. View of Whisper Wind Turbine Test Site........................................8
Figure 2-2. Southwest Windpower Whisper 500 Hybrid Energy System Schematic..........9
Figure 2-3. Data Acquisition Monitoring and Signal Analysis Equipment ..................10
Figure 2-4. Published Whisper 500 Power Curve...........................................12
Figure 2-5. Published Whisper 500 Energy Curve ..........................................12
Figure 2-6. Notation Schematic for Tower System ........................................14
Figure 2-7. Schematic of System to Raise / Lower Tower ................................15
Figure 2-8. Tower Raise and Lower Loads Analysis Schematic and Nomenclature .........16
Figure 2-9. Tower Raise and Lower Loads Analysis ........................................16
Figure 2-10. View of test turbine toward 290° wind direction ................................18
Figure 2-11. Plot of Test Site Elevation Survey (Blue lines are 5’ elevation contours) ....19
Figure 2-12. Plot for Tree Obstructions for Evaluation ....................................21
Figure 2-13. Schematic for Zone of Disturbed Flow around an Obstruction (11) .........22
Figure 2-14. Diagram of Whisper 500 Electrical System ..................................23
Figure 2-15. EZ-Wire Charge Controller Wiring Schematic ................................25
Figure 2-16. Photo of EZ-Wire Charge Controller Circuitry ................................25
Figure 2-17. Diversion Load Default Resistor Configuration for 24V Battery Bank ....27
Figure 2-18. Photo of Whisper 500 Diversion Load ........................................28
Figure 2-19. Photo of Controller and Inverter Equipment ..................................30
Figure 2-20. Photo of Data Acquisition Setup ..............................................Error! Bookmark not defined.
Figure 2-21. Power Measurement System 17-Pin Connector Signal Configuration ..........32
Figure 2-22. Power Measurement System Block Diagram.........................................33
Figure 2-23. DC Current Sensor Signal: Baseline (Top) and While Diverting (Bottom) ....35
Figure 2-24. Meteorological Measurement System Block Diagram ..........................37
Figure 2-25. LabVIEW Program "Wind_Turbine_Acquistion.vi" Block Diagram ..........38
Figure 2-26. "Wind_Turbine_Acquistion.vi" Front Panel ........................................38
Figure 3-1. Three-Phase Delta Wiring Diagram ..........................................................42
Figure 3-2. Three-Phase AC Voltage Fluctuation .......................................................42
Figure 3-3. Delta Connection Configuration ..............................................................44
Figure 3-4. Turbine generator output voltage signal with rotational pulses (2 pulses/rev) ....46
Figure 3-5. Anemometer locations for Whisper 500 Test Site ....................................51
Figure 3-6. Calibration of AC Anemometer in the wind tunnel ...................................52
Figure 3-7. Calibration results for AC anemometer ......................................................52
Figure 3-8. Calibration of Inspeed Vortex Anemometer A ..........................................53
Figure 3-9. Inspeed E-Vane Wind Direction Sensor ..................................................54
Figure 3-10. Biasing Effect with Binning \(^{(13)}\) .........................................................63
Figure 3-11. Bias Correction for 30 s Data \(^{(13)}\) ........................................................65
Figure 3-12. Bias Correction for 10 min Data \(^{(13)}\) .....................................................65
Figure 3-13. WT_realtimeproc.m Block Diagram ......................................................70
Figure 3-14. WT_processing_7.m Block Diagram ....................................................72
Figure 4-1. Energy Extracting Actuator Disc and Stream-tube .................................73
Figure 4-2. Blade Element Theory and an Annular Ring \(^{(13)}\) .......................................78
Figure 4-3. Blade Element Velocities and Forces \(^{(13)}\) ...............................................78
Figure 4-4. Assumed Linear Variation of Loading for BEMT Model ..........................81
Figure 4-5. Comparison of Theoretical and Measured Values of Thrust Coefficient \(^{(13)}\) ....82
Figure 4-6. Qualitative comparison of two different designs .................................................. 86
Figure 4-7. Variation of Blade Geometry Parameter with Local Speed Ratio \(^{13}\) .................... 87
Figure 4-8. Variation of Inflow Angle with Local Speed Ratio \(^{13}\) ........................................ 87
Figure 5-1. Whisper 500 and Betz Optimum Rotor Chord Distribution .................................. 89
Figure 5-2. Whisper 500 and Betz Optimum Rotor Local Inclination (\(\beta\)) Distribution ............ 90
Figure 5-3. Shape of Wortmann FX 60-126 Airfoil ................................................................. 90
Figure 5-4. Estimated alternator efficiency data derived from XL.1 alternator experiments .......................................................... 93
Figure 5-5. Turbine power vs. free stream wind speed using WT_Perf and Manufacturer's data ............................................................ 94
Figure 5-6. Turbine Coefficient of Power vs. Wind Speed using WT_Perf ................................. 95
Figure 5-7. Turbine Coefficient of Power vs. Wind Speed using WT_Perf Compared against the Manufacturer Specs \(^{8}\) ................................................................. 96
Figure 5-8. Turbine Coefficient of Power vs. Tip-Speed Ratio using WT_Perf ......................... 97
Figure 5-9. Turbine Thrust vs. Wind Speed using WT_Perf ...................................................... 98
Figure 5-10. Turbine Coefficient of Thrust vs. Wind Speed using WT_Perf ............................. 99
Figure 5-11. Turbine Coefficient of Thrust vs. Tip-Speed Ratio using WT_Perf ....................... 100
Figure 6-1. 1-Second Averaged Data Histogram ..................................................................... 102
Figure 6-2. 1-Second Averaged Data Wind Rose ................................................................. 103
Figure 6-3. Turbine power output versus RPM ..................................................................... 104
Figure 6-4. Turbine power output versus RPM for Diverted and non-Diverted loading conditions .......................................................................................... 105
Figure 6-5. 1-Second Bin Averaged Turbine Power Output versus Rotor RPM .................... 106
Figure 6-6. Raw rotor RPM vs. wind speed data ..................................................................... 106
Figure 6-7. Ensemble averaged rotor RPM vs. wind speed data ........................................... 107
Figure 6-8. Raw electrical power vs. wind speed data (1-second averaging) ........................ 108
Figure 6-9. Raw electrical power vs. wind speed data (60-second averaging) ....................... 109
Figure 6-10. Measured and corrected power curves for 1 sec averaging interval data........110
Figure 6-11. Measured and corrected power curves for 10 sec averaging interval data........111
Figure 6-12. Measured and corrected power curves for 60 sec averaging interval data........111
Figure 6-13. Average coefficient of power versus binned wind speed............................112
Figure 6-14. Average coefficient of power and wind speed versus tip-speed ratio..............113
Figure 6-15. Average rotor torque versus binned wind speed ...........................................114
Figure 6-16. 1-D momentum theory axial induction factors versus binned wind speed .......115
Figure 6-17. Average rotor thrust versus binned wind speed ............................................116
Figure 6-18. Average thrust coefficient versus binned wind speed .................................117
Figure 7-1. Comparison of measured and predicted electric power coefficient for the Whisper 500..................................................................................................................................................119
Figure 7-2. Average coefficient of power versus tip-speed ratio compared with WT_Perf data..........................................................................................................................................................120
Figure 7-3. Average turbine thrust versus binned wind speed compared with WT_Perf data..................................................................................................................................................122
# LIST OF TABLES

Table 1. Whisper Turbine Specifications ................................................................. 12
Table 2. Parameters for Obstructions Close to the Whisper Wind Turbine ................. 21
Table 3. Uncertainty Components \(^{(13)}\) .................................................................. 66
Table 4. Uncertainty in Power Performance Measurements ..................................... 67
Table 5. Inspeed E-Vane Specifications .................................................................... 148
### NOMENCLATURE

- $a$: axial flow induction factor
- $a'$: tangential flow induction factor
- $A, A_D$: rotor swept area
- $A_U, A_W$: upstream and downstream stream-tube cross-sectional areas
- $c$: blade chord; Weibull scale parameter
- $C_d$: sectional drag coefficient
- $C_f$: sectional force coefficient (i.e., $C_d$ or $C_l$ as appropriate)
- $C_l$: sectional lift coefficient
- $C_p$: pressure coefficient
- $C_T$: thrust coefficient
- $C_x$: coefficient of sectional blade element force normal to the rotor plane
- $C_y$: coefficient of sectional blade element force parallel to the rotor plane
- $D$: drag force; rotor diameter
- $E$: energy capture, i.e., energy generated by turbine over defined time period
- $f$: tip loss factor
- $f_m$: measured frequency of the turbine AC electrical signal
- $F$: force
- $F_x$: force in $x$ (downwind) direction
- $F_y$: force in $y$ direction
- $F(\mu)$: function determining the radial distribution of induced velocity normal to the plane of the rotor
- $h$: height of atmospheric boundary layer
- $H$: hub height
- $I$: current
- $I_l$: line current
- $I_p$: phase current
- $k$: shape parameter for Weibull function
- $K_p$: power coefficient based on tip speed
- $L$: lift force
- $m$: mass per unit length
- $N$: number of blades
- $p$: static pressure
- $P$: aerodynamic power; electrical real (active) power
- $P_T$: number of alternator poles or magnets
- $Q$: rotor torque; electrical reactive power
- $r$: radius of blade element or point on blade; correlation coefficient
- $r'$: radius of point on blade
- $R$: blade tip radius; electrical resistance
- $S$: electrical complex (apparent) power
- $T$: rotor thrust
- $t$: time (sec)
- $U_\infty$: free stream velocity
- $U, U(t)$: instantaneous wind speed in the along-wind direction
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$\bar{U}$</td>
<td>mean component of wind speed in the along-wind direction – typically taken over a period of 10 min or 1 hr</td>
</tr>
<tr>
<td>$U_{ave}$</td>
<td>annual average wind speed at hub height</td>
</tr>
<tr>
<td>$U_d$</td>
<td>streamwise velocity at the rotor disc</td>
</tr>
<tr>
<td>$U_w$</td>
<td>streamwise velocity in the far wake</td>
</tr>
<tr>
<td>$U_{ref}$</td>
<td>reference wind speed defined as 10 min mean wind speed at hub height with 50 year return period</td>
</tr>
<tr>
<td>$V$</td>
<td>longitudinal air velocity at rotor disc, $U_\infty(1-\alpha)$; voltage</td>
</tr>
<tr>
<td>$VA$</td>
<td>electrical volt-amperes</td>
</tr>
<tr>
<td>$V_l$</td>
<td>line voltage</td>
</tr>
<tr>
<td>$V_m$</td>
<td>amplitude of fluctuation for AC electrical signal</td>
</tr>
<tr>
<td>$V_p$</td>
<td>phase voltage</td>
</tr>
<tr>
<td>$V_t$</td>
<td>blade tip speed</td>
</tr>
<tr>
<td>$W$</td>
<td>wind velocity relative to a point on a rotating blade</td>
</tr>
<tr>
<td>$X$</td>
<td>electrical inductive reactance</td>
</tr>
<tr>
<td>$Z$</td>
<td>electrical impedance</td>
</tr>
<tr>
<td>$z_o$</td>
<td>ground roughness length</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>angle of attack – i.e., angle between air flow incident on the blade and the blade chord line; wind-shear power law exponent</td>
</tr>
<tr>
<td>$\beta$</td>
<td>inclination of local blade chord to rotor plane (i.e., blade twist plus pitch angle, if any)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>flow angle of resultant velocity $W$ to rotor plane</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>tip speed ratio</td>
</tr>
<tr>
<td>$\lambda_t$</td>
<td>tangential speed of blade element at radius $r$ divided by wind speed: local speed ratio</td>
</tr>
<tr>
<td>$\mu$</td>
<td>non-dimensional radial position, $r/R$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>phase angle between voltage and current of AC electrical signal</td>
</tr>
<tr>
<td>$\rho$</td>
<td>air density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>blade solidity</td>
</tr>
<tr>
<td>$\sigma_r$</td>
<td>rotor solidity</td>
</tr>
<tr>
<td>$\omega$</td>
<td>angular frequency (rad/s)</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>rotational speed or rotor</td>
</tr>
<tr>
<td>$\psi$</td>
<td>blade azimuth</td>
</tr>
</tbody>
</table>
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I would like to thank my thesis advisor, Dr. Dennis McLaughlin, for giving me the opportunity to work with him and for providing his guidance and experience on this research.

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Chapter 1

Introduction

The purpose of this study was to develop a wind turbine field testing data analysis methodology which demonstrates data fidelity comparable to current industry practices and which abides by established testing standards. Experiments have been performed on a 3 kW Southwest Windpower Whisper 500 residential-scale wind turbine. This study develops the basic measurement capabilities required to perform advanced wind energy systems research which could allow these technologies to contribute a more significant portion of the world's future energy needs.

1.1 Wind Energy Overview

Wind Energy has become a leading renewable energy source around the world. The success of wind energy is related to the fact that it is free of emissions and water usage, is to some extent available in every nation, has low environmental impact, and has an existing technology and production infrastructure.

1.1.1 Wind Energy Growth

The wind energy sector has seen significant growth worldwide since the mid 90’s. As seen in Figure 1-1, in the infancy of wind energy development, the United States was the most significant contributor to worldwide annual growth in the wind energy sector. This contribution was primarily spurred by high oil prices in the early to mid 80’s and ended as soon as oil prices
stabilized in the early 90’s. Development overseas, and in particular in the European Union, has continued through today and therefore the United State has to this point, not been a significant player in worldwide wind energy production.

Even with limited growth, the U.S. Department of Energy statistics have shown that over 30,000 megawatts (MW) of wind energy capacity has been installed in the United States. This brings the United States proportion of worldwide cumulative capacity to just over 15%. The wind energy industry has demonstrated its potential to be a long-standing part of the energy sector. The U.S. Department of Energy has recognized this potential when it released its “20% Wind Energy by 2030” report in July 2008 \(^{(1)}\). The 20% by 2030 scenario, shown in Figure 1-2, shows that to keep up with projected growth the United States wind energy sector must undergo large and sustained growth throughout the next two decades.

![Figure 1-1. Non-US and US Capacity with Proportion of Annual Wind Energy Growth Since 1982](image-url)
1.1.2 Small Wind Energy Systems

Portions of the projected growth by 2030 will include applications which range in size from residential scale machines of 1 kW all the way up to arrays of large 3 MW machines. Though much of the projected growth in wind energy capacity will come from the deployment of large wind systems an important amount can be provided by the average home owner by the small wind sector. From 2006 through 2009, the small wind energy industry has shown significant growth. As of 2009, approximately 20,000 kW of worldwide installed wind energy capacity can be contributed to the small wind energy (0 – 100 kW systems) industry. \(^2\) This growth, even though modest when compared with large wind system capacity, shows that small wind electric systems have been an increasingly competitive solution to residential and community energy needs. Small wind systems have shown a cost or energy of $0.10$-$0.15$ / kWh compared to $0.15$ /kWh for photovoltaics and approximately $0.10$ /kWh for natural gas
fired power plants.\(^{(2)}\) The cost competitiveness of small wind systems makes increasingly more economic sense in areas where the wind resource is more readily available.

Small wind systems are typically deployed in residential, small business, agricultural, and industrial applications. Aside from their rated power output, the most obvious attributes which distinguish small wind systems from large wind systems are their smaller rotor diameters and tower heights as well as their lower system capital costs. These systems are typically found in capacities ranging from 1 kW to 50 kW with 2 to 7 meter rotor diameters and can have tower heights in excess of 30 meters. It is important to note that hybrid small wind and solar power hybrid systems have shown to be particularly successful and promise to play a role in the future of home power for those who live in areas where renewable wind and solar resources are abundant.

1.2 Project Background

The Pennsylvania State University Department of Aerospace Engineering has made it a goal since 2008 to become increasingly involved in Wind Energy research and workforce development. It is believed that contribution in this field at this time will provide the technological advances and educated workforce required to achieve the 20% Wind Energy by 2030 scenario set forth by the U.S. Department of Energy. The Southwest Windpower Whisper 500 wind electric system discussed in this paper has been used for educational, research, and outreach initiatives at Penn State.

The Whisper 500 small wind research facility is part of the Penn State Center for Sustainability as well as the newly established Pennsylvania Wind Applications Center at Penn State. Since the installation of the wind-electric system on the Center for Sustainability at Penn State in 2005, it has been used as:
• A supporting energy system for the Center for Sustainability homestead research program.

• A hands-on learning tool for undergraduate and graduate Aerospace Engineering, Mechanical Engineering, Energy Engineering, and Architectural Engineering students through the Department of Aerospace Engineering, Department of Architectural Engineering, and Applied Research Laboratory at Penn State.

• A research facility for the study of wind turbine aerodynamic and electro-mechanical performance.

The primary goal for the facility is to develop it into a full-time research platform for wind turbine performance analysis and testing by the Department of Aerospace Engineering. The current facility employs an instrumentation and control system which allows for the measurement of wind turbine performance, tower vibrations, turbine loads, and atmospheric conditions data. These measurements are used in a variety of ways for educational and research projects.

1.3 Research Scope

The study of small wind energy system performance has been underway for many years at professional and educational institutions. Specific research on small wind electro-mechanical performance has been performed by several institutions, many of which are used as references to the development of the testing methodologies presented in this paper. These include but are not limited to Clarkson University\(^3\), University of California, Davis\(^4\), The Center for Energy Studies in Monterrey, Mexico\(^5\), and the National Renewable Energy Laboratory (NREL)\(^6\). Research into the mechanical loads of small wind turbines has also been performed by the National Wind Technology Center (NWTC) and NREL\(^7\). System data from wind turbine
manufacturers, specifically Southwest Windpower\(^{(8)}\), is also used as a reference for the included experiments.

Each of the mentioned researchers performed experiments dealing with small wind-electric systems. The focus of this paper is to accumulate details regarding the methods from each research initiative cited and develop a data acquisition and processing methodology best suited to improve data fidelity and allow for continued development of the Penn State small wind field testing facility. The included discussion of results will address (1) the use of computational models to predict system performance, (2) the methodology to acquire electro-mechanical system performance, and (3) the methodology to process data with high fidelity results.

Particular attention is paid during the development of data acquisition and processing methodologies to ensure that both the International Electrotechnical Committee (IEC) standards IEC 61400-12-1\(^{(9)}\), for power performance data, and IEC 61400-13\(^{(10)}\), for mechanical loads data, were followed.

Results of this study show reasonable correlation to the manufacturer published power performance data. Differences can be found between experimental power and thrust data from the wind turbine and computational predictions made by the NREL blade element momentum theory based performance prediction code WT_Perf. These differences are discussed in detail and suggestions for facility measurement and code prediction improvements are made.

1.4 Research Objectives

The contributions to the field of small wind energy resulting from this study are in several areas. These include:

1. The study of the Whisper 500 wind turbines electrical power and coefficient of power performance which are compared against available manufacturer data and
computational predictions. Preliminary results with regard to turbine rotor thrust
and coefficient of thrust are also examined.

2. Development of data acquisition hardware and software systems necessary for
advanced wind energy system performance assessment.

3. Implementation and validation of novel data processing and interpretation
techniques. This includes the validation of a correction technique which allows
for higher data acquisition rates and therefore lower testing time required to
resolve a wind-electric systems performance curve.
Chapter 2

Facilities and Instrumentation

This chapter will describe the equipment used in the experiments conducted on the Southwest Windpower Whisper 500 located at the Center for Sustainability. A general overview of the small wind generator system is included. Detailed documentation of the electrical, meteorological, tower and data acquisition sub-systems are also presented. An evaluation of the test site obstructions and terrain is made according to International Electrotechnical Commission (IEC) standards.

2.1 System Overview

The Whisper 500 wind system located on the Center for Sustainability at Penn State is shown in Figure 2-1.

Figure 2-1. View of Whisper Wind Turbine Test Site
The system has been configured as an off-grid battery charge system. The Whisper 500 EZ-wire controller is capable of being wired with solar power systems to run as a hybrid renewable energy controller. Figure 2-2 shows a schematic of the basic system configuration recommended by the manufacturer.

Figure 2-2. Southwest Windpower Whisper 500 Hybrid Energy System Schematic

The test site configuration is that of a standalone off-grid system that has been slightly modified for demonstration and experimental purposes. This particular system consists of the 3-kW wind turbine, turbine tower, meteorological instrumentation, a system brake, charge controller, dump (diversion) load, inverter for AC power, and a data acquisition system. The loading source requiring the inverter is the data acquisition system and support instrumentation.

Power performance measurements for wind systems require that both wind speed and power output be measured simultaneously. Because of this wind speed and wind direction
sensors are also installed at the site in positions that do not interfere with the wind turbine performance and allows for the most accurate representation of the wind resource at the time of power measurements.

For monitoring both the turbine and meteorological metrics at the time of testing, a data acquisition system was developed to connect to a laptop computer, with the purpose of enabling researchers to get both real-time feedback on system performance and acquire data for analysis off-site. The computer and data acquisition equipment are shown in Figure 2-3. In the future these systems will be moved to a more permanent indoor facility close to the wind turbine site. A full schematic of the testing system is presented in Appendix A.
2.2 Wind Turbine

The Whisper 500 wind turbine was purchased originally by the Penn State University Center for Sustainability to provide power for a small sustainable dwelling. After the magnets in the rotor became chipped, the turbine was given over to the Aerospace Engineering department for refurbishment. During the spring of 2009, the generator was lowered, the rotor was replaced, and the controller was refurbished. The generator was then raised, and performance testing has been continued on and off for about 1 year.

At the present, the wind turbine facility consists of a Whisper 500 3 kW turbine whose specifications are listed in Table 1. The generator charges a battery bank that is made up of two 12-volt batteries whose level of charge is regulated by a controller. The Whisper 500 has a maximum power output of 3 kW at a wind speed of 24 mph, but power production starts at the cut-in wind speed of 7.5 mph. The turbine is protected from damage caused by excessively high winds with a side-furling mechanism. Furling begins at a wind speed of 27 mph. The manufacturer claims that the turbine system has a maximum survival wind speed of 120 mph.

The generator weighs approximately 155 lbs that interfaces to two bolt-on, fiberglass-reinforced blades. Attached to the generator is a tail assembly that keeps the generator facing into the prevailing winds. The generator, blades, and tail assembly are mounted on a 30 ft tilt-up tower supported by four guy-wires. This tower allows for the generator to be lowered and removed for maintenance and repairs. The adjustable guy-wires are secured to the ground via four concrete pads, and the controller and dump load are mounted to a small tower that is located on one of the concrete pads.
Table 1. Whisper Turbine Specifications

<table>
<thead>
<tr>
<th>General Configuration:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Make, Model</td>
<td>Southwest Windpower, Whisper 500</td>
</tr>
<tr>
<td>Rotation Axis (H/V)</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Orientation (upwind/downwind)</td>
<td>Upwind</td>
</tr>
<tr>
<td>Number of Blades</td>
<td>2</td>
</tr>
<tr>
<td>Rotor Hub Type</td>
<td>Rigid</td>
</tr>
<tr>
<td>Rotor Diameter (ft)</td>
<td>15</td>
</tr>
<tr>
<td>Hub Height (ft)</td>
<td>31</td>
</tr>
<tr>
<td>Performance:</td>
<td></td>
</tr>
<tr>
<td>Rated Electrical Power (kW)</td>
<td>3</td>
</tr>
<tr>
<td>Rated Wind Speed (mph)</td>
<td>27</td>
</tr>
<tr>
<td>Cut-In Wind Speed (mph)</td>
<td>7.5</td>
</tr>
<tr>
<td>Furling Wind Speed (mph)</td>
<td>27</td>
</tr>
<tr>
<td>Rotor:</td>
<td></td>
</tr>
<tr>
<td>Swept Area (ft^2)</td>
<td>175</td>
</tr>
<tr>
<td>Blade Pitch Control</td>
<td>None</td>
</tr>
<tr>
<td>Direction of Rotation</td>
<td>Clockwise</td>
</tr>
<tr>
<td>Rotor Speed (rpm)</td>
<td>0-500</td>
</tr>
<tr>
<td>Power Regulation (active or passive)</td>
<td>Passive</td>
</tr>
<tr>
<td>Tower:</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Tilt-Up Guy-wired</td>
</tr>
<tr>
<td>Height (ft)</td>
<td>30</td>
</tr>
<tr>
<td>Control / Electrical System:</td>
<td></td>
</tr>
<tr>
<td>Controller: Make, Type</td>
<td>Southwest, Solar Hybrid Controller</td>
</tr>
<tr>
<td>Electrical Output Voltage</td>
<td>24VDC</td>
</tr>
<tr>
<td>Yaw System:</td>
<td></td>
</tr>
<tr>
<td>Wind Direction Sensor</td>
<td>Tail Vane</td>
</tr>
</tbody>
</table>

Figure 2-4. Published Whisper 500 Power Curve  
Figure 2-5. Published Whisper 500 Energy Curve
The blades for the Whisper 500 were analyzed and mapped in-lab to obtain the airfoil type, span wise twist, the root pitch angle, and the chord distribution. These data were used for input to the blade element momentum theory predictions for the wind turbines performance. It was determined that the airfoil shape for the blade can be best approximated by a Wortmann FX60-126. The performance characteristics for this airfoil as well as the blade chord and twist distributions are presented later in Chapter 5. Full CAD dimensional drawings for the blade are included in Appendix B.

The wind turbine produces power with an 8 pole pair, permanent magnet, asynchronous alternator which is directly coupled to the turbine rotor. The turbine alternator outputs a “wild” variable frequency three-phase alternating current electrical signal. The frequency and amplitude of the varying signals are proportional to the rotational speed of the wind turbine. The three-phase electrical output is sent down tower, via a brush plate at the yaw joint, to the charge controller which rectifies the signal to DC for distribution to either the battery bank or the diversion load.

The Whisper 500 is equipped with an over-speed mechanism designed to protect the turbine’s mechanical and electrical components during high wind events. The mechanism is referred to as auto-furling and functions by turning the turbine rotor away from the incoming wind. Manufacturer specifications indicate that the rotor will furl in a 27 mph wind but continue to peak power extraction of 3 kW just beyond the furling speed.

2.3 Tower Systems

The tower system for the Whisper 500 wind turbine is a standard tubular steel tilt-up tower. The structure for the tower consists of two 5” schedule 40 tubular steel sections which are 9’ and 21’ in length. The advantage to using a tilt-up tower is that maintenance is made easier
since the tower can be lowered without a crane or personnel to climb the tower. A schematic of the tower system is shown in Figure 2-6.

![Diagram of tower system]

Figure 2-6. Notation Schematic for Tower System

The purpose for the gin pole is that it gives a mechanical advantage while raising and lowering the tower structure. While lowering the tower, personnel will detach the raise / lower guy wire from the raise / lower anchor and reattach the wire to the anchor end of the gin pole. When attaching a system of chains (tower lift line) from the anchor end of the gin pole to the raise / lower anchor, less force is required to now lower the entire system away from the lift /
raise anchor. When the main tower lower’s to the ground, the gin pole will be straight up in the air while being supported by three gin pole guy wires. Also, the tower lift line which was attached between the gin pole and the raise / lower anchor should also remain in place for additional support for the gin pole.

![Figure 2-7. Schematic of System to Raise / Lower Tower](image)

Since the terrain at the site is not conducive to vehicle access or heavy machinery to pull the lift line an alternative chain-system method was used. In order to size chains and linkages correctly a thorough analysis of the lifting line forces had to be completed. Figure 2-8 establishes the nomenclature for the analysis; the tower loads analysis spreadsheet is presented in Appendix C. Figure 2-9 shows the expected loads in the lifting line cable as a function of angle of the main tower with respect to the ground.
From these results it was determined that the lift line chains and linkages should be sized for at least a factor of safety above a 1000 lbs load. If guy wires are ever replaced they should be sized for the same loading requirement as the lifting line. For the standard tower supplied by the manufacturer, 5/16” steel guy wire was used which is rated for approximately 8,000 lbs. The
procedure for raising and lowering the tower complete with equipment inventory is in Appendix C. Additional information regarding the wind turbine bolt pattern, list of components, maintenance requirements, and footing construction can be found in the user’s manual on the Southwest Windpower website.

2.4 Test Site Evaluation

The sitting of the Southwest Windpower Whisper 500 is evaluated in this section. Sitting of a wind energy system is the single most important contributor to whether or not the system will maximize its capable performance. Care should be taken to ensure that the system is high enough above nearby obstructions and that local ordinances for wind energy system construction are followed.

2.4.1 General Description

The Southwest Windpower Whisper 500 under test is located on the Center for Sustainability at Penn State, approximately 1.5 miles northeast of State College, Pennsylvania. The site is located in very complex terrain at an approximate elevation of 1050 ft. above sea level. Figure 2-10 shows a picture of the turbine toward the prevailing wind direction of 290°. Figure 2-11 shows a test site survey with topography lines listed in feet above sea level.
Figure 2-10. View of test turbine toward 290° wind direction
Figure 2-11. Plot of Test Site Elevation Survey (Blue lines are 5° elevation contours)
2.4.2 Evaluation of Obstructions

The IEC standard has adopted the expression “measurement sector” to define wind directions which can be included in power performance measurements. As part of the initial stages of this research it should be a goal to establish an adequate measurement sector for the test site under discussion. Since data could not be constantly acquired at the test site, only days which had higher than normal average winds (predominantly from the prevailing wind direction) were chosen for the analysis. Using these data and future site calibrations, the measurement sector can be established to avoid wind directions where terrain and obstacles affect the wind.

The first step toward defining the measurement sector for this study is to consider historical interpretations of the test site. This is best done with wind direction data when available. Since localized wind direction data were not available the prevailing wind direction of 290° was chosen based off of experience at the site from both the Center for Sustainability and personnel working on developing the test site. Winds have been found to come from this direction most readily during the dominant wind season, normally lasting from October to March.

The next step is to analyze the site is to estimate the wakes from obstructions. The measurement sector should avoid wake effects on the turbine and the meteorological tower. Observation and measurements at the test site show that the predominant wake obstructions at the site are the multiple tree lines located on the Center for Sustainability property. Figure 2-12 shows the most relevant obstructions in proximity of the wind turbine. Table 2 lists the positions and characteristics of these obstructions.
Table 2. Parameters for Obstructions Close to the Whisper Wind Turbine

<table>
<thead>
<tr>
<th>Obstruction</th>
<th>Height (m)</th>
<th>Distance (m)</th>
<th>Diameters</th>
<th>Bearing</th>
<th>Relative to:</th>
<th>Sector Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree (Obs. 1)</td>
<td>12</td>
<td>20</td>
<td>4.5</td>
<td>355°</td>
<td>Test Turbine</td>
<td>330°</td>
<td>30°</td>
</tr>
<tr>
<td>Tree (Obs. 2)</td>
<td>9</td>
<td>22</td>
<td>4.8</td>
<td>310°</td>
<td>Test Turbine</td>
<td>295°</td>
<td>325°</td>
</tr>
<tr>
<td>Tree (Obs. 3)</td>
<td>6</td>
<td>33</td>
<td>7.3</td>
<td>290°</td>
<td>Test Turbine</td>
<td>265°</td>
<td>275°</td>
</tr>
<tr>
<td>Tree line (Obs. 4)</td>
<td>12</td>
<td>34</td>
<td>7.5</td>
<td>165°</td>
<td>Test Turbine</td>
<td>150°</td>
<td>225°</td>
</tr>
</tbody>
</table>

Based on the obstruction analysis outlined above it becomes clear that the test turbine is poorly sited given its 30 foot (9 m) tower height. Distances between the test turbine and obstructions are non-dimensionally quantified via diameters of the wind turbine rotor (4.5 m). Locations of the anemometer locations are noted as items A through D in Figure 2-12. The locations of these stations are also non-dimensionally quantified via rotor diameters distance.
away from the wind turbine. Wake regions have been shown in external studies to exist downstream of obstructions as much as 20 times the objects height (See Figure 2-13)\(^{(11)}\). It is also common to find that the disturbed flow region can be present at 2 times the height of the object at some locations downwind of the obstruction.

![Figure 2-13. Schematic for Zone of Disturbed Flow around an Obstruction\(^{(11)}\)](image)

In order to avoid operating the wind turbine within the wake region of obstructions it would be necessary to extend the tower. With the existing shorter tower, it proves difficult to establish a measurement sector which satisfies clearance requirements for performance testing. It was therefore decided that a “preliminary measurement sector” would be established so to capture the most amount of wind resource and avoid the most intrusive obstacles. Based on these findings and limited observations of the most probably prevailing wind direction, a preliminary measurement sector of 210° to 300° bearing relative to the wind turbine was chosen. On days in which experimental data were recorded, time segments in which the wind direction varied from this segment were set aside from the data processing.
2.5 Electrical Systems

The Whisper 500 wind turbine test facility at the Center for Sustainability operates as an off-grid wind electric system. Off-grid wind-electric systems are battery based and are typically chosen because the load center (e.g., House) is not connected to the grid, and connection could be expensive. An off-grid system is limited in capacity by the size of the generating sources (wind turbine, solar-electric, fuel-fired generator, etc.), the resource available, and the battery bank size. Off-grid load centers must be adapted to the limitations of the system capacity. A schematic of the Whisper 500 test facility electrical system is presented in Figure 2-14.

![Diagram of Whisper 500 Electrical System](image)

Figure 2-14. Diagram of Whisper 500 Electrical System

The power signal routed down the tower from the wind generator is “wild” 3-Phase AC. “Wild” power signals are called such since they vary in both frequency and amplitude. The AC signal is monitored and rectified to DC power by the charge controller. A charge controller’s primary function in the system is to protect the battery bank from becoming overcharged. If the controller detects that the battery bank is fully charged then power is diverted to the dump load
(resistor bank) and dissipated as heat. Controlled AC power is then maintained by the system inverter which pulls charge from the battery bank to be used in whatever AC electrical loads are needed at the site.

2.5.1 Controller

Any wind-electric system which employs battery backup or battery banks will require a charge controller and/or regulator. The wind-electric charge controller’s primary function is to protect the battery bank from overcharging. It does this by monitoring the battery bank; when the bank is fully charged, the controller sends energy from the battery bank to a dump (diversion) load.

The wind-electric charger used by the Whisper 500 has the rectifiers (AC-to-DC converters) built-in. Southwest Windpower provides the EZ-Wire controller for its Whisper wind energy systems. This controller has the capability to draw from both wind-electric and solar-electric energy systems. A schematic of the EZ-wire controller is presented in Figure 2-15. Figure 2-16 presents a photograph of the controller’s voltage regulation and rectifying circuitry.
Controller Circuit Diagram

Voltage Regulation Circuitry

AC to Positive VDC Rectifying Diodes (70HF10)

AC to Negative VDC Rectifying Diodes (70HF10)

Conductive Material

Phase 1 AC Phase 2 AC Phase 3 AC

Solar Panel 1 & 2 Controller Load

Solar Panel 1 & 2 Controller Load

DC Battery Dump Load

Figure 2-15. EZ-Wire Charge Controller Wiring Schematic

Figure 2-16. Photo of EZ-Wire Charge Controller Circuitry
The 3-phase AC power signal is rectified via the positive and negative diode banks mounted on the far right and left heat-sinks respectively. Each phase of the AC signal is passed through individual positive (Model 70HF10) and negative (Model 70HFR10) diodes. The result is a slightly rippled DC signal with a voltage level proportional to the power output of the wind turbine. Negative DC voltage can be sensed from the negative heat sink diode bank and positive DC voltage can be sensed from the positive heat sink diode bank. The voltage regulation circuitry, located on the center heat sink, monitors the rippled DC level of the wind turbine and the charge level of the battery in order to decide whether to divert power to the battery bank or to the diversion load.

The voltage regulation circuitry has the flexibility to be adjusted to monitor battery banks of 24VDC, 36VDC, and 48VDC in size. Refer to the Whisper 500 user manual for the procedure to adjust the system voltage regulation level. The voltage regulation circuitry works by monitoring the voltage level of the battery bank and turning on or off the metal-oxide-semiconductor field-effect transistors (MOSFET: Model IRF540N) to switch the electrical signal from either the battery charge or diversion load path. In practice, the MOSFET diversion load circuitry does not stay on constantly when required but will instead pulse at a varying frequency while diverting power to the diversion load.

It is important to note that the instance of diverting power introduces a deviation from the typical operational load on the wind turbine. Due to this fact, the wind turbine will likely operate slightly differently when it is diverting power to the diversion load versus transferring power to the battery bank. It was therefore decided that the DC current levels would be analyzed in post-processing and any instance where the system was diverting power would be removed from performance testing analysis; designated as an unavailable state (unconventional electrical configuration) as prescribed by the system testing methodology outlined later in the thesis.
2.5.2 Diversion Load (Dump Load)

The main purpose for use of a diversion load (dump load) in a wind-electric system is to provide a load when no battery charging or grid-tied load can be supplied. Most wind generators should not run unloaded. It is likely that the system will run too fast and too loud, and may self-destruct due to the high loads incurred at high rotational speeds. Normally, a charge controller has the capability of being a diversion controller itself or can be integrated with a diversion load system. The concept of a diversion controller is that it takes surplus energy from the battery bank and sends it to a dump load.

The dump load used in the Whisper 500 system is an electrical resistance heater. It has been sized to handle the full generating capacity of the wind generator (3 kW). The dump load is configured as an air heater unit and is activated by the charge controller whenever the batteries cannot accept the energy being produced.

There are four resistors in the diversion load for the Whisper 500 system. Each resistor has been measured to be approximately 0.75\(\Omega\). In their default configuration for 24V, the resistors are wired such that 2 sets of parallel resistors are wired in series with one another. The default configuration is shown in Figure 2-17. If the size of the battery bank is ever changed the resistor configuration will need to be reset according the Whisper 500 user manual (8), “Changing the System Battery Voltage” procedure.

![Figure 2-17. Diversion Load Default Resistor Configuration for 24V Battery Bank](image-url)
At the beginning stages of testing the wind turbine, alternative diversion load configurations were tried in order to examine the effect of a varying resistive load. This was achieved by connecting the diversion load leads in place of the main battery bank load connections and examining the RPM and power production of the system. In the process of this testing the MOSFET controller regulation board was damaged due to over current as the result of an incorrectly configured electronics. Nonetheless, results from this experiment were useful in that it provided a better feel for how the variation in loading of the wind generator affects the power output and in particular the RPM of the unit. As the resistance of the diversion load increases it more closely approximates an open circuit thus the wind turbine will spin faster while producing less current. If the resistance of the diversion load decreases the configuration approximates a closed circuit whereby the wind turbine will spin slower while producing more current.

Figure 2-18. Photo of Whisper 500 Diversion Load
2.5.3 Battery Bank

Whenever the wind blows above the cut-in speed, the speed at which the wind turbine begins to produce electricity, a method of energy storage is needed for off-grid systems. The battery bank is simply a system of batteries wired together to store energy when electricity is needed. Battery banks are typically sized to keep household electricity running for a typical number of “windless” days for the specific site.

Only deep-cycle batteries are used in wind electric systems with lead-acid being the most common battery type. The battery being used at the Whisper 500 test site is a 12V Diehard Deep Cycle Marine/RV 29HM. Two of these batteries are configured in series to provide a 24V battery bank for the wind system. Each battery is rated for 115 Amp-Hours at a 20 hour rate.

2.5.4 Brake (Emergency Shutdown)

The Whisper 500 wind turbine has a shutdown brake in order to stop the turbine for repairs, in an emergency, for routine maintenance, or when the energy is not needed. For the test site, the brake is mounted on the exterior of the controller so that it is readily accessible. This brake acts as a “dynamic brake”, which simply shorts out the three electrical phases. The brake switch has two modes, “on” or “off”. When the brake is “on” the three phases have been shorted and the wind turbine should stop.

2.5.5 Inverter

Inverters transform the electricity produced by the wind generator into the AC electricity commonly used in most applications. Battery-based inverters for off-grid systems most often include a battery charger for charging the battery bank from either a grid connection or backup
generator. The inverter at the Whisper 500 test site pulls DC power from 12V of the 24V battery bank. While testing, the primary load draws from the inverter are the data acquisition systems and auxiliary equipment (ex. Power tools, electronics, etc.). A Xantrex Prosine 2.0 inverter-charger is being used at the test site and is shown in Figure 2-19. The inverter is rated for 2000 watts (4500-watt surge) and can handle a 50 Amp peak in current. The user instructions for the inverter can be found in Appendix D.

![Figure 2-19. Photo of Controller and Inverter Equipment](image-url)
2.6 Data Acquisition Systems

2.6.1 General Overview

Experimental measurements were made via a control and data acquisition system built around the National Instruments DAQPad-6020E system and a laptop PC running LabVIEW. This data acquisition system interfaces with the power and meteorological measurement systems so that performance data can be acquired and analyzed on-site. The setup was designed so that it can be assembled and disassembled easily for full day testing with short notice. An oscilloscope, a signal generator, and a BNC connector box were typically connected to the data acquisition system to facilitate setup and debugging. A photograph of these components is shown in Figure 2-3.

The data acquisition system is limited to 8 channels. The signals available during acquisition were down-selected to eight according to priority for performance testing. For the majority of the measurements the following signals are acquired:

1. DC Current ($I_{bat}$)
2. DC Voltage ($V_{bat}$)
3. Line 1 AC Current ($I_1$)
4. Phase 1-2 AC Voltage ($V_{1-2}$)
5. Wind Speed at Station 1 (AC Type Anemometer)
6. Wind Speed at Station 2 (Pulse Type Anemometer)
7. Wind Direction at Station 1
8. Wind Direction at Station 2

2.6.2 NI DAQPad-6020E

The NI DAQPad-6020E is a portable data acquisition device. The 30 cm enclosure features BNC connectivity which offers a low-profile package that fits under the laptop computer.
This configuration proves ideal for the current system configuration since it is both portable and capable of quick connectivity. The device can be quickly connected to the driving laptop computer via a USB bus.

The DAQPad-6020E family of devices is capable of 8 differential analog inputs. It has a maximum sampling rate of 100kS/s with 12 bits of input resolution. Input voltages for the device can range from ±0.05 to ±10 V. The system also has the capability of producing 2 analog output signals of ± 10 V in range and a maximum rate of 20 S/s.

2.6.3 Power Measurement System (Voltage and Current Transducer’s)

The power measurement system for the Whisper 500 test site allows for the measurement of all three phases of the power signal as well as power measurement on the DC side of the rectifying circuitry. Prepared by ARL, all sensors for the power measurements are located inside the controller for the Whisper 500 wind-electric system. These signals are transferred outside of the NEMA box enclosure via a 17-pin connector.

![Power Measurement System 17-Pin Connector Signal Configuration](image-url)
In order to power the measurement sensor’s ±15 VDC excitation is required. In order to provide this DC voltage a power converter was fabricated so that standard 120 VAC electrical power could be drawn from the inverter, then converted to ±15 VDC for power to the measurements system.

Figure 2-21. Power Measurement System Block Diagram

The sensors used by the power measurement system consist of 3 voltage transducers and 4 current transducers. All three phases of the AC power were monitored for both current and voltage levels. Voltage sensors for the three phase power were located such that they would measure phase voltage (i.e. between phases) V12, V23, and V13. For example, leads for the V12 transducer were connected across phase 1 and phase 2 of the AC power signal so that the resulting signal is representative of the phase voltage between line voltage 1 and line voltage 2. Current sensors for the three phase power were located such that they would measure line currents I1, I2, and I3. The remaining fourth current transducer was located at the positive terminal of the battery bank connection to the controller and is designated as I-bat. Positive
The current indicates charge going to the battery. Negative is indicative of charge going from the battery to the diversion load. For clarification of sensor placement refer to the diagram in Appendix A.

The voltage transducer sensor being used is the LV 25-P by LEM. Three of these transducers are used in the data acquisition system to measure phase voltages for all three phases ($V_{1-2}$, $V_{2-3}$, and $V_{3-1}$). These transducers are designed for DC, AC, and time pulsed measurement of voltages. For voltage measurement, a current proportional to the measured voltage must be passed through an external resistor (noted as $R_1$ in Appendix E) which is selected by the user and installed in series with the primary circuit of the transducer. As noted in the Appendix E diagram provided by ARL, 6.04 KΩ resistors were used to result in a nominal voltage setting for the transducer ($V_{PN}$) of 60 Volts. As indicated by the sensor specifications, in this configuration the transducer will be accurate to 0.9% of 60 Volts. The calibration for the voltage transducer is based off of the $V_{RMS}$ level of the cross-phase AC voltage signal. For the setting described above a calibration of $12.666 \text{ VAC} \div V_{RMS}$ of the AC voltage should be used.

The current transducer sensor being used is the HAL 100-S by LEM. Four of these transducers are being used to measure all three phases of line current and DC current to the battery bank. These current transducers can measure both DC and complex AC waveform current levels. The 100-S is capable of ±50 Amps with a maximum output excitation of ±4 Volts. Therefore, the calibration for this transducer is $12.5 V_{RMS} \div V_{OUT}$ where $V_{OUT}$ is the output excitation and $V_{RMS}$ is the root-mean-squared level of the AC current signal in Amps.

The I-bat current sensor is used to monitor the flow of power from the wind turbine generator and either the battery bank or diversion load. During operation of the controller, the MOSFET diversion load circuitry will pulse at a varying frequency while diverting power to the diversion load. The difference between the typical operating current signal (to the battery bank)
and the pulsed diversion current signal, the frequency of which is controlled by the main system circuit board on the controller lid, is shown in the experimental data presented in Figure 2-15.

Figure 2-22. DC Current Sensor Signal: Baseline (Top) and While Diverting (Bottom)
2.6.4 **Meteorological Measurement System**

The meteorological measurement system for the Whisper 500 test site allows for the acquisition of wind speed and wind direction information from two separate meteorological stations. Each station consists of a 20’ PVC tower with the wind speed anemometer and wind direction vane mounted at the top. The towers are easily mobile to allow for the adjustability of measurement locations at the site.

The primary meteorological station, station 1, was located at position B as indicated in Figure 3-3. This station consisted of the AC anemometer and wind direction vane sensor. Station 2 was located at position A and consisted of the pulse-type anemometer as well as the same wind direction sensor type as Station 1. The AC anemometer does not require an excitation to the signal thus it could be connected directly into the data acquisition system. Both the wind direction sensors and the pulse-type anemometer required an excitation signal be sent to the sensor. A 5 VDC excitation was chosen since it was safe for both sensors. This DC level signal is generated by a signal generator which was powered by the wind-electric system inverter. Refer to section 3.3 for information regarding the type, specifications, and calibrations for the anemometers and wind direction vanes.
2.6.5 LabVIEW Program ("Wind_Turbine_Acquisition.vi")

Experimental measurements were controlled via a custom LabVIEW program. The program has four primary functions: (1) control the data acquisition from the NI DAQPad 6020E device, (2) store experimental data to file, (3) provide real-time feedback for wind-electrical system performance, and (4) provide a troubleshooting platform for sensor setup and measurements. The program used during field testing is “Wind_Turbine_Acquisition.vi.” (WTA code)
The primary functionality of the WTA code is to acquire the digitized sensor signals to file. Data post processing for performance analysis will be entirely completed from these raw
digitized signals. During testing, the digitized sensor signals are saved to files with the naming system “WTMMDDYY##_realtime.txt” where “WT” is the designator for the Whisper Turbine, “MM” is the numerical indicator for the month of testing (04 is April), “DD” is for the day of testing, “YY” is for the year of testing (10 is 2010), and “##” is the run number for that acquisition file. The WTA code will stream all channel data to files of this designation at an acquisition rate of 1 kHz. The file size for each run is limited to 20 minutes of data since that is the maximum data handling capability of MATLAB. Once 20 minutes is completed for that run number, the code will automatically iterate to the next run number and execute through the next 20 minutes.

In order to allow for the troubleshooting of sensor signals while on-site, a dynamic signal analysis routine is also included. While the code is running, the user may select two channels to analyze and compare. The code will then proceed to compute and display on the front panel the power spectrum, cross spectrum, and coherence information for those two signals. In order to supplement this capability, the user can also choose to display any real-time acquisition channel on the front panel for signal diagnostics.

A secondary functionality of the WTA code is that it allows for the real-time display of wind-electric system performance. On the front panel the code will display information pertaining to AC power, DC power, Station 1 MET information, and Station 2 MET information. This data is logged both graphically on the front panel and saved to file for post processing analysis. Every three seconds the code will update this information. The file naming system for the wind-electric system performance data is “WTMMDDYY##_average.txt.” These files contain 20 minutes of performance information in 3 second intervals. All performance measurement computations are executed the subroutine “Wind Turbine Calculations.vi.” The block diagram code structure for both the WTA code and the “Wind Turbine Calculations.vi” subroutine are included in Appendix F.
Chapter 3

Experimental Methods and Calculations

In this chapter, the electrical and mechanical system experimentation methods are presented. In addition to the experimental methods, the methods for data analysis, procedures for determining measurement uncertainty, and standard NREL field testing methodologies are also presented.

3.1 Experimentation Overview

The Southwest Windpower Whisper 500 experimentation development consists of three phases. In the first phase, the turbine was refurbished to an operational state and a high-resolution data acquisition system was developed. Preliminary bench testing was conducted at this phase of the project which validated the capabilities of the system. The second phase, and the primary focus of this paper, consists of the installation and application of the instrumentation to assess the performance of the wind turbine. In the third phase additional improvements will be made involving integration of a data acquisition shed, extension of the main tower, improved MET systems, and data streaming via the internet.

Performance testing of the wind turbine includes measurements of: (1) meteorological conditions of wind direction, air humidity, barometric pressure, and air temperature, (2) turbine specific parameters including rotor rotational speed, output voltage (3 Phase AC and DC), and output current (3 Phase AC and DC). The integration of these measurements allows for the assessment of system performance.
3.2 Electrical System Measurement

The primary interest in wind turbine field testing is to quantify the power output of the system and relate it to the meteorological conditions at the time. In baseline performance testing the net power output is typically extracted via a combination of voltage and current sensors or more directly through power transducers. Regardless of which method is used, these sensors should be located downstream of any auxiliary loads. For variable speed operation, the IEA (International Energy Agency) has indicated that the rotor speed must also be measured to enable for changes in kinetic energy to be compensated for in performance measurements. However, the IEC (International Electro-technical Commission) does not include such recommendations and NREL (National Renewable Energy Laboratory) has thus adopted no such requirement in its own performance testing of variable speed machines.

The Southwest Whisper 500 outputs three-phase variable frequency AC which is received at the controller. Voltage ranges for this system can be adjusted to charge a 12V, 24V, 36V, or 48V battery bank or likewise compatible inverter equipment. The recommended approach for power measurement is either the “3 wattmeter” method or the “2 wattmeter” method. Monitoring a three-phase, three-wire connected load only requires a two-element wattmeter or transducer\(^{(12)}\). Kirchhoff’s law states that the algebraic sum of the current in all lines of a circuit and the algebraic sum of voltages among all nodes must be zero at a given instant. Following this rule the following can be stated about a three-wire circuit:\(^{(12)}\)

1. If two of the three currents are known, the third must be equal to the sum of the other two but opposite in direction or sign. Thus, if one measures the instantaneous current in two branches of a three-wire circuit, one can determine the instantaneous value of the third.

2. If two of the three voltages are known, the third must be equal to the sum of the other two but opposite in direction or sign. Thus, if one measures the instantaneous voltage between two pairs of lines; one can determine the instantaneous value of the third pair.
Figure 3-1 and Figure 3-2 give a graphical representation of Kirchhoff’s law as applied to a three-phase and three-wire connected load. From inspection of Figure 3-2 it can be seen that at any time $t$ the sum of the three phase voltages will be zero. Therefore if any two voltages are measured then the third can be inferred to be the negative of the addition of those two voltages.

The same observations hold for line currents in a three-phase and three-wire circuit.

\[ I_{ab} \]

\[ V_{2-3} \]

\[ V_{3-1} \]

\[ I_3 \]

\[ I_1 \]

\[ I_2 \]

\[ V_{1-2} \]

\[ V_{2-3} \]

Figure 3-1. Three-Phase Delta Wiring Diagram

Figure 3-2. Three-Phase AC Voltage Fluctuation

3.2.1 Turbine Voltage and Current

The Southwest Windpower Whisper 500 power measurement system consists of three voltage transducers to monitor cross-phase voltage and three Hall Effect sensors to measure line currents. Both sensors have analogue signal outputs therefore pose no limitation with regard to sampling rate for the data acquisition systems. Manufacturer specifications for both sensors for both sensors can be found at LEM’s website.

The IEC standard recommends a transducer with an error no greater than 0.5 percent at rated power (class 0.5 or better). If a current and voltage sensor system is used, the combination of the errors should achieve an equivalent standard. Whatever transducer is chosen, a calibration
for each sensor should be obtained. The transducer should be able to cope with the full capable power range of the wind turbine – considered to be 50 percent to 200 percent of the turbine rated capacity.\(^{(13)}\)

### 3.2.2 Three Phase Circuits and Turbine Power

To obtain the power output of the wind turbine generator a basic understanding of three-phase circuits and three phase power is necessary. Most electric power systems are three-phase in that they involve three voltage sources having the same amplitude and frequency but displaced from each other by 120 degrees in phase.

\[
V_a = V_m \sin \omega t \\
V_b = V_m \sin(\omega t - 120^\circ) \\
V_c = V_m \sin(\omega t - 240^\circ)
\]

\(V_a, V_b, \) and \(V_c\) represent instantaneous voltages in phases a, b, and c respectively. The three phases for the Whisper 500 wind turbine are mutually connected in a delta configuration. A schematic of a delta-connected system is presented in Figure 3-3.
Figure 3-3 shows phase voltages ($V_a$, $V_b$, and $V_c$), line currents ($I_a$, $I_b$, and $I_c$), and phase currents ($I_{ab}$, $I_{bc}$, and $I_{ca}$). From phasor analysis, line voltages ($V_l$) can be related to phase voltages ($V_P$) and line currents ($I_l$) can be related to phase currents ($I_P$) for a delta configuration. Apparent, reactive, and active powers can then be defined for delta configured three phase power; these equations only apply if it is determined that all three phases are well balanced. The variable $\theta$ is defined as the phase angle between $V$ and $I$.

\[
delta \text{ connection: } \quad V_l = V_P \quad \& \quad I_l = \sqrt{3} I_P
\]

\[
\text{apparent power, } S \ (VA) = \sqrt{3} V_l I_l = 3 V_P I_P
\]

\[
\text{active power, } P \ (W) = \sqrt{3} V_l I_l \cos \theta
\]

\[
\text{reactive power, } Q \ (var) = \sqrt{3} V_l I_l \sin \theta
\]
During Phase 1 bench testing it was confirmed that the three phases are in fact balanced thus a rather accurate representation of the active power could be made if one phase of power is known. As a result, *power for the wind turbine system is defined as three times the active power of one phase.*

### 3.2.3 Turbine RPM

To obtain the rotational velocity of the turbine rotor, or turbine RPM, a signal analysis of the turbine generator 3-Phase output signal was used. The turbine was mounted in a fixed position and direct measurement of RPM was made through a reflective laser system which emitted two pulses per rotation. Since passing a signal through a slip-ring assembly down-tower was found to not be practical, the rotor RPM was related to the AC output of the wind generator.

The Whisper 500 uses an 8 pole pair (16 poles total), permanent magnet, and asynchronous alternator. During operation the turbine alternator outputs a three-phase alternating current electrical signal with a frequency and voltage amplitude proportional to the rotational speed (wild AC signal). The proportionality between the frequency of the AC electrical signal and the rotational rate of the rotor is directly related to the number of poles in the alternator. Figure 3-4 shows that all phase voltage signals will oscillate eight times per revolution of the rotor; in the figure each pulse represents half a rotation of the rotor. All three line current signals show the same frequency characteristics. It can therefore be concluded that any single (of the three) AC phase voltage or AC line current signal could be obtained and used to compute rotor RPM.
As a result, the scaling factor used to compute turbine rotational speed (in RPM) from either the phase voltage signals or the line current signals is defined as:

\[
RPM = \frac{60 f_m}{\frac{P_T}{2}}
\]  

Where  
- \( f_m \) is the measured frequency of the turbine AC output signal  
- \( P_T \) is the number of alternator poles or magnets (sixteen for the Whisper 500)
3.2.4 Turbine Thrust and Torque

Once the wind turbines power output and RPM have been established it is possible to analyze the torque and thrust on the rotor. Torque is defined in this case as the rotational moment being applied to and integrated along the blade length in the plane of rotation and resolved at the shaft of the generator. Thrust is defined as the force being exerted normal to the rotor plane and acts in the direction of the wind inflow. For these experiments, no systems were developed to measure thrust or torque directly. Assumptions are made whereby thrust and torque can be estimated directly from the RPM and power quantities.

A rotor system producing power has a torque moment which is directly proportional to the power production. The power developed by the rotor is \( P = Q \Omega \) where \( \Omega \) is the rotational speed of the rotor and \( Q \) is torque. Torque data for these experiments are therefore computed directly from the power data. Both the power and torque performance of the rotor are indicators as to the efficiency of performance for the rotor system. These quantities are typically analyzed in a non-dimensional form and compared against a non-dimensional relationship between rotor rotational speed and incoming air flow called tip-speed ratio \( (\lambda = \Omega R / U_\infty) \).

\[
C_P = \frac{P}{\frac{1}{2} \rho U_\infty^2 \pi R^2} 
\]

\[
C_Q = \frac{C_P}{\lambda} 
\]

Since the torque coefficient is derived from the power coefficient it generally does not give any additional information about the turbine performance. The maximum power coefficient occurs at a tip speed ratio for which the axial induction factor, \( \alpha \), which varies with radius, approximates most closely to the Betz limit value of 1/3.
At lower tip speed ratios the axial flow induction factor can be much less than 1/3 and aerofoil angles of attack are high leading to stalled conditions thus low torque and power outputs. At high tip speed ratios the axial flow induction factor is high, angles of attack are low and drag begins to be predominate therefore low torque and power outputs will also result. This is why it would be best if a turbine can operate at all wind speeds with a tip speed ratio closest to that which gives the maximum power coefficient.

Experimental thrust would be best determined from means separate from direct calculation from the power output. A UC Davis report (see reference (4)) shows that a system of load cells can be integrated into the main tower guy-wire system to directly determine thrust loading at the wind turbine. This system was not developed for this baseline performance testing but should be considered in the future.

Thrust for this experiment was determined directly from actuator disc and momentum theory which relates coefficient of power, $C_p$, to the axial induction factor, $\alpha$, of the rotor (both terms are further defined later). Also from actuator disc and momentum theory, the coefficient of thrust for the rotor, caused by the pressure drop across the rotor, can be related to the axial induction factor of the wind turbine. From the coefficient of thrust, the thrust force on the rotor can be approximated.

$$C_p = 4a(1 - a)^2$$ \hspace{1cm} \text{(3.11a)}

$$C_T = 4a(1 - a)$$ \hspace{1cm} \text{(3.11b)}

$$C_T = \frac{\text{Thrust}}{\rho U_{\infty}^2 \pi R^2}$$ \hspace{1cm} \text{(3.11c)}
A problem with this thrust approximation arises for values of $\alpha > 1/2$ because the wake velocity, defined as $(1-2\alpha)U_\infty$, becomes zero, or even negative. In these conditions momentum theory no longer applies and an empirical modification has to be made (see section 4.2.2). Since in this report experimental thrust data is directly related to the power output of the turbine there are limitations to the validity of the thrust results.

### 3.3 Meteorological Measurements

Meteorological measurement procedures typically consist of taking a series of measurements of wind speed, wind direction, atmospheric pressure, atmospheric temperature, and air humidity. These measurements should be taken over as wide of a range of wind speeds as possible. All data should be checked for accuracy and consistency and if any of the variables are found to be misread or to have errors then those samples should be discarded. For instance, data collected while the anemometer is in the wake of the wind turbine should be discarded.

#### 3.3.1 Wind Speed Measurement

Wind speed is the most critical parameter to be measured therefore an emphasis should be made on ensuring anemometer information is accurate. The IEA suggests that the anemometer should have an accuracy of 5 percent or better over the range of relevant wind speeds and specifically recommends that they be accurate to ±0.1 m/s or less for wind speeds between 4 and 25 m/s. The IEC only requires calibration against a traceable instrument and that its accuracy is known and maintained throughout the test. Another characteristic of an anemometer is its distance constant, which the IEC states should be less than 5 m. The distance constant is defined as the length of wind run which must pass the anemometer for its output to reach 63% of its final
value. A large distance constant can give rise to large errors because the anemometer will be more responsive to increases in wind speed versus decreases in wind speed. It is likely that anemometer’s will show more over-speeding error than under-speeding error.

The wind speed that is measured should be as representative as possible of wind which would have been present at the wind turbine rotor in the absence of the wind turbine. Since it is presumably impossible to measure this wind a suitable upstream velocity is chosen. The anemometer locations are chosen so to minimize any interference from the wind turbine and to maintain reasonable correlation between the measured wind speed and the response of the wind turbine. IEC standards recommend between 2 and 4 rotor diameters from the wind turbine with 2.5 diameters being optimal. The IEA recommends between 2 and 6 rotor diameters.

The height of the anemometer tower is recommended to be as close to the same height (relative to ground level) as the hub of the wind turbine as possible. The IEC specifies a height within 2.5 percent of the turbine hub height. Although corrections can in theory be made to take account of wind shear for anemometers not at hub height, the IEC discourages this practice.

For the experiments included, two anemometer units were used. Each unit was placed on 20 ft. PVC pipe towers and located within the proximity standards provided by NREL. For each testing date anemometer location and relative height was noted and data corrections driven by correlation between measured wind speed and wind turbine response were only applied to experiments with like anemometer locations. Four potential anemometer locations were identified for the Whisper 500 test site. For all experiments presented, the two anemometer towers were located at position A (station 2; pulse anemometer) and position B (station 1; AC anemometer) as indicated in Figure 3-5.
The primary anemometer was located at location B and is noted as station 1 in data acquisition and processing documentation. The anemometer model is a Campbell Scientific 03101. This anemometer outputs an analog AC signal with amplitude and frequency proportional to the rotational rate, and thus wind speed at that location. The calibration for this anemometer was confirmed and completed during wind tunnel testing. Figure 3-6 and Figure 3-7 present a picture of the anemometer in the wind tunnel and the results respectively. The calibration for the AC anemometer was determined to be:

\[
\text{Wind Speed (mph)} = 53.599 \times V_{RMS}
\]

\[
V_{RMS} = \frac{V_{PP}}{\sqrt{2}}
\]

Where, \(V_{PP}\) is defined as the peak-to-peak voltage of the AC signal.
Figure 3-6. Calibration of AC Anemometer in the wind tunnel

Figure 3-7. Calibration results for AC anemometer

Wind Speed = 53.599*RMS of Signal
The secondary anemometer was located at location A and is noted as station 2 in data acquisition and processing documentation. The model is an Inspeed Vortex anemometer. This anemometer outputs a DC pulse analog signal with frequency proportional to wind speed. Calibration for this anemometer was provided by the manufacturer and confirmed in wind tunnel testing. Figure 3-8 presents the results of the calibration. It was confirmed that the unit outputs DC pulses with a calibration of 2.5 MPH / Hz. The acquisition rate of 1 kHz for the data acquisition system was set based off of the need to precisely acquire the duty cycle of the pulse for the vortex anemometer signal.

![Figure 3-8. Calibration of Inspeed Vortex Anemometer A](image)

3.3.2 Wind Direction Measurement

In performance testing of wind turbines wind direction is measured so as to eliminate data taken in excluded testing zones. Wind vanes should be located at the same height as the anemometers (as close to the height of the turbine as possible) and in its proximity but not so as
to interfere with the wind speed measurement. The IEC recommends accuracy better than 5 degrees for the wind direction measurements.

Inspeed E-Vane wind direction vanes were used during experiments. The vanes were located at the same locations noted for the wind anemometers and are referred to as Vane 1 (at station 1) and Vane 2 (at station 2) in all data acquisition and data processing documentation. These sensors are comprised of a balanced wind vane connected to an active, non-contact, zero friction Hall Effect sensor. A magnet hovers over the sensor to provide ~0-5VDC output. The accuracy of the vane is quoted from the manufacturer as being +/-0.3 to 0.5% of the signal range. Full specifications for the E-Vane are included in Appendix G.

During installation of the vane systems the minimum voltage excitation output of the vane was made to align with the support arm on the unit. The wind vane can therefore be calibrated for direction in the field by using a compass and taking the magnetic heading in the direction of the support arm: this heading is referred in this paper as the calibration offset direction. Given the DC output \( (V) \), max excitation \( (V_{\text{max}}) \), minimum excitation \( (V_{\text{min}}) \), and the calibration offset direction \( (\psi_{\text{min}}) \) from a vane, the algorithm given in Appendix G can be followed to compute its orientation in degrees.

![Figure 3-9. Inspeed E-Vane Wind Direction Sensor](image)

Figure 3-9. Inspeed E-Vane Wind Direction Sensor
3.3.3 Barometric Temperature, Barometric Pressure, and Humidity

For a given wind velocity the energy in the wind depends on the air density. In order to be able to correct for changes in air density, the air temperature, pressure and humidity should be measured. Density corrections with regard to humidity need only be made on high temperature days. Accuracy for all measurements should result in an air density on a given day to a precision of ±1 percent. The IEC standard states that pressure should be measured at hub height. It is also recommended that data be normalized to two different reference air densities; the average measured air density at the test site, and standard conditions at sea level defined as 15°C and 1013.3 mbar, corresponding to a density of 1.225 kg/m$^3$.

At the testing facility for the Whisper 500, sensors are currently unavailable for measuring local temperature, pressure, and humidity at the site. This data was instead extracted from weather history data at the University Park Airport. The website wunderground.com logs barometric temperature, sea level pressure, and humidity at 20 minute resolution daily. This data is downloaded to file for each day of testing to be inserted into weather input files. An example of this weather input file is presented in Appendix H. This file is called during the data processing routine.

3.4 Data Collection

For the acquisition of data, a data sampling rate of 1 kHz was used for each of eight different measurements. These data were saved to file for the duration of testing – usually a few hours on high wind days – and then the data was post processed and sorted. Acquisition to file was limited to 20 minute increments in order to allow for the analysis of data in MATLAB.
The post processing of data consisted of each raw data file (WT04281001_realtime.txt) being broken down and averaged to 0.5 second data resolution. These 0.5 second data files (WT04281001_realtime_highres.txt) were then further post processed by averaging the data over a variable period X (e.g. X = 3 secs, 10 secs, 60 secs,...) to yield an X-second data point. The IEC standard allows for a maximum data sample averaging of 10 minutes. Because analysis of the rotor aerodynamics requires a high resolution of data, shorter averaging periods were chosen and compared. For these experiments, data averaging periods of 1 second, 3 seconds, 10 seconds, and 60 seconds were analyzed.

As an example of this procedure, the calculation of the turbine AC current and voltage was first resolved to 0.5 second intervals by finding the $V_{\text{RMS}}$ of these AC signals and applying the transducer calibrations over a 0.5 second snapshot of data. AC Power can then be calculated and resolved to a 0.5 second interval from AC current and AC voltage via equation 3.5. These 0.5 second AC power levels were then averaged over the user specified data averaging period in order to obtain the X-second AC power data point.

$$P_{N_{\text{avg}},j} = \frac{1}{N} \sum_{i=1}^{N} P_{0.5_{\text{avg}},i} \tag{3.13}$$

Where
- $N$ is the number of 0.5 second AC power levels over the X-second period
- $j$ is the reference number for the data point in the X-second data set
- $i$ is the reference of the 0.5 second AC power data point
- $P_{0.5_{\text{avg}},i}$ is 0.5 second average AC power calculated from equation 3.5
3.5 Performance Calculation Method

After collecting and sorting all measurement data, the data was corrected for differences between the test site air density and standard air density. The process is referred to as standard normalization and was applied to all wind speed measurements. After all data was normalized, it was then sorted by wind speed using the method of bins, calculations for system performance were made, and a bias correction was applied to account for correlation differences between wind speed and wind turbine electrical measurements.

3.5.1 Analysis Method

Analysis of power performance data collected from the wind turbine occurs in two steps as prescribed by NREL \(^{14}\) and IEC standards \(^{9}\). Firstly, it is determined which data is usable. Then the usable data is processed to obtain power curves and estimate the annual energy production and the uncertainty of measurements.

Data brought into the database is first sorted to see if there was a data acquisition failure. NREL has set precedence to describe a data acquisition failure if any of the following occur:

1. Data logger or data acquisition shutdown or loss of power
2. Temperature of the acquisition system exceeds operational limits (-40°C to 80°C)
3. Record contains too few samples; in this case at least 1200k samples (1kHz for 20 minutes)
4. Any channel is over data acquisition range (-9.99 V, 9.99 V, or NaN)

Usable data are then filtered in accordance to IEC standards. The IEC standard requires that all data be used unless the following conditions are present:

- The wind turbine is unavailable
• The test equipment fails
• The wind direction is outside of the prescribed preliminary measurement sector

Examples of the system being defined as unavailable would include:

• The turbine is faulted
• The turbine is not in a conventional run mode (i.e. manual furl, unconventional electrical configuration, etc.)
• The inverter is faulted or not available

Once the above criteria have been applied, the remaining data from testing the power performance of the system can be analyzed and reported. The following list of computations is made on the data set:

1. When a site calibration is available, Equation 3.14 is used to adjust the average wind speed measured at the meteorological tower (MET) to calculate the turbine hub height wind speed according to the site calibration results. If no site calibration was performed, such as for these experiments, then $\Gamma_{\text{Site}} = 1.0$.

$$ V_{\text{Turb}} = \Gamma_{\text{Site}} \cdot V_{\text{MET}} $$  \hspace{1cm} 3.14

where:
- $V_{\text{Turb}}$ = wind speed at turbine (m/s)
- $\Gamma_{\text{Site}}$ = site calibration factor
- $V_{\text{MET}}$ = wind speed at MET (m/s)

2. ISO 2533 mandates that if the pressure sensor is more than 10 meters below hub height, then for each data point the measured pressure is corrected to hub height:

$$ p = p_b \cdot \left[ 1 + \frac{\beta}{T_b} \cdot (H - H_b) \right]^{\frac{\gamma_n}{\beta \cdot R}} $$  \hspace{1cm} 3.15
where:

- \( p \) = pressure at hub height (Pa)
- \( p_b \) = measured pressure (Pa)
- \( \beta \) = temperature gradient (-6.5 K/m)
- \( T_b \) = measured temperature (K)
- \( H \) = hub height above ground (m)
- \( H_b \) = pressure transducer height about ground (m)
- \( g_n \) = acceleration of gravity (9.807 m/s\(^2\))
- \( R \) = specific gas constant (287.053 J/kg-K)

3. For each averaged data point, the average air density is calculated by the Ideal Gas Law

\[
\rho_{ave} = \frac{B_{ave}}{R \cdot T_{ave}}
\]

where:

- \( \rho_{ave} \) = derived air density averaged over X-second period (kg/m\(^3\))
- \( T_{ave} \) = measured air temperature averaged over X-second period (K)
- \( B_{ave} \) = measured air pressure averaged over X-second period (Pa)
- \( R \) = gas constant for air (287.053 J/kg-K)

4. For each data point, the derived air density is used to calculate the average site air density for the test period; round the result to the nearest 0.05 kg/m\(^3\)

5. For small turbines that use furling, the method used to normalize the power curve is to adjust wind speed in accordance with equation 3.17. In this application, data is normalized with respect to the average air density at the site.

\[
V_n = V_{ave} \cdot \left(\frac{\rho_{ave}}{\rho_o}\right)^{1/3}
\]

6. Equation 3.17 should be applied a second time with \( \rho_o \) being replaced with standard sea-level air density (1.225 0kg/m\(^3\)), creating a standard normalized wind speed (\( V_{ns} \)).
7. All data is then sorted according to normalized wind speeds, into bins which are 0.5 m/s wide, with bin centers at integer multiples of 0.5 m/s. Each power, DC and AC, is averaged for each bin. As a result, two power curves and AEPs can be calculated.

8. For each data bin, the following parameters are calculated:

- Bin average air temperature (K)
- Bin average corrected air pressure (Pa)
- Bin average measured wind speed (m/s)
- Bin average standard deviation of wind speed (m/s)
- Bin average measured power (W)
- Bin average standard deviation of measured power (W)
- Bin average site average density normalized power (W)
- Bin average site average density standard deviation normalized power (W)
- Bin average sea-level density normalized power (W)
- Bin average sea-level density standard deviation normalized power (W)
- Site average density (kg/m³)
- Amount of X-second average data points in bin
- Bin average uncorrected air pressure (Pa)
- Bin power coefficient
- Bin average wind turbine RPM

9. The test power curve is formed by the resulting average normalized wind speed and average power (average for site average density, standard for sea-level density) at each bin. For each bin, the generator power coefficient is calculated by Equation 3.18.

\[
C_{P,i} = \frac{P_i}{\frac{1}{\rho_o A V_i^3}}
\]

where: \(C_{P,i}\) = generator power coefficient in bin i (non-dimensional)
\(V_i\) = normalized wind speed in bin i (m/s)
\(P_i\) = average power in bin i (W)
$A = \text{swept area of the turbine rotor (m}^2\text{)}$

$\rho_o = \text{reference air density (same as used to normalize } V_i)$

10. The measured power curve is then used to estimate annual energy production (AEP) for a variety of Rayleigh wind speed distributions. The AEP estimations are made according to Equation 3.19 and Equation 3.20.

$$AEP = N_h \sum_i^N [F(V_i) - F(V_{i-1})] \left( \frac{P_{i-1} + P_i}{2} \right)$$

3.19

where:

- $AEP = \text{annual energy production (kWh)}$
- $N_h = \text{number of hours in one year } \approx 8760 \text{ hr}$
- $N = \text{number of bins}$
- $V_i = \text{normalized and average wind speed in bin } i$
- $V_{i-1} = \text{normalized and average wind speed in bin } i-1$
- $P_i = \text{averaged measured power in bin } i$
- $P_{i-1} = \text{averaged measured power in bin } i-1$
- $F(V) = \text{the accumulated Rayleigh distribution}$

**Note:** The summation of equation 3.19 is initiated by setting $V_{i-1}$ equal to $V_i - 0.5 \text{ m/s}$, and $P_{i-1}$ equal to $0 \text{ kW}$.

$$F(V) = 1 - \exp\left( -\frac{\pi}{4} \cdot \left( \frac{V}{V_{\text{ave}}} \right)^2 \right)$$

3.20

where:

- $V_{\text{ave}} = \text{annual average wind speed at hub height (m/s)}$
- $V = \text{wind speed (m/s)}$

11. An uncertainty analysis is then performed as prescribed by Annex C of the IEC standard for both the measured power and estimated AEP. (see section 3.5.3)
3.5.2 Bias Correction and Expected Results

It has been determined that there is a need to assess the aerodynamic or instantaneous performance of the wind turbine in order to study detailed features such as stall characteristics and diversion loading effects. These more detailed measurements will tend to be smoothed out when applying 10 min or even 10 second averaging intervals to power performance assessments. Because of this fact shorter averaging intervals need to be considered but will result in further limitations to the application of the method of bins. It has been shown that poor correlation between power and wind speed results in a systematic distortion of the binned relationship (ref. (14)) and shorter averaging times result in poorer correlation.

The poor correlation between wind speed and power results can be described as follows. In considering a short gust of high wind at the anemometer, the likelihood is that at this instant, the wind speed at the turbine will be lower. Consequently, the power output measured will be less than would have been expected from the power curve and the wind speed as measured at the anemometer. This will bias the measured power curve down at higher than average wind speeds. The same analysis can be applied for a lull in wind speed whereas the measured power curve will be biased up at lower than average wind speeds. This effect is illustrated in Figure 3-10.
Dragt (ref (14)) has developed a formula for correcting the measured wind speed based on the statistics of the sampled data set. The corrected wind speed, $U^*$, is given by:

$$U^* = U - (1 - r)(U - \bar{U})$$  \hspace{1cm} 3.21

where:

- $U = \text{measured wind speed (m/s)}$
- $\bar{U} = \text{sample mean wind speed (m/s)}$
- $r = \text{correlation coefficient between power and wind speed}$

It is important to note that this correction was derived based on the assumption of a normal distribution for the wind speed variations thus care should be taken to ensure that this is the case. If data is collected so that the wind speed range is covered evenly then no systematic distortion should occur.
The correlation coefficient, $r$, is defined in equation 3.29. The following notation is used to describe the derivation of these statistical relationships: in the velocity bin around $v_i$, the $n_i$ power samples $p_{ij}$ ($j=1,\ldots,n_i$) have been measured. Due to the method of bins, measured data $p_{ij}$ are only used to compute the mean $\bar{p}_i$ and variance $\sigma_i^2$.

\[ \bar{p}_i = \sum_j \frac{p_{ij}}{n_i} \quad 3.22 \]

\[ \sigma_i^2 = \sum_j \frac{(p_{ij} - \bar{p}_i)^2}{n_i} \quad 3.23 \]

Now, the overall means and variances can be calculated:

\[ \bar{p} = \sum_i \frac{n_i \bar{p}_i}{N} \quad \text{where } N = \sum_i n_i \quad 3.24 \]

\[ \bar{v} = \sum_i \frac{n_i v_i}{N} \quad 3.25 \]

\[ \sigma_v^2 = \sum_i \frac{n_i (v_i - \bar{v})^2}{N} \quad 3.26 \]

\[ \sigma_p^2 = \sum_i \frac{n_i \sigma_i^2}{N} + \sum_i \frac{n_i (\bar{p}_i - \bar{p})^2}{N} \quad 3.27 \]

The covariance of $P$ and $v$ is:

\[ \sigma_{p,v}^2 = \sum_i \frac{n_i (\bar{p}_i - \bar{p})(v_i - \bar{v})}{N} \quad 3.28 \]

And by definition, the correlation coefficient is:

\[ r = \frac{\sigma_{p,v}^2}{\sigma_p \sigma_v} \quad 3.29 \]
Figure 3-11 and Figure 3-12 show the expected effect of applying the biasing correction. It can be seen that the 30 second averaged data is preferable to 10 minute averaged data since the range of wind speeds achieved is greater. Similarity between the corrected results from differently averaged intervals, if proven, is what shows confidence in the technique.

Figure 3-11. Bias Correction for 30 s Data

Figure 3-12. Bias Correction for 10 min Data

It must be noted that another potential approach to minimizing the averaging time while maintaining high correlation is to measure the wind closer to the wind turbine. If an anemometer is mounted close to the turbine so as to produce minimal interference with the system, bin measurements will be more successful. However, it has been shown (according to ref (13)) that as close as one radius distance from the wind turbine some velocity deficit will be apparent and measured by the anemometer. In order to account for this it is suggested to experimentally determine the relationship between the boom anemometer readings and the measured free wind speed.
### 3.5.3 Uncertainty Evaluation

Testing guidelines and procedures should be devised so to minimize errors and uncertainty. Due to the nature of wind turbine field experiments, inaccuracies are assured and IEC standards clearly state how these should be assessed.

In wind turbine performance testing the measurands are the power curve and the estimated annual energy production. Uncertainties in the measurements are converted into uncertainty in the measurands by means of sensitivity factors. Table 3 lists the most common and minimal parameters which must be included in the uncertainty analysis.

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Uncertainty Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Power</td>
<td>Current Transducers, Voltage Transducers, Data Acquisition System, Variability of Electrical Power</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>Anemometer Calibration, Operational Characteristics, Mounting Effects, Data Acquisition System, Flow Distortion Due to Terrain</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>Temperature Sensor, Radiation Shielding, Mounting Effects, Data Acquisition System</td>
</tr>
<tr>
<td>Air Pressure</td>
<td>Pressure Sensor, Mounting Effects, Data Acquisition System</td>
</tr>
<tr>
<td>Data Acquisition System</td>
<td>Signal Transmission, System Accuracy, Signal Conditioning</td>
</tr>
</tbody>
</table>

Sensitivity factors show how changes in a particular measured parameter affect the relevant measurand. As an example, temperature measurements are used to calculate the air density used in the power curve calculation through correction of the wind speed or power. Therefore, we are interested in the rate of change of power with temperature.
Table 4. Uncertainty in Power Performance Measurements

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Transducer</td>
<td>1 (± 1% of max) A</td>
<td>Specs</td>
</tr>
<tr>
<td>Voltage Transducer</td>
<td>0.54        V</td>
<td>Specs</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>25          W</td>
<td>Estimate</td>
</tr>
<tr>
<td><strong>Wind Speed</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Anemometer</td>
<td>0.1         m/s</td>
<td>Calibration Est.</td>
</tr>
<tr>
<td>Pulse Anemometer</td>
<td>0.1         m/s</td>
<td>Calibration Est.</td>
</tr>
<tr>
<td>Operational Characteristics</td>
<td>1.5%</td>
<td>Estimate</td>
</tr>
<tr>
<td>Mounting Effects</td>
<td>1%</td>
<td>Estimate</td>
</tr>
<tr>
<td>Terrain Effects</td>
<td>2%          IEC Recommendation</td>
<td></td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>0.00        Estimate</td>
<td></td>
</tr>
<tr>
<td><strong>Wind Direction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Direction Vane</td>
<td>± 5         Deg</td>
<td>Specs</td>
</tr>
<tr>
<td>Operational Characteristics</td>
<td>1.5%</td>
<td>Estimate</td>
</tr>
<tr>
<td>Mounting Effects</td>
<td>1%</td>
<td>Estimate</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>0.00        Estimate</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>0.15        K</td>
<td>Typical Spec</td>
</tr>
<tr>
<td>Mounting Effects</td>
<td>0.5         K</td>
<td>Off-site Estimate</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>0.03        K</td>
<td>Typical Spec</td>
</tr>
<tr>
<td><strong>Air Pressure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>2.0         hPa</td>
<td>Typical Spec</td>
</tr>
<tr>
<td>Mounting Effects</td>
<td>0.07        hPa</td>
<td>IEC Recommendation</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>0.8         hPa</td>
<td>Typical Spec</td>
</tr>
</tbody>
</table>

The process of determining total experimental design uncertainty uses the resolution of uncertainty of each instrument, the data acquisition uncertainty, and as described before the sensitivity of each measurand in the final equation. The definition of experimental design uncertainty, $u_i$, is:

$$u_i = \sqrt{u_{\text{inst}}^2 + u_{\text{adc}}^2}$$  \hspace{1cm} (3.30)

where:  
- $u_{\text{inst}}$ : instrument uncertainty presented in Table 2  
- $u_{\text{adc}}$ : analog to digital converter error

The design uncertainty is then combined with the individual parameter sensitivities to obtain the total design stage uncertainty, $U_{D,i}$. For each performance calculation ($P_i$, $\text{RPM}_i$, $C_{p,i}$),
the design stage uncertainty were determined and are shown below in Equation 3.31 through Equation 3.33.

\[ U_{D,P} = \pm \left( \frac{\partial P_{\text{rotor}}}{\partial V_{\text{Turbine}}} \cdot u_{V_{\text{Turbine}}} \right)^2 \]  

3.31

\[ U_{D,RPM} = \pm u_{\text{RPM}} \]  

3.32

\[ U_{D,C_P} = \pm \sqrt{\left( \frac{\partial C_P}{\partial V_{\text{Turbine}}} \cdot u_{V_{\text{Turbine}}} \right)^2 + \left( \frac{\partial C_P}{\partial P_{\text{Air}}} \cdot u_{P_{\text{Air}}} \right)^2 + \left( \frac{\partial C_P}{\partial T_{\text{Air}}} \cdot u_{T_{\text{Air}}} \right)^2 + \left( \frac{\partial C_P}{\partial U} \cdot u_U \right)^2} \]  

3.33

After the total experimental design uncertainty for each measurement is determined, the data reduction uncertainty is then calculated. Data reduction uncertainty is the result of the random scatter of the data. Precision errors for data reduction were computed for electrical power and rotor RPM (outlined by IEC 61400-12-1). As an example, the data reduction error for the electrical power measurements is defined as:

\[ S_{P,i} = \frac{\sigma_{P,i}}{\sqrt{N_i}} \]  

3.34

where: \( \sigma_{P,i} \) = standard deviation for the electrical power data per bin i
N\( _i \) = number of samples within bin i

To compute the total uncertainty, including experimental design uncertainty and data reduction errors, Equation 3.35 was used (example of electrical power shown):

\[ U_{n_{P,i}} = \sqrt{U_{D,P,i}^2 + S_{P,i}^2} \]  

3.34
3.6 Data Processing Procedure

This section presents in detail the data processing procedure used for the experimental data presented. The established procedure uses two primary MATLAB codes: (1) WT_realtimeproc.m for preliminary processing and (2) WT_processing_7.m for primary performance data processing. The need for codes was driven by the resolution limitations imposed by the pulse anemometer sensor as well as the needed flexibility of using varying averaging intervals in the primary performance data processing routine. The data processing procedure has been established as follows:

1. Create a weather data file for each WTMDDYY##_realtime.txt acquisition file. Weather information is best accessible from the Weather Underground website; The University Park Airport. (See Appendix H for an example file format and Section 3.3.3 for additional details)

2. Run the MATLAB code WT_realtimeproc.m in the same directory that the WTMDDYY##_realtime.txt acquisition files are stored. Be sure that the MATLAB code vane2angle.m is also located in that directory. This code will produce the 0.5 second data files WTMDDYY##_realtime_highres.txt.

3. Move all the WTMDDYY##_realtime_highres.txt data files which will be included in the performance computations to the same directory.

4. Run the MATLAB code WT_processing_7.m from the same directory where the WTMDDYY##_realtime_highres.txt data files are located. The code will prompt for the desired averaging interval for processing. This code will output four processed data files and many figures. The files include:
   a. Output_master.txt: Summary of all data averaged over the user specified averaging interval.
b. Output_processing.txt: Summary of all normalized data averaged over the user specified averaging interval

c. Output_A1_bin.txt: Summary of the bin averaged information from the data processing routine for anemometer station 1.

d. Output_A2_bin.txt: Summary of the bin averaged information from the data processing routine for anemometer station 2.

The code “WT_realtimeproc.m” is a pre-processing code meant to take raw digitized sensor data and compute performance quantities over 0.5 second intervals. During execution, the code will compute all testing parameters highlighted in Figure 3-13. The details of the testing parameters are too detailed to document individually but can be referenced in the provided code in Appendix I. It is important to note that this code will not execute correctly if the “vane2angle.m” subroutine is not located in the same directory.

Figure 3-13. WT_realtimeproc.m Block Diagram
The code “WT_processing_7.m” is the final processing routine which prompts the user for the specified averaging interval to be analyzed. For the results analyzed in this paper, averaging intervals of 1, 3, 10, and 60 seconds were examined. The code’s main looping structure will open and read all WTMDDYY##_realtime_highres.txt files chosen for examination by the user. It will then produce all summary output files highlighted earlier in this section. The code has the biasing correction methodology presented in section 3.5.2 built in. Results for both the unbiased and biased performance data can be compared for each anemometer bin information file. The plots created by the code are typical plots for performance analysis however custom figures can be created from the summary output files in Excel or MATLAB. The “WT_processing_7.m” code can be found in Appendix I.
Input Files

- User will select and the code will load multiple 0.5 Second Data Files. The user should only select the 0.5 Second Data File he wishes to include in the performance analysis.

Figure 3-14. WT_processing_7.m Block Diagram
Chapter 4

Horizontal Axis Wind Turbine Aerodynamics and Blade Optimization

Horizontal axis wind turbine aerodynamics is in many ways similar to that of helicopter aerodynamics. However, the differences in the design process arise from the vastly dissimilar specified parameters as well as the practical changes in dynamic loading priorities. But in order to begin to generate a basic understanding of either systems operation one must start with the same basics of rotor aerodynamics.

4.1 1-D Momentum and Rotor Disc Theory

In the initial analysis of the aerodynamics of a wind turbine it is prudent to concentrate on the energy extraction process without specific design details of the system. The flow analysis through a wind turbine can be approximated by an energy extracting actuator disc located within a stream-tube. Upstream of the actuator disc the stream-tube is assumed to have a cross-sectional area smaller than the actuator disc and an area larger than the disc downstream.

![Figure 4-1. Energy Extracting Actuator Disc and Stream-tube](image-url)
Using a quasi-one-dimensional approximation of the stream-tube, the expansion is the result of the mass flow rate being the same everywhere along the stream-tube.

\[ \rho A \infty U \infty = \rho A_d U_d = \rho A_w U_w \tag{4.1} \]

As indicated in Figure 4-1, the symbol \( \infty \) refers to conditions far upstream, \( d \) refers to conditions at the disc and \( w \) refers to conditions in the far wake. Since the velocity variation induced by the actuator disc is not directly known, it can be assumed that the flow at the disc is something partial to the free-stream velocity. The stream-wise component of this induced flow at the disc can therefore be given by \(-aU_\infty\), where \( a \) is called the axial flow induction factor.

\[ U_d = U_\infty (1 - a) \tag{4.2} \]

Using Bernoulli’s equation, one can relate the stagnation pressures from the free stream to pressures just before the actuator disc and from pressures just after the actuator disc to the wake, equations 4.3 and 4.4 can be derived. Combining these equations leads to a relationship between the pressure drop across the actuator disc and velocities at the free stream inlet and wake of the actuator disc. \((\Delta p = p^+ - p^-)\)

\[ p_{\infty} + \frac{1}{2} \rho U_{\infty}^2 = p_d^+ + \frac{1}{2} \rho U_d^2 \tag{4.3} \]

\[ p_d^+ - \Delta p + \frac{1}{2} \rho U_d^2 = p_\infty + \frac{1}{2} \rho U_w^2 \tag{4.4} \]

\[ \Delta p = \frac{1}{2} \rho (U_{\infty}^2 - U_w^2) \tag{4.5} \]
The difference in the momentum flux between the inlet and the outlet of the stream tube (shown in Figure 4-1) is:

\[
Rate \text{ of change of momentum flux} = (U_\infty - U_w)\rho A_d U_d \quad 4.5
\]

In order to cause a change in momentum flux a force is required. This force, called thrust, is assumed to come entirely from the pressure difference across the actuator disc.

\[
T = \Delta p A_d = (U_\infty - U_w)\rho A_d U_\infty (1 - a) \quad 4.6
\]

By combining equation 4.6 with equation 4.5 a relationship can be established between the far wake velocity and the far upstream velocity.

\[
U_w = (1 - 2a)U_\infty \quad 4.7
\]

The force on the actuator disc can then be described solely in terms of the far upstream velocity entering the stream-tube. This allows the power extraction to be quantified at the actuator disc knowing that power is equivalent to the rate of work done by a force.

\[
T = \Delta p A_d = 2\rho A_d U_\infty^2 a(1 - a) \quad 4.8
\]

\[
Power = F U_d = 2\rho A_d U_\infty^3 a(1 - a)^2 \quad 4.9
\]

The power coefficient is then defined with respect to power available in the air without the actuator disc present.
\[ C_p = \frac{\text{Power}}{\frac{1}{2} \rho U_e A_d} \]  
\[ C_p = 4a(1 - a)^2 \]

The maximum value of \( C_p \) will occur where the differentiation of equation 4.11 is zero. Hence, a maximum power coefficient and optimum induction factor can be established based off of the 1-D momentum theory presented in this chapter.

\[ \frac{dC_p}{da} = 4(1 - a)(1 - 3a) = 0 \quad \therefore \quad a = 1/3 \]

\[ C_{pmax} = \frac{16}{27} = 0.593 \]

This maximum achievable power coefficient is known as the Betz limit. Named after German aerodynamicist Albert Betz (1919), to date, no wind turbine has been designed to exceed this limit. It is important to note, the limit is not a deficiency in design but instead is the result of the free-stream inlet being smaller than the area of the actuator disc.

The thrust force on the rotor disc, given by equation 4.8, can also be non-dimensionalized to give a coefficient of thrust.

\[ C_T = \frac{T_{\text{hust}}}{\frac{1}{2} \rho U_e A_d} \]

\[ C_T = 4a(1 - a) \]

Actuator disc and momentum theory only allow designers to account for free stream momentum flow analysis. Since wind turbines almost certainly use an actuator disc which is comprised of rotational components there must be some consideration for the wake rotation and
angular momentum of the flow. \(15\) Rotor disc theory is the basis of this rotational approximation. The rotation of the actuator disc, or now a rotor, is the result of a torque being exerted on the rotor. This rotation and torque induces a reactionary rotation to the flow which can be assumed to remain relatively constant as the flow moves downstream of the rotor. Because of this effect, in order to accurately calculate power extraction an additional tangential flow induction factor \(a'\) must be introduced and derived.

When considering angular momentum theory the driving torque of the rotor can be related to total power by \(\delta P = \delta Q \Omega\).\(15\) Combining this relationship with the standard definition of power (force x velocity) and torque (mass flow rate x change of tangential velocity x radius), equation 4.16 can be derived. Introducing non-dimensional radial position \(\mu = r/R\), and tip speed ratio \(\lambda = \Omega R/U_{\infty}\), equation 4.17 can be used to relate the tangential flow induction factor to the axial flow induction factor.

\[
U_\infty^2 a (1 - a) = \Omega^2 r^2 a' \tag{4.16}
\]
\[
a' = a (1 - a)/\lambda^2 \mu^2 \tag{4.17}
\]

### 4.2 Classical Blade Element Momentum Analysis

The most commonly used method in blade design and performance analysis is that of blade element momentum theory. This method uses assumptions which eliminate interactions between subsequent blade element annuli (see figure 4-2). By eliminating these interactions, span-wise velocity components and three-dimensional effects can be neglected. BEMT also assumes the force from the blades on the flow is constant in each annular element; this corresponds to a rotor with an infinite number of blades.
It is assumed that the forces on a blade element can be calculated via two-dimensional aerofoil characteristics using an angle of attack $\alpha$ determined from the incident resultant velocity. Rotor inclination angle $\beta$ (blade twist plus pitch angle) and flow angle $\phi$ are thus defined with respect to angle of attack as seen in Figure 4-3. The resultant relative velocity of a rotating blade will then include tangential (in rotor plane) and axial (free stream) components.

$$W = \sqrt{U_{\infty}^2(1 - a)^2 + \Omega^2r^2(1 + a')^2}$$  \hspace{1cm} 4.18

Figure 4-2. Blade Element Theory and an Annular Ring$^{(13)}$

Figure 4-3. Blade Element Velocities and Forces$^{(13)}$
The force of a blade element is entirely responsible for the change of momentum of air in the annulus with which that element rotates. Given the inflow, the rotational rate of the rotor, and both induction factors ($\alpha$ and $\alpha'$) the flow angle $\phi$ can be computed from equation 4.20; this allows for the calculation of the local angle of attack from equation 4.19. From the lift-drag polar data for the selected airfoil, the performance coefficients can be referenced for the given angle of attack. Knowing these performance parameters, the local loading coefficients for the section can be computed from equation 4.21 and equation 4.22.

$$\tan \phi = \frac{(1-a)U_{\infty}}{(1+a)\omega r}$$  \hspace{1cm} 4.20

$$C_n = C_l \cos \phi + C_d \sin \phi$$ \hspace{1cm} 4.21

$$C_t = C_l \sin \phi - C_d \cos \phi$$  \hspace{1cm} 4.22

From these values new $\alpha$ and $\alpha'$ terms can be calculated via equation 4.23 and equation 4.24. If $\alpha$ and $\alpha'$ have changed more than an established tolerance then repeat the algorithm from equation 4.20 using the newly computed induction factors. Once the resulting induction factors are within the set tolerances then local loads on each segment can be computed.

$$\alpha = \frac{1}{\frac{4 \sin \phi^2}{\sigma r_n} + 1}$$  \hspace{1cm} 4.23

$$\alpha' = \frac{1}{\frac{4 \sin \phi \cos \phi}{\sigma c_z} - 1}$$  \hspace{1cm} 4.24
Given equations 4.18 through 4.24 presented previously, an algorithm can be developed to compute local loading at each segment of the blade. Since each control volume is assumed independent from another, the solution should be computed for each strip separately and thus the solution at one radius can be completed before proceeding to the next. *(15)*

Step 1. Initialize $\alpha$ and $\alpha'$, typically $\alpha = \alpha' = 0$.

Step 2. Compute the flow angle $\phi$ using equation 4.20.

Step 3. Compute the local flow angle of attack using equation 4.19.

Step 4. Read off $C_\ell(\alpha)$ and $C_d(\alpha)$ from table (airfoil performance).

Step 5. Compute $C_n$ and $C_t$ from equations 4.21 and 4.22.

Step 6. Calculate $\alpha$ and $\alpha'$ from equations 4.23 and 4.24.

Step 7. If $\alpha$ and $\alpha'$ has changed more than a certain tolerance, go to step 2 or else finish.

Step 8. Compute the local loads on the segment of the blades.

After applying the BEMT algorithm to all radial blade control volumes, the tangential and normal load distribution is known and performance quantities such as power and thrust can be computed. For instance, in order to integrate the tangential loads to give shaft torque, the tangential force per length $P_{T,i}$ is known for each segment at radius $r_i$ and a linear variation between $r_i$ and $r_{i+1}$ is assumed. Thus the load $P_T$ between $r_i$ and $r_{i+1}$ is given by:

$$P_T = A_i r + B_i \quad 4.25$$

Where,

$$A_i = \frac{P_{T,i+1} - P_{T,i}}{r_{i+1} - r_i} \quad and \quad B_i = \frac{P_{T,i+1} r_i - P_{T,i} r_{i+1}}{r_{i+1} - r_i} \quad 4.26$$

*See Figure 4-4 for clarification of terms in equations 4.25 and 4.26.*
4.2.1 Tip-Losses and Prandtl’s Correction

Prandtl’s tip loss factor corrects for the assumption of an infinite number of blades in BEMT theory. The vortex wake system is different for a rotor with a finite number of blades versus a rotor with an infinite number of blades. Prandtl derived a correction factor $F$ to be applied to the differential thrust and torque equations from blade-element momentum theory.

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

$$ f = \frac{B \cdot R - r}{2 \cdot r \cdot \sin \phi} $$

B is the number of blades, R is the total radius of the rotor, r is the local radius, and $\phi$ is the flow angle. Using differential thrust and torque relationships which include Prandtl’s tip correction, equations for $\alpha$ and $\alpha'$ can be derived.
Equations 4.29 and 4.30 should be used in place of equations 4.23 and 4.24 in step 6 of the BEMT algorithm and an extra step computing Prandtl’s tip loss factor F should be included after step 2.

4.2.2 Glauert Correction for High Values of Axial Induction Factor

Experiments have determined that 1D momentum theory for an ideal wind turbine is only valid for an axial induction factor of less than approximately 0.4. If momentum theory were to hold for high induction factors the velocity in the wake would have to become negative (see equation 4.7). Figure 4-5 shows experimental measurements of $C_T$ as a function of $\alpha$ for different rotor states.

![Figure 4-5. Comparison of Theoretical and Measured Values of Thrust Coefficient](image-url)
As $C_T$ increases the expansion of the wake also increases. In addition to wake expansion, the velocity jump from $U_\infty$ to $U_w$ must also increase. For a wind turbine, this means a high thrust coefficient and thus a high axial induction factor is present at low wind speeds. Simple momentum theory does not hold true for this state because the free shear layer at the edge of the wake becomes unstable. When the velocity jump $U_\infty - U_w$ becomes too high, eddies are formed which transport momentum from the outer flow into the wake. In rotor aerodynamics, this state is called the turbulent wake state.

Different empirical relationships between the thrust coefficient $C_T$ and $\alpha$ can be made to fit with the measurements presented in Figure 4-5.

\[
C_T = \begin{cases} 
4a(1 - a)F & a \leq \frac{1}{3} \\
4a(1 - \frac{1}{4}(5 - 3a)) & a > \frac{1}{3}
\end{cases} \quad 4.31
\]

\[
C_T = \begin{cases} 
4a(1 - a)F & a \leq \alpha_c \\
4(a^2 + (1 - 2\alpha_c)a)F & a > \alpha_c
\end{cases} \quad 4.32
\]

The expression in equation 4.32 is found in Spera (1994) and $\alpha_c$ is defined to be approximately 0.2. The application of Prandtl’s tip loss factor $F$ corrects for the assumption of an infinite number of blades in the expression. In application, the correction presented is applied locally on an annular element. From local aerodynamics, the thrust $dT$ on the annular element is given by equation 4.33. Thrust coefficient $C_T$ can be defined by equation 4.34 for an annular control volume.

\[
dT = \frac{1}{2} \rho B \frac{U_\infty^2 (1-a)^2}{\sin^2 \phi} CC_n dr \quad 4.33
\]

\[
C_T = \frac{dT}{\frac{1}{2} \rho U_\infty^2 2\pi r dr} \quad 4.34
\]
If equation 4.33 is substituted for \(dT\), equation 4.32 then becomes;

\[
C_T = \frac{(1-a)^2 \sigma C_n}{\sin^2 \phi}
\]

4.35

For application to the blade momentum theory algorithm, this expression for \(C_T\) can now be equated with the empirical expression presented previously (equation 4.32).

For \(a \leq a_c\):

\[
4a(1-a)F = \frac{(1-a)^2 \sigma C_n}{\sin^2 \phi}
\]

4.36

\[
a = \frac{1}{\frac{4F \sin^2 \phi}{\sigma C_n} + 1}
\]

4.37

For \(a > a_c\):

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

4.38

\[
a = \frac{1}{2} \left[ 2 + K(1 - 2a_c) - \sqrt{(K(1 - 2a_c) + 2)^2 + 4(Ka_c^2 - 1)} \right]
\]

4.39

\[
K = \frac{4F \sin^2 \phi}{\sigma C_n}
\]

4.40

In order to use the Glauert correction in momentum theory, equations 4.39 and 4.37 must replace equation 4.29 given the conditions for \(a\) stated above.
4.3 Rotor Optimization

After deriving all the necessary equations to compute the performance of a given wind turbine, one should be in the position to use these same equations to compute an optimum design. An optimum design can be defined as a wind turbine which when designed to produce electricity, does so at a competitive cost for a reasonable lifetime and will produce optimal power at a given site with a given wind distribution. For this section, a concentration will be made on how to design a rotor optimally for a given wind condition.

The annual energy production for a wind system is a combination of the wind distribution and the power curve. Thus, it is inherent that the optimal rotor design is site specific. Typically, a BEMT code is coupled with an optimization algorithm with constraints to optimize the geometry of the blades. It is of course also necessary afterwards to ensure that the optimum design will survive the entire design period, taking into account both extreme and fatigue loads. Control mechanisms are typically used by wind turbine systems so that the optimal operational power coefficient can be held through a wide range of wind condition states. This is typically achieved by maintaining the optimum tip speed ratio and pitch angle.

Figure 4-6 presents a qualitative performance curve for two possible designs. It is important to note that in these two different designs: design 1 has a high $C_{P,\text{max}}$ but $C_p$ drops off quickly at different tip speed ratios; design 2 has a lower $C_{P,\text{max}}$ but performs better over a range of tip speed ratios. Again, the decision on which design is best would need to take into account both the wind distribution at the site and power curve (which includes controlling mechanisms) for the wind turbine.
The first step of optimal design is to choose a good airfoil. The airfoil must be relatively roughness insensitive and posses an acceptable stall characteristic. In design, the effective angle of attack for each section along the span should be chosen such that the ratio between the lift and drag is highest. Once an airfoil and angle of attack is chosen, equations 4.41 and 4.42 can be combined to give an optimum relationship between local element speed ratio, \( x (\omega r/V_o) \) and \( \alpha \).

\[
\begin{align*}
  x^2 a' (1 + a') &= a(1 - a) \\
  a' &= \frac{1-3a}{4a-1} \\
  16a^3 - 24a^2 + a(9 - 3x^2) - 1 + x^2 &= 0
\end{align*}
\]

Figure 4-6. Qualitative comparison of two different designs
The optimal value for $\alpha'$ is found using equation 4.42. Since flow angle $\Phi$ can be found from equation 4.20 the optimal local pitch angle can be computed:

$$\theta_{opt} = \phi - \alpha_{opt}$$  \hspace{1cm} 4.44

The optimum chord distribution is found from equation 4.23 using the optimum values for $\alpha$ and $\alpha'$.

\[ c(x) = \frac{8\pi x \sin^2 \Phi}{(1-a)BC_n \lambda} \]  \hspace{1cm} 4.45

Figure 4-7. Variation of Blade Geometry Parameter with Local Speed Ratio \(^{(13)}\)

Figure 4-8. Variation of Inflow Angle with Local Speed Ratio \(^{(13)}\)
Chapter 5

Computational Performance Prediction Methods

A theoretical performance analysis for the wind turbine was performed to supplement and validate experimental measurements. The analysis includes the determination of the rotor aerodynamic and geometric properties, an estimation of the turbine alternator efficiency, and subsequent performance computations completed by the National Renewable Energy Laboratories rotor performance code WT_Perf (Ref. (16)).

In order to predict the aerodynamic performance of the wind turbine several steps had to be taken in both preparation for and execution of the WT_Perf code. The first step was to obtain rotor geometries for the wind turbine and approximate the airfoil used in the design. Once the airfoil was identified, aerodynamic performance polars had to be obtained for a range of relevant Reynolds numbers using the software XFOIL (Ref. (17)). The WT_Perf code, based on blade element momentum theory (BEMT), was then executed for rotational speeds, wind speeds, and resulting tip-speed ratios observed during field testing. From these computations, the mechanical power input to the turbine alternator was calculated from the integrated torque and speed of the rotor. A simple approximation for the alternator efficiency was applied to the mechanical power predictions for the rotor to yield calculated electrical power estimations for the turbine system.

5.1 Rotor and Airfoil Specifications

In order to accurately analyze the Whisper 500 rotor the chord, twist, airfoil design distributions were obtained. Specifications which could not be located in the wind turbine manual (Ref. (8)) were measured using a linear displacement voltage transducer (LVDT). The
rotor blades with rotor hub assembly were secured on a laboratory bench-top for the survey. An arrangement of linear traverse assemblies was used to measure the local rotor inclination $\beta$ (see Figure 4-3 for definition), local chord length, and local airfoil coordinates at seven stations along the blade. The results of this survey were used to create a CAD model of the blade. The local rotor inclination distribution and local chord distribution can be seen in Error! Reference source not found. and Error! Reference source not found.. The Whisper 500 wind turbine is compared against the Betz Optimum Rotor (as discussed in section 4.3).

![Whisper 500 and Betz Optimum Rotor Chord Distribution](image.png)

**Figure 5-1.** Whisper 500 and Betz Optimum Rotor Chord Distribution
The geometry for the Whisper 500 rotor blade airfoil was confirmed during the aforementioned LVDT survey. It was determined that the Wortmann FX 60-126 airfoil provided a good fit to results from the survey. Figure 5-3 shows the shape of the Wortmann FX 60-126 airfoil. Detailed airfoil coordinates are presented in Appendix J.
Once the turbine blade geometries were known they were then normalized to the rotor radius of 2.25 meters and then used as inputs into the WT_Perf code. Coordinates for the Wortmann FX 60-126 airfoil are used as inputs into XFOIL to calculate the performance polars for the cross-sections.

5.2 Xfoil

XFOIL version 6.9 was used to generate lift and drag performance polars for the Wortmann FX 60-126 airfoil. XFOIL is freely distributed program for design and analysis of airfoils in uniform subsonic flow. The code was selected due to its ability to rapidly generate lift and drag polars for the subsonic flow conditions under consideration. The XFOIL user guide (Ref. (17)) is available for a more complete explanation of the code with technical details.

The resulting lift and drag polars for the Wortmann FX 60-126 airfoil were then used as inputs in the WT_Perf BEMT turbine performance model. Performance polars for the FX 60-126 airfoil can be found in Appendix J.

5.3 Wind Turbine Performance Analysis, WT_Perf

The National Renewable Energy Laboratory performance code WT_Perf was applied to the rotor geometries and airfoil data to determine the torque and thrust of the Whisper 500 rotor. The code uses a very similar computational algorithm to the one presented by Hansen (Ref. (15)) and discussed in Chapter 4. Specific details regarding the contents of the algorithm can be referenced in the AeroDyn User Manual (Ref. (18)). The primary outputs of the analysis used are the torque, power, and thrust on the rotor at various rotor RPMs and wind speeds. WT_Perf
cannot take into account resistive torques due to loads within the alternator, turbulent air flow conditions, or alternator efficiencies.

The WT_Perf computational code has been validated and commonly employed by the National Wind Technology Center (NWTC) as well as multiple industry, research, and university studies (Ref. (18)). The BEMT based code was created by Aeroenvironment Inc. and has since been improved. Detailed information regarding the algorithm can be found in the AeroDyn User Manual (Ref. (19)) and WT_Perf User’s Guide (Ref. (20)). For more information regarding the specific simulation input parameters for this analysis see Appendix K.

5.4 Experimental Corrections and Considerations

Once the theoretical mechanical performance of the turbine was calculated using WT_Perf, the data was corrected using estimated efficiencies for the Whisper 500 generator. Estimates were made based off of alternator efficiencies determined by Martinez et al (5) for a Bergey Windpower XL.1 alternator. The XL.1 is a 2.5 m (8.2 ft.) rotor diameter wind turbine with a rated power of 1 kW in an 11 m/s (24.6 mph) wind. The XL.1, rated at a rotational speed of 490 RPM in an 11 m/s wind, has a lower rotor speed when compared to the Whisper 500 in the same 11 m/s wind. The alternator for the XL.1 is also of the same “can type” variable rotational speed design which exists on the Whisper 500. Considering these similarities, application of the efficiencies reported in Martinez (Ref. (5)) seemed reasonable to within engineering accuracy until generator tests can be run on the Whisper 500 system.

Shown in Figure 5-4, data for the XL.1 alternator were shifted to the operational rotational speed ranges of Whisper 500 to establish estimated generator efficiencies for the system. In order to shift the data, the operational rotational speed range of the XL.1 was assumed from Martinez et al (Ref. (5)) data and slightly shifted to the experimentally determined rotational...
speed range of the Whisper 500. This efficiency data was used in the determination of turbine electrical power performance predictions given the mechanical power performance predictions from WT_Perf.

![Efficiency Graph](image)

**Figure 5-4.** Estimated alternator efficiency data derived from XL.1 alternator experiments

### 5.5 Computational Results

In the next section computational results for the turbine power, coefficient of power, rotor thrust, and coefficient of thrust, are presented. These results were determined from the use of XFOIL and the NREL developed Wind Turbine Performance (WT_Perf) code.
5.5.1 WT_Perf, Power vs. Wind Speed

In Figure 5-5 the computational results for the wind turbine mechanical power production versus wind speed are shown for a range of typical turbine rotational speeds. The manufacturer specified power curve is also presented in the figure.

![Graph of turbine power vs. wind speed](image)

*Figure 5-5. Turbine power vs. free stream wind speed using WT_Perf and Manufacturer’s data*

The theoretical power output of the wind turbine is presented as a composition of curves at various rotational speeds of the turbine rotor. In order to make such predictions more useful, the performance characteristics of the controller and generator need to be employed. The result of such modifications to the prediction will provide insight into how the wind turbines rotational speed changes with wind speed and electrical loading. Because the wind turbine operates at
variable rotational speeds, these curves are not as useful as the non-dimensional power coefficient, $C_p$, and tip-speed ratio, $\lambda$, results presented in Figure 5-6 and Figure 5-8.

![Diagram showing turbine coefficient of power vs. wind speed using WT_Perf predictions.](image)

**Figure 5-6. Turbine Coefficient of Power vs. Wind Speed using WT_Perf**

In Figure 5-6, the coefficient of power, $C_p$, is shown versus wind speed for the WT_Perf performance predictions. Results are again shown for a range of rotational speeds which are typical for Whisper 500 operation. Using the estimated alternator efficiencies discussed previously, code predictions were corrected to more accurately portray the electromechanical performance of the Whisper 500 wind turbine. The manufacturer does not provide coefficient of power versus wind speed data but can be $C_p$ be computed via Equation 4.10. In Figure 5-7, the manufacturer specified coefficient of power versus wind speed curve is compared against alternator efficiency corrected WT_Perf data.
From Figure 5-7 it can be seen that there are significant differences between the WT_Perf performance predictions and the manufacturer specifications (Ref. (8)). Specifications for the Whisper 500 show a peak coefficient of power around 0.43 in a 4.5 m/s wind. The WT_Perf performance predictions show lower coefficient of power levels across all wind speeds. There are no references available to validate the manufacturer’s specifications for the Whisper 500 therefore it is difficult to develop explanations for differences between the results. If the specification data are experimentally determined then this should be confirmed by the experimental data produced by this study.
Figure 5-8 presents coefficient of power, $C_p$, versus tip-speed ratio, $\lambda$, results from WT_Perf. The performance prediction results include those with and without the alternator efficiencies applied. The prediction including alternator efficiency will be compared in Chapter 7 to the experimental results presented in Chapter 6. The prediction shows that the rotor can be expected to perform with a maximum coefficient of power of 0.34 at a tip-speed ratio of approximately 10.5. This prediction cannot be compared against manufacturer specifications since the rotational speeds at different wind speeds are not specified.
5.5.2 WT_Perf, Thrust vs. Wind Speed

The WT_Perf thrust predictions are now discussed. In Figure 5-9 the results for rotor thrust versus wind speed are shown for several rotational speeds. The rotor thrust is shown as a compilation of constant rpm curves throughout the known rotational speed range of the wind turbine. The WT_Perf performance prediction shows values of rotor thrust increasing through 1800 N [400 lbf] at a rotational speed of 600 rpm in a 20 m/s [45 mph] wind. The manufacturer specifications report a lateral thrust of 1720 N [400 lbf] (Ref. (8)).

![Figure 5-9. Turbine Thrust vs. Wind Speed using WT_Perf](image)

The thrust data predicted by WT_Perf for a range of turbine rotational speeds and wind velocities can also be plotted in non-dimensional terms, first as thrust coefficient versus wind
speed and then as a function of tip-speed ratio. The plot of coefficient of thrust versus wind speed is shown in Figure 5-10.

![Plot of coefficient of thrust versus wind speed using WT_Perf](attachment:image.png)

**Figure 5-10. Turbine Coefficient of Thrust vs. Wind Speed using WT_Perf**

Similar to power versus wind speed, a more detailed analysis considering the variable rotational speed of the turbine, using dimensionless parameters, was used. The WT_Perf performance prediction code produced thrust coefficient versus tip-speed ratio results which are shown in Figure 5-11. It can be seen that coefficient of thrust increases with increasing tip-speed ratio. The result can be expected since at high tip-speed ratios the local inflow tangential velocity \( \Omega r(1+a') \) of the blade will be larger with respect to the local normal velocity \( U_{\infty}(1-a) \). Referring to Figure 4-3, the effect is that the local flow angle, \( \phi \), will be small and therefore more of the local lift loading on the blade will be applied in the thrust (normal to the rotor plane) direction.
Figure 5-11. Turbine Coefficient of Thrust vs. Tip-Speed Ratio using WT_Perf
Chapter 6

Experimental Results

In the following chapter the experimental results for the turbine RPM, electrical performance, rotor torque, and rotor thrust are presented. Data obtained from experiments are compared to the manufacturers published performance curves for the Whisper 500 wind system. The results presented validate the electrical performance analysis methodologies presented previously. Comparisons between different averaging intervals show that the biasing correction methodology presented in section 3.5.2 produces a similar performance curve for each case. Results from the turbine power performance data shows similar characteristics to the National Renewable Energy Laboratory’s analysis of a Bergey Excel wind system\(^6\). Rotor thrust estimations are suspect as expected since the computations are derived from one-dimensional momentum theory and are not direct experimental measurements.

6.1 Data Distribution and Wind Direction

In Figure 6-1, the data distribution histogram for the Whisper 500 power performance measurements is presented. Only the wind speed data bins with at least 10 minutes or greater in data acquired were included in the proceeding analysis sections.
As shown in Figure 6-1, the distribution of data was heavily centered on the average testing wind speed of 4.7 m/s. In total, 675 minutes worth of data was included in the performance analysis of the Whisper 500 wind system. The application of the biasing correction between wind speed and the turbine power output requires that there be a normal distribution of wind speed variations. Figure 6-1 demonstrates a relatively normal distribution of data across wind speeds therefore the correction can be applied with some confidence in its accuracy. Ideally, more wind speeds would be acquired at higher than average wind speeds so to more fully populate the data library and produce the most ideal normal distribution across wind speeds.

In Figure 6-2, the wind rose is presented for the 1-second averaged data processing values. The most ubiquitous conclusion of the site analysis discussed in section 2.4 is that performance analysis should be limited to the prevailing wind direction of 290° as much as possible. The wind rose presented in Figure 6-2 shows that this was done successfully.
All data values included in the performance analysis of the wind turbine fell within the preliminary measurement sector of 210° to 330° bearing relative to the wind turbine. Consistency in wind direction amongst data points also adds to the accuracy of the biasing correction between wind speed and the power output of the wind turbine. If wind can be considered to most often be coming from the same direction then on average the delay between the anemometer response and turbine response will be similar.

### 6.2 Turbine RPM Performance

In Figure 6-3, un-averaged raw data for electrical power versus rotor rotational velocity (RPM) is shown for all samples acquired in the study.
Figure 6-3. Turbine power output versus RPM

As shown in Figure 6-3, the power output of the wind turbine increases with rotor RPM at a fairly predictable rate. Some deviation from the overall trend can be seen between RPM values of 200 and 500. This range is important since it is the most predominant operating range of the system. This deviation can most likely be explained by variations in the load resistance on the wind turbines three-phase AC circuitry. It was shown during preliminary diversion load testing (see Sect. 2.5.2) that varying the diversion load resistor setting can cause the wind turbine to operate in a different RPM – Power production mode. For simplicity of data analysis and isolation of a typical operating state, no changes to the resistor/diversion load were made and the turbine was allowed to divert to the dump load or charge the battery based on the controller operation for the duration of testing. In Figure 6-4, raw data samples are separated based on the diversion state of the wind turbine.
As shown in Figure 6-4, as power output and the RPM increase for the wind turbine the system begins to divert more often. This is expected since the wind energy system will likely be creating more power than can be consumed by load requirements at the site. However, due to the lack of non-diverting data points at high wind speeds it is impossible to conclude whether or not the power versus RPM relationship for the wind turbine is greatly affected during normal operation of the system. The results presented in Figure 6-3 and Figure 6-4 establishes the most precise representation of the performance of the wind energy system generator.

The results shown in Figure 6-5 establish a relationship between power output and RPM of the wind turbine. Only wind speed bins with at least 10-minutes of data sampled are included. The RPM and AC power values were obtained for each bin based on the average of those quantities which fell within the same wind speed bins. The fit presented for the data can be used to relate RPM performance of the rotor to the expected power output of the generator.
Figure 6-5. 1-Second Bin Averaged Turbine Power Output versus Rotor RPM

Figure 6-6. Raw rotor RPM vs. wind speed data
The result of binning and ensemble averaging rotor RPM performance data is shown in Figure 6-7. Data scatter can be simplified down to individual data points for each bin. As expected, the rotor RPM increases as wind speed increases. Sufficient data for resolution of the performance curve was acquired for wind speed bins between 3.5 m/s and 9 m/s. The wind speed values presented were corrected using the biasing methodology presented in section 3.5.2. Results show that the typical operating rotor RPM for the wind system was between 200 RPM and 400 RPM.
6.3 Turbine Power and Coefficient of Power

Figure 6-8 shows the raw data plot of the 1 sec averaged values— as required in the IEC 61400-12-1 testing standard of power vs. wind speed. The scatter illustrates that there is significant deviation between the expected power curve established by the manufacturer and individual raw power data points from experiments. This is an indicator of poor correlation between raw power and wind speed measurements. Figure 6-9 shows the raw data plot of the 60 sec averaged values. This data shows better correlation between raw power and wind speed measurements. The downside of the 60-second averaging results is that wind speed bins are populated and that more detailed aerodynamics effects can be distorted by averaging.

Figure 6-8. Raw electrical power vs. wind speed data (1-second averaging)
Figure 6-9. Raw electrical power vs. wind speed data (60-second averaging)

In Figure 6-10, the average power for each 0.5 m/s wind speed bin is shown for an averaging interval of 1 sec. For each bin, the minimum data point, maximum data point, and standard deviation of data within each bin is also presented. Two power curves are presented; the “Measured Power” curve represents the result of straight ensemble averaging of data points within each data bin and the “Corrected Power” curve is the result after application of the biasing correction to the “Measured Power” curve. Also presented are error bars which result from the uncertainty analysis presented in section 3.5.3
Results in Figure 6-10 agree well with the manufacturers’ power curve when examining the corrected power curve. The uncorrected measured power curve does not agree as well due to the lack of correlation between wind speed and power measurements without the biasing correction. There is a noticeable wide spread between maximum and minimum data points in each bin. This is expected since an averaging interval of 1 sec is considerably small thus it is unlikely that individual data points are an accurate representation of the performance of the system. This wide spread in data is quantified by the high standard deviation levels within each data bin.

In order to validate the accuracy of the biasing correction it should be shown that application of the correction will result in similar corrected power curves at different and much greater averaging intervals. Figure 6-11 and Figure 6-12 presents’ power curves for averaging intervals of 10 sec and 60 sec respectively.
In Figure 6-11 and Figure 6-12, the corrected power curves agree well with the manufacturers’ published power curve for the Whisper 500. It can also be noted that as the averaging interval increases the spread of minimum to maximum data points and standard deviation within each bin also decreases. This is an expected result since increasing the
averaging interval will result in a more accurate representation of the wind turbines performance for each individual data point.

The biasing correction applied to the measured power curve in Figure 6-12 resulted in only a slight shift to the corrected power curve. This result validates the biasing correction methodology. It is important to note that using a 1 sec averaging interval not only allows for better resolution of performance results but also a wider range of wind speeds since data is not over-concentrated through averaging down to a smaller range.

In Figure 6-13, the average values of $C_p$ are shown versus the binned wind speed. The maximum average coefficient of power value of 0.29 falls well below the maximum theoretical value of 0.59 based on the Betz limit.

![Figure 6-13. Average coefficient of power versus binned wind speed](image)
As shown in Figure 6-14, the average values of $C_p$ versus tip-speed ratio data gives the operational range of the rotor for the sufficiently populated wind speed bins included in the analysis. Peak $C_p$ levels are found to be present at low wind speeds and high tip speed ratios. The tip-speed ratio range for the wind turbine was found to be between 11 and 16. The actual peak $C_p$ of 0.29 was found to occur at a tip-speed ratio slightly above 13 and at a wind speed of 4.7 m/s.

Figure 6-14. Average coefficient of power and wind speed versus tip-speed ratio
6.4 Rotor Torque

Since the torque coefficient is derived from the power coefficient simply by dividing by the tip speed ratio it does not give any additional information about the turbines performance. The most prevalent use of rotor torque information is for assessment purposes when the rotor is connected to a generator.

Figure 6-15 shows how the torque developed by the Whisper 500 rotor rises with increasing wind speed. This result can be used in the future to evaluate the electromechanical performance of the wind system generator. It should be noted that since these values are derived from the AC power output of the generator it is likely that the inclusion of electrical losses would result in higher rotor torque levels being “seen” at the wind turbine rotor shaft.

![Figure 6-15. Average rotor torque versus binned wind speed](image-url)
6.5 Rotor Thrust and Coefficient of Thrust

The thrust force on the rotor is directly applied to the tower on which the rotor is mounted so it is critical to structural design of the tower. In Figure 6-17 average thrust values are shown versus binned wind speed. It should be noted that these thrust levels were computed from 1-dimensional momentum theory relationships which are generally invalid for axial induction factors greater than 0.4 and it approximates idealized rotor performance. Equation 4.11 was used to compute an “idealized” axial induction factor, $\alpha$, from power coefficient levels shown in Figure 6-13. The resulting axial induction factors were then used to compute thrust coefficients via equation 4.15. Figure 6-16 presents the axial induction factors which result from this approach.

![Figure 6-16. 1-D momentum theory axial induction factors versus binned wind speed](image)

At the axial induction factors presented in Figure 6-16 the rotor will be performing in the turbulent wake state region ($0.5 \leq \alpha \leq 1$) of the rotor axial loading curve. As can be seen in
Figure 4-5, it is likely that for an axial induction factor of 0.5 or greater that the wind generator will actually experience thrust coefficient levels greater than those predicted by 1-dimensional momentum theory.

In Figure 6-18, the average rotor thrust coefficient is shown versus binned wind speed. Thrust coefficient levels of approximately 0.85 correspond well with common 1-dimensional momentum theory based quantities presented in Figure 4-5.
It is likely that the thrust levels presented in this section are low estimates of the actual thrust being experienced by the wind turbine. Empirical and experimental evidence presented in Figure 4-5 suggest that thrust coefficients on the order of 1.25 should be expected for an experimental induction factor of 0.7. Referring to equation 4.14 and a thrust coefficient of 1.25, it could then be expected that a thrust force of approximately 900 N [200 lbs] would exist at a wind speed of 8.5 m/s [19 mph].
Chapter 7

Experimental and Computational Comparisons

The following sections present comparisons between the experimental results discussed in Chapter 6 and the WT_Perf computational results discussed in Chapter 5. Similarities and differences between results are compared and discussed. Where applicable, generator efficiency estimations are included in the computational results presented. Such comparisons not only produce evaluation data for the computational prediction methods but also indicate areas within the experimental data set that could be improved.

7.1 Turbine Power and Coefficient of Power

In Figure 7-1, the experimental power coefficient curve resolved from field testing is compared with the theoretically predicted curves (WT_Perf). The WT_Perf results are obtained at constant rotor rotational speeds (200, 300, and 400 RPMs) typical of normal operation for the wind turbine. Experimental results were obtained at varying RPM due to the variable rotational speed operation of the wind turbine. Because of this the experimental data points are expected to cross the WT_Perf constant RPM curves.

Through the majority of wind speeds the measured power coefficients fall lower than those predicted at the most prevalent rotational rates of the wind turbine; typically 300 to 400 rpm. Uncertainties for power measurement data are estimated to be ± 25 Watts based on the uncertainty methods presented in section 3.5.3. Differences between theory and experimental results can be attributed to WT_Perf model conditions (idealized flow assumptions common to all
BEMT models), conditions at the test site, and any additional electrical inefficiencies which are not accounted for in the correction for efficiency estimations.

Figure 7-1. Comparison of measured and predicted electric power coefficient for the Whisper 500

In Figure 7-2 the power coefficient for the turbine is plotted as a function of the tip-speed ratio instead of the wind speed. WT_Perf computational results at constant rotational speeds are compared against experimental power coefficient data. It should be noted that when analyzing the field data presented in Figure 7-1, low tip-speed ratios correspond with high speed data points and high tip-speed ratios correspond with low wind speed data points. It can be seen that the experimental and computational curves show some agreement at tip-speed ratios between 13 and 14 with a power coefficient of 0.28. The apparent peak power coefficient level of the experimental data occurs at a higher tip-speed ratio than what is predicted by WT_Perf.
From these results, it can be concluded that the rotor is likely operating at a non-optimum tip-speed ratio for which there could be two complementary causes. It can be deduced that there is an incorrect matching between rotor design and electrical loading on the generator. Since the experimental maximum power coefficient occurs at approximately 0.28 improvements to the rotor can likely be made at decreased tip-speed ratios so to better match the generators performance. The twist distribution of the Whisper 500 turbine is very far from the Betz optimum rotor indicating that operation at low tip speed ratios is producing non-optimum loading along the various radial positions of the rotor.

![Figure 7-2](image)

**Figure 7-2.** Average coefficient of power versus tip-speed ratio compared with WT_Perf data

The experimental power coefficient values shown in Figure 7-2 are lower than those in Figure 7-1 as a result of the binning process. Data for Figure 7-2 have a binning process which is
applied to tip-speed ratio (not wind speed) and the power coefficient data for each bin are averaged.

Closer examination of Figure 7-2 leads to questions about the measurement and data processing of results at higher wind speeds and lower tip-speed ratios. Since the power coefficient at low tip speed ratios falls off so drastically it may indicate that the controller is loading the wind turbine at a point where it is less efficient in high winds. Another possibility is that the data processing routine for this study is being applied incorrectly on the high wind data to produce accurate non-dimensional results.

Differences between the experimental power coefficient values and the WT_Perf predictions can also be attributed to the following factors: (1) differences in the inflow conditions between the experiments and WT_Perf data, (2) the resistive electrical loads on the alternator are not accounted for in the WT_Perf data, and (3) the assumptions of the WT_Perf model does not apply as well at high values of tip-speed ratio (Ref. (13)).

The introduction of resistive loads into the WT_Perf computations will more accurately represent the electro-mechanical performance of the wind turbine thus accounting for system torque losses which are not included in the computations. BEMT models “breakdown” in high tips-speed ratio operating conditions because a rotor operating at increasingly high tip speed ratios presents a decreasingly permeable disc to the flow. Empirical corrections are applied in the WT_Perf code for heavily loaded wind turbines, when a is high, but can still be considered suspect in these operating circumstances.
7.2 Rotor Thrust and Coefficient of Thrust

In Figure 7-3, estimated thrust data based on 1-dimensional momentum theory relationships are plotted against binned wind speed and compared with WT_Perf results through the full rotational speed range of the Whisper 500. Estimated thrust results are for varying rotational speeds whereas WT_Perf results are given along lines of constant rotational speeds. As noted previously, thrust data should be considered to have low fidelity since the data is directly calculated from power coefficient results through 1-dimensional momentum theory relationships. In the future, the facility should be instrumented to measure thrust in a more direct manner. That being said, estimated thrust data agree well with computational results. The result also seems to contradict the expectation that the computational results will show the highest possible thrust coefficients due to the assumptions made in the models.

Figure 7-3. Average turbine thrust versus binned wind speed compared with WT_Perf data
Discrepancies seen in Figure 7-3 can be attributed to several factors which are not accounted for in the WT_Perf performance predictions. The first factor is that the resistive torque from loading on the generator is known to greatly affect the operational loading of the wind turbine rotor. At present time, the available WT_Perf code cannot account for the variable electro-mechanical resistive torque loading on the generator since it is a purely BEMT based algorithm. Extensive testing of the electro-mechanical loading on the generator should be executed in the future so that the resistive torque can be quantified at various rotational speeds and a more accurate electrical efficiency correction can be applied. The second factor is that turbulent or obstructed airflow is not accounted for in the WT_Perf predictions. The computational predictions assume much idealized flow conditions which are never typical during testing on the Whisper 500 wind turbine due to the rotor’s high tip speeds. The third factor is the likely errors involved with computing the thrust loading on the wind turbine directly from 1-dimensional momentum equations based off of measured power coefficient data. A more extensive study of the rotor thrust will be included once an accurate method to measure thrust has been developed.
Chapter 8

Conclusions

The following section summarizes conclusion which can be made from this study. Important similarities and differences between results are compared and discussed so to examine necessary changes to the experimental methodology and facility setup. Where applicable, experimental improvements are suggested and projections on future facility developments are made.

9.1 Computational and Experimental Performance Conclusions

This research into the electro-mechanical and aerodynamic performance of a Southwest Windpower Whisper 500 system has provided a means to develop and validate data acquisition and processing methodologies for future research projects. Analysis of the wind turbine verified that parameters such as turbine electrical power and rotor rotational speed were accurately measured for a range of wind speeds.

The experimental results for electrical power agreed well with the power curve specifications provided by the manufacturer. A marginally resolved power curve was established for wind speeds ranging from 2 to 8.5 m/s. If more time was given for testing of the Whisper 500 system then more wind speeds would be resolved. The maximum coefficient of power measured was 0.29 for a tip-speed ratio of 13.5. Since the maximum coefficient of power is low and the resulting tip-speed ratio is high it is likely that a better match between the alternator and rotor design can be made to improve the efficiencies of the system.
The measured power performance results differed greatly from computational prediction results using the WT_Perf code. These differences were likely the result of the low quality of the test site as well as deviation between how the Whisper 500 rotor operated and assumptions applied by BEMT computations. WT_Perf, a BEMT based performance analysis code, runs under the assumptions of 2-Dimensional airfoil aerodynamics, empirical root-tip loss modeling, steady state inflow and turbine operation, and no consideration for radial flow along the span of the blade. All of the said assumptions will be less applicable to a wind turbine rotor operating at high tip-speed ratios. In addition, a more accurate analysis of the electro-mechanical efficiencies of the system may lead to better computational performance prediction results.

The estimated thrust values based on 1-dimensional momentum theory were found to be higher than those predicted by the WT_Perf code. It was estimated that the wind turbine produced 500 N [112 lbf] of thrust at a wind speed of 8 m/s [17.9 mph]. The Whisper 500 manual specifies that the rotor will produce a lateral thrust of 1720 N [≈ 400 lbf] at an unspecified wind speed. Extrapolating from the estimated thrust at 8 m/s aforementioned, and knowing that thrust is expected to increase with the square of wind speed (see Equation 4.14), it can be expected that the turbine will produce a thrust of 1750 N [≈ 400 lbf] in a 15 m/s [33.5 mph] wind. This result is reasonable since the manufacturer likely specified a peak lateral thrust loading which would occur at a wind speed close to 15 m/s, assuming the furling system does not immediately deploy at 12 m/s. Though the estimated thrust results seem reasonable relative to the manufacturer’s specifications, an alternate method to measure thrust on the wind turbine rotor should be developed.
9.2 Experimental Methods and Facility Improvements

The results from this round of experimental testing on the Whisper 500 system identify the need for several improvements which could be made to the facility and experimental methods. Facility improvements could be made in the areas of: instrumentation and equipment, data acquisition hardware, and data management. Experimental methods improvements can be made in the areas of: thrust measurement, additional sensing instrumentation, and more accurate examination of the electro-mechanical performance of the system.

In the area of instrumentation and equipment improvements, several additions to the measurement system could be made to improve the accuracy of wind turbine aerodynamic performance assessments. First, the addition of a thrust measurement system should be considered so that a more thorough examination and comparison of design changes can be made. Experimental methods involving thrust measurement will need to be changed when a new thrust measurement system is developed.

Another improvement which should be considered is the addition of a rotor direction encoder system which would allow for precise determination of the orientation of the rotor. At present the system depends solely on the wind direction measured at the wind direction vanes which may not be the direction the rotor is facing. In addition, extension of the main wind turbine tower should be considered so that obstacles near the testing facility become less of an obstruction during field testing.

The installation of a data acquisition and facility management building on the test site, which is presently in the process of being built, should allow for greater protection of facility components as well as more efficient testing during future research projects. The building will also provide a consistent load source for the wind-electric systems being tested. This will bring
the wind turbine controller into a more conventional operational state which will require less dumping to the diversion load and “healthier” charging/discharging of the system battery bank.

In the area of data acquisition hardware and data management, changes should be made to the system so that field testing is more autonomous. Even with improved data processing techniques which require a shorter testing duration, there is still a need to eliminate personnel having to be on-site during field testing. This is of particular concern during winter months when the wind resource is at its best but it is inconvenient to have system operators exposed to the weather. This can be achieved if a remote data logging system is located on site and either a wireless data transfer or on-site data storage system is developed. This improvement could be further facilitated if a data acquisition and facility management building is made operational. Not only will the building provide a load to the wind-electric system but important data acquisition and storage systems can also be facilitated and protected by the structure.

More advanced research with regard to wind turbine aerodynamic performance will require that measurements be made on components in rotation forward of the non-rotational armature structure of the wind turbine. Any measurements on components in rotation add the complexity of transmitting data signals “down-tower” through rotational connections which will require either a slip ring or telemetry system for data transfer. Due to the scale of the wind turbine components and the intricacy of the design, it would prove difficult to install a slip ring to the system. Therefore, a telemetry system needs to be developed so that data can be transferred from the rotor down to the data acquisition systems station. The addition of such a system will allow for the blades to be instrumented with accelerometers, strain gauges, and pressure sensors. These additional measurements will offer insight into the dynamic response of the rotor, aerodynamic loading on the blades, and further sensing to develop condition based health monitoring techniques.
9.3 Future Work

This research provides a strong experimental foundation so that several areas of further study can be made with the Whisper 500 testing facility. Future research at the facility will be able to build upon the fundamental techniques presented in this paper and perform experiments which will advance the state-of-the-art for wind energy technologies. At present, the wind energy industry faces issues with noise production, power generation in-efficiencies, system durability, inadequate condition based health monitoring systems, and the low fidelity of computational analysis tools. Further studies on the existing system should include: (1) the experimental development and verification of a thrust measurement technique, (2) improved understanding of the load controller and its interaction with the battery bank, (3) experiments to generate electro-mechanical efficiencies for the system, (4) experimentation with different blade geometries and materials, and (5) improved understanding of the high wind speed furling system.

As mentioned previously, further study of the thrust loading on the wind turbine rotor needs to be made. This study will allow for more accurate comparisons between experimental data and computational performance predictions. Development and validation of a thrust measurement technique will provide a more thorough examination of rotor performance as design changes are introduced in future experiments.

The electrical interaction between the load controller and battery bank should be better understood so that system performance assessments can be more accurate and more comprehensive. The introduction of a data acquisition and facility management building should help develop this understanding since the structure will provide a sustained load on the wind-electric system. The addition of a modified and variable load bank could also allow for a more thorough examination of the wind turbines performance with various rotor designs.
Experiments to determine the electro-mechanical efficiencies of the Whisper 500 system are necessary so that computational predictions can be adjusted accordingly. Computational models of the wind turbine only account for predicted rotor aerodynamic performance but not overall efficiency of the alternator and electrical connections. A bench-top examination of the system electrical output with known input torques will yield electro-mechanical efficiencies which could then be applied to computational predictions as a function of rotor rotational rates.

Experimentation with different blade geometries and materials will offer insight into ways to improve system performance, durability, and safety. These experiments will also give further insight into the validity of experimental methods and computational predictions for system performance. Results from such studies will lead to the examination of design improvements such as wingtip changes for improved efficiencies, trailing edge serrations for reduced noise, scaling methodologies for industry, and optimum blade design techniques.

Lastly, examination of the high-wind furling system will be made so to develop a more thorough understanding of the systems performance. This study will require a rotor direction encoder which indicates instances of rotor furling as well as an accurate thrust measurement technique. Such a study will be novel to the small wind industry allowing for improved high speed control designs and system durability improvements.
Bibliography


Appendix A

Full Schematic of the Data Acquisition System
Appendix B

CAD Drawing of the Whisper 500 Blade
### Appendix C

Tower Information: Loads and Procedures

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**Lowering Procedure Explained**

The first step to lower the turbine was to acquire all necessary material used to lower the turbine and understand the workings of each device. The list of materials can be seen below:

1 Chain Pull  
1 7’ Hand Power Pull  
2 Safety Chains (at least 14’ in length) {one ¼” and one 5/8”}  
1 D-Link Carabineer with thread lock (Part No. CMBP-1265 from Southwest Windpower)  
2 ¼” Chain Quick Hooks  
1 5/8” Chain Quick Hook  
4 quick links chain attachments (2 large and 2 small)  
3 Large Adjustable Wrenches  
Sawhorse or equivalent support device  
13 and 17mm hex and socket wrenches  
4mm Allen wrench  
Masking Tape and Sharpie  
String and Duct Tape

After acquiring the materials the wind turbine could then be taken down. This was done by first attaching 2’ of the 14 foot 5/8” chain to the anchor cemented into the ground via a 5/8” Chain Quick Hook; this acts as a safety chain. The other end was attached to a bolt passing through the inside of the gin pole via a small quick link chain attachment. Tension is then released from the turnbuckle on the gin pole anchor. The guy wire was then disconnected from the anchor support and attached to the gin pole through an already existing 1” hole via the D-Link Carabineer already attached to the guyed wire. Now the turbine is free to tilt.

In order to get the turbine to start falling, a force of approximately 100 pounds must be applied. This value was found via a static analysis which can be found in appendix G. In order to provide this force one must pull on the guy cable opposite of the cable now attached to the gin pole. This will cause the tower to tilt the 8 degrees necessary to cause tension on the attached safety chain. With the tower in the tilted position, the power pull, which was previously extended to the length of the safety chain, was attached to the anchor and the other end of the power pull was attached to the bolt passing through the inside of the gin pole via the hook attached to the come along. The power pull is then put in tension to bring tension off of the 5/8” safety chain. The ¼” safety chain is then preset to 7’ and attached in place of the 5/8” safety chain on the anchor end; this will leave the 5/8” safety chain to hang from the gin pole. After the power pull and 5/8” safety chain was attached it was slowly released to its extended most position of 7’ which was done one notch at a time to ensure the turbine did not fall or accelerate too rapidly. The loose end of the 5/8” safety chain was then attached to the end of the chain pull via a large quick link chain attachment. The geared end of the chain pull was attached to the anchor via its existing hook.
After attaching the chain pull it had to be put under tension to carry the load of the turbine. Once under tension the power pull was detached from the system. The wind turbine was then lowered the remainder of the distance via the chain pull keeping in mind to periodically check tension in the side guyed wires. Once low enough, a saw horse or an equivalent support structure was used to support some of the load of the turbine so that the cable was not bearing the entire load at such a high angle.

At this point the turbine and blades could be detached for proper maintenance. In order to detach the turbine the blades were first removed to make it easier to work with. The blades were removed by undoing the 4 bolts on each blade with a 17mm crescent wrench. Once the blades were attached the hub was removed from the pole by removing all bolts from the tower mounting piece. The wires were then tied off via string and duct tape and the pre-existing bolts holes. Masking tape and a sharpie was then used to mark the connections. Upon securing the wires they were detached from the split bolts on the tower insert and the Chinese finger attachment.
Appendix D

Inverter User Instructions

Aerospace Department Battery/Inverter Cart

User’s Guide

General Setup:

Make sure all switches are set to “OFF” before touching any cables.

The cart should never be placed fully upright with a battery attached!

Try to keep the cart as horizontal as possible.

The inverter has a 15A circuit breaker installed to limit AC power. Keep this in mind when choosing equipment to take with you.

Make sure the temperature sensor is in place on. By default it is attached to battery 1. If using only battery 2, it should be placed on that battery’s negative terminal.

When taking the cart for use outside, bringing along a tarp is not a bad idea.

When moving, make sure the pin that holds the handle is in place. After moving, check to make sure all connections are tight.
The battery furthest from the inverter is designated Battery 1, and the battery next to the inverter Battery 2. Battery 1 should not be removed from the cart. Cables to hook up Battery 2 are in the accessory box.

The Power Selector Box is attached above the inverter, and contains the Battery Selector Switch and Current Selector Switch. The Console box is attached to the inverter via a phone cord, and optionally, a remote switch. If the console panel is not attached, plug it into one of the plugs at the bottom of the panel (one of the plugs doesn’t work sometimes, just use the other one.)

The inverter cart is wired to allow the inverter to be turned on and off remotely at the console box. This is only necessary if remote shutdown of the inverter is required. To do this, make sure all switches are off, and then use the stereo cable that connects from the top of the selector box, to the bottom of the console box. Set the switch on the inverter to “Remote”. The red switch on the console box will now turn the inverter on and off.
Mode 1: Field Power Supply

As a field power supply, the cart draws power from the deep cycle batteries, and the inverter transforms it into 120V AC.

For 1 battery:

Set the battery selector to the battery to be used, the default is 1. If unsure, and only one battery is hooked up to the cart (MAKE SURE), the selector switch can be set to “1 + 2”.

The Current Selector Switch is then set to “AC”. The inverter switch is set to “ON” or “REMOTE” (above). With the inverter turned on, the mode on the console box is then set to “Inverting”.

When done, make sure to turn all switches to “OFF”.

For 2 batteries:

If using 2 batteries, wire the 2 batteries in parallel (see diagram). Set the battery selector to “1 + 2”.

The Current Selector Switch is then set to “AC”. The inverter switch is set to “ON” or “REMOTE” (above). With the inverter turned on, the mode on the console box is then set to “Inverting”.
When done, make sure to turn all switches to “OFF”.

Mode 2: Battery Charger

The inverter cart can charge 12V batteries. If more than one battery is on the cart, make sure they are wired in parallel. Make sure the temperature sensor is attached to the negative terminal of the battery being charged. Set the battery selector switch to the battery that needs charged (Do not set it to “1 + 2”), and the current selector switch to “AC”. Plug the inverter into the wall, and turn the switch to “ON” or “REMOTE”.

On the console, set Charging to “ON”.

When done, make sure to turn all switches to “OFF”.

DC Power Mode:

In the future, DC mode for the inverter will be added. To install, add a pair of “binding posts”, which will allow you to use the dual banana plug to BNC connectors (Newark part # 46F2329 looks like it should work). Additionally, to limit current, a 24V 15A DC circuit breaker should be added (McMaster part #4212T3) A toggle switch rated for 15A can be optionally added to the circuit (McMaster #8001k33 or any other switch rated 15A at 24V). The binding posts and circuit breaker are designed to go in the empty space to the right of the handle on the Power Selector Box.

Ideally, the circuit should be wired using 12 gauge wire, although 14 will do, and with the circuit breaker between the positive lead from the DC side of the current select switch, to the positive binding post. Note that the connections on the big red/orange switches are reversed from the label. The label on the top of the switch is “1”, the connection lug on the bottom is wired to “2”, and vice versa.
To obtain 12V DC power, set the Batter Selector switch to the appropriate battery. For 24V DC power, wire the 2 batteries in parallel as shown, and set the Battery Selector Switch to “1”. Set the Current Selection Switch to DC. When done, make sure to turn all switches to off, and rewire to 12V to prevent damage to the inverter.

Battery Life:

The battery installed on the cart has a capacity of ~100 Amp Hours. Each AC amp drawn is approximately 10 DC amps. This means that the maximum load of 15A AC, the battery will be depleted in approximately 40 minutes. To increase battery time, keep current draw to a minimum. Make sure the inverter battery is fully charged. Try to use laptops with fully charged batteries, and set its power needs to the lowest possible settings. If needed, a second batter can be installed in parallel to effectively double the time.
Appendix E

Voltage Transducer Wiring Diagram
Appendix F

LabVIEW Codes

Wind_Turbine_Acquisition.vi
**See Appendix D for vane2angle.vi algorithm.**
# Appendix G

## Wind Direction Vane Specifications and Algorithm

Table 5. Inspeed E-Vane Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSOR TYPE</td>
<td>Balanced wind vane connected to an active, non-contact, zero friction Hall Effect sensor (novotechik RFC4000 Model 600)</td>
</tr>
<tr>
<td></td>
<td>Sealed magnetic Hall Effect sensor</td>
</tr>
<tr>
<td></td>
<td>Magnet hovers over the sensor to provide ~0-5VDC output</td>
</tr>
<tr>
<td>SENSOR RANGE</td>
<td>Full 360 degrees, zero deadband</td>
</tr>
<tr>
<td>ACCURACY/LINEARITY</td>
<td>+/- 0.3 to 0.5% of signal range</td>
</tr>
<tr>
<td>RESOLUTION</td>
<td>12 bit or 0.025 degrees</td>
</tr>
<tr>
<td>ELECTRICAL</td>
<td>3 wire flying leads</td>
</tr>
<tr>
<td></td>
<td>Supply voltage 4.5 to 5.5 VDC</td>
</tr>
<tr>
<td></td>
<td>Current 15 mA typical</td>
</tr>
<tr>
<td></td>
<td>Output 5% to 95% of input voltage</td>
</tr>
<tr>
<td></td>
<td>Length of wire: 100 ft.</td>
</tr>
<tr>
<td>MOUNTING</td>
<td>The E-Vane has an offset aluminium bracket with 2 mounting holes. The mounting is compatible with the Inspeed Vortex Wind Sensor</td>
</tr>
<tr>
<td>DIMENSIONS</td>
<td>Directional Vane is approximately 8 inches</td>
</tr>
<tr>
<td>COMPATIBILITY</td>
<td>The Inspeed e-Vane is compatible with Inspeed WindWorks. Also capable of custom use setup</td>
</tr>
</tbody>
</table>
Variables:

- $V_{\text{min}}$ : minimum excitation voltage for sensor
- $V_{\text{max}}$ : maximum excitation voltage for sensor
- $\Psi_{\text{min}}$ : direction of sensor (usually magnetic) at minimum $V_{\text{min}}$ in radians
- $V$ : sensor excitation (VDC)

Algorithm:

1. $y = V \sin\left(\frac{2\pi}{V_{\text{max}}-V_{\text{min}}}\right) - \left(\frac{2\pi}{V_{\text{max}}-V_{\text{min}}}\right)V_{\text{min}}$
2. $x = V \cos\left(\frac{2\pi}{V_{\text{max}}-V_{\text{min}}}\right) - \left(\frac{2\pi}{V_{\text{max}}-V_{\text{min}}}\right)V_{\text{min}}$
3. CONDITIONAL IF LOOP
   a. IF $x = y = 0$: angle $= 0 + \Psi_{\text{min}}$
   b. ELSEIF $x >= 0$: angle $= \text{asin}(y) + \Psi_{\text{min}}$
   c. ELSE ($x < 0$): angle $= -1\times\text{asin}(y) + \pi + \Psi_{\text{min}}$
4. CONDITIONAL IF LOOP
   a. IF angle $> 2\pi$: coor angle $= \text{angle} - 2\pi$
   b. ELSE (angle $\leq 2\pi$): coor angle $= \text{angle}$
5. CONVERT “angle” from radians to degrees to get “dangle”
6. CONDITIONAL IF LOOP
   a. IF dangle $>= 0$: Azi_Angle $= \text{dangle}$
   b. ELSE (dangle $< 0$): Azi_Angle $= \text{dangle} + 360$
**Appendix H**

**Example Weather Data Input File**

Variables: {Index; Temperature (°F); Humidity (%); SL Pressure (in. Hg)}

FILE: weather_file_edit.txt

<table>
<thead>
<tr>
<th>Index</th>
<th>Temperature</th>
<th>Humidity</th>
<th>SL Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.7</td>
<td>50</td>
<td>29.74</td>
</tr>
<tr>
<td>2</td>
<td>48.7</td>
<td>50</td>
<td>29.74</td>
</tr>
<tr>
<td>3</td>
<td>49.5</td>
<td>48</td>
<td>29.74</td>
</tr>
<tr>
<td>4</td>
<td>49.8</td>
<td>44</td>
<td>29.74</td>
</tr>
<tr>
<td>5</td>
<td>51.4</td>
<td>40</td>
<td>29.73</td>
</tr>
<tr>
<td>6</td>
<td>50.2</td>
<td>40</td>
<td>29.74</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>41</td>
<td>29.74</td>
</tr>
<tr>
<td>8</td>
<td>51.1</td>
<td>40</td>
<td>29.74</td>
</tr>
<tr>
<td>9</td>
<td>50.5</td>
<td>40</td>
<td>29.73</td>
</tr>
<tr>
<td>10</td>
<td>52.7</td>
<td>38</td>
<td>29.73</td>
</tr>
<tr>
<td>11</td>
<td>54.3</td>
<td>37</td>
<td>29.73</td>
</tr>
<tr>
<td>12</td>
<td>54.3</td>
<td>37</td>
<td>29.73</td>
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<td>13</td>
<td>52.7</td>
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<td>14</td>
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</tr>
<tr>
<td>15</td>
<td>53.2</td>
<td>34</td>
<td>29.73</td>
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<tr>
<td>16</td>
<td>53.6</td>
<td>36</td>
<td>29.74</td>
</tr>
<tr>
<td>17</td>
<td>53.1</td>
<td>34</td>
<td>29.74</td>
</tr>
<tr>
<td>18</td>
<td>53.6</td>
<td>34</td>
<td>29.74</td>
</tr>
<tr>
<td>19</td>
<td>53.6</td>
<td>33</td>
<td>29.74</td>
</tr>
<tr>
<td>20</td>
<td>53.1</td>
<td>33</td>
<td>29.74</td>
</tr>
<tr>
<td>21</td>
<td>53.1</td>
<td>33</td>
<td>29.75</td>
</tr>
</tbody>
</table>
Appendix I

MATLAB Codes

WT_realtimeproc.m

clear all;
close all;
clc;
format long e;
disp(' ');
disp('********************************************************************************');
disp('Wind Turbine Realtime Data Processing');
disp('********************************************************************************');
disp(' ');
disp('For every input, be aware that they are case sensitive...');
disp(' ');

%____________________________________________________________________________

%% Inputs

R = 4.571/2; %Input Rotor Radius in Meters

% Atmospheric Conditions
rho_std = 1.225; %kg/m^3
Temp_std = 288.15; %degR
Baro_std = 1013.3; %mbar

% Vane Direction Zero Offsets and Constants
Vane_1_offset = 48;
Vane_2_offset = 342;
Vane_Max = 3.462;
Vane_Min = 0.18;
Ratio_1 = (2*pi) / (Vane_Max - Vane_Min);
Ratio_2 = Ratio_1*Vane_Min;

% Prompt for user inputs; enabling mutliselect for the data filename
% inputs; t, press, and Velmax are numeric inputs; output is a string input

mult_option = input('Do you want to process a single or multiple data acquisition files? Single (1) or Multiple (2): ');

if mult_option == 2

    [FileName,PathName,FilterIndex] = uigetfile('*.txt','Select Realtime Data files to be used in processing','MultiSelect','on');
    [WFileName,WPathName,WFilterIndex] = uigetfile('*.txt','Select Weather Data file to be used in processing','MultiSelect','off');
    Num_Files = length(FileName);
    Weather = char(WFileName);
    W_Matrix = dlmread(Weather, '\t');

else


[FileName, PathName, FilterIndex] = uigetfile('*.txt', 'Select Realtime Data file to be used in processing', 'MultiSelect', 'off');
    Num_Files = 1;
end

Fs = input('Enter data acquisition rate (hz): ');
if mult_option == 1
    plot_q = input('Do you want to plot 0.5 second data for these acquisition file(s)? Yes (1) or No (2): ');
    plot_ave = input('Do you want to compare 0.5 second data to averaged data? Yes (1) or No (2): ');
else
    plot_q = 2;
    plot_ave = 2;
end

Ts = 1/Fs;
if (plot_ave == 1) && (mult_option == 2)
    [AVGFileName, AVGPathName, AVGFilterIndex] = uigetfile('*.txt', 'Select Averaged Data files to be used in processing', 'MultiSelect', 'on');
elseif (plot_ave == 1) && (mult_option == 1)
    [AVGFileName, AVGPathName, AVGFilterIndex] = uigetfile('*.txt', 'Select Averaged Data file to be used in processing', 'MultiSelect', 'off');
end

file_create = input('Do you want to create a 0.5 second data file? Yes (1) or No (2): ');
quick_process = input('Do you want an expedited processing routine; this will limit resolution of RPM data? Yes (1) or No (2): ');

if quick_process == 1
    Factor = 2;
else
    Factor = 100;
end

for j = 1:1:Num_Files
    if (file_create == 1) && (mult_option == 2)
        S = char(FileName(j));
        output = char([S(1:19), '_highres.txt']);
    end
end
else if (file_create == 1) && (mult_option == 1)
    S = char(FileName);
    output = char([S(1:19), '_highres.txt']);
else
    S = char(FileName);
end

disp(' ');
disp(['**FILE: ', S, '**']);
disp(' ');
if (file_create == 1) && (mult_option == 2) && (Factor == 100)
    COND(1,1) = W_Matrix(j,2);
    COND(1,2) = W_Matrix(j,4);
    COND(1,3) = W_Matrix(j,3);
else if (file_create == 1) && (mult_option == 1) && (Factor == 100)
    file = dir(fullfile(PathName,char(FileName)));
    disp([file.name, ' was executed on ', file.date]);
    Temp = input(['Enter atmospheric temperature during testing for ', file.name, ' (deg F): ']);
    Press = input(['Enter barometric pressure measured during testing for ', file.name, ' (in Hg): ']);
    Hum = input(['Enter relative humidity measured during testing for ', file.name, ' (%): ']);
    COND(1,1) = Temp;
    COND(1,2) = Press;
    COND(1,3) = Hum;
end

disp(' ');
disp('Wait while the files and data are loaded.....');

allfields = dlmread(S,'%t',1,0); %reads all columns from a tab delimited file
DC_Current = allfields(:,1);
DC_Voltage = allfields(:,2);
AC_Current = allfields(:,3);
AC_Voltage = allfields(:,4);
WindSpeed1 = allfields(:,5);
WindSpeed2 = allfields(:,6);
WindDir1 = allfields(:,7);
WindDir2 = allfields(:,8);

Num_points = length(DC_Current);
Final_Time = (Num_points-1)*Ts;
Time = 0:(Ts):((Num_points-1)*Ts);
Time = Time.';
time = Time;

disp('Data has been loaded.....');
disp('Wait while data is processed.....
');

%% Covert Pulse Anemometer Voltages to 0.5 second Wind Speed Data

% Set the threshold to 3.25 V to mark the rise and fall of the signal
threshold = 3.25;

% Create the offset data. Need to append a NaN to the final sample since
% both vectors need to have the same length.
offsetData = [WindSpeed2(2:end,1); NaN];

% Find the rising edge.
risingEdge = find(WindSpeed2(:,1)< threshold & offsetData > threshold &
offsetData - WindSpeed2(:,1) >= 1);

% Find the falling edge.
fallingEdge = find(WindSpeed2(:,1) > threshold & offsetData < threshold);

% Construct a vector to hold all of the times.
pulseIndices = zeros(length(risingEdge), 1);
% Store the rising edge times.
pulseIndices(1:end) = risingEdge;
Pulse_Time = pulseIndices(2:end)*Ts;
pulseTimes = zeros(1,length(pulseIndices)-1);

for i=1:length(pulseIndices)-1
    pulseTimes(1,i)=pulseIndices(i+1)-pulseIndices(i);
end

WindSpeed2_Period = pulseTimes*Ts;
WindSpeed2_freq = WindSpeed2_Period.^-1;
WindSpeed2_Vel = WindSpeed2_freq*2.5;

xi = 0.5:0.5:floor(Final_Time);
WindSpeed2_Vel_cubic = interp1(Pulse_Time,WindSpeed2_Vel,xi,'cubic');

%% Separate Signals into 0.5 Second Intervals and Process

ave_t_index = floor(Num_points / (0.5*Fs));
ave_t_index_pts = 0.5*Fs;

Time_Int = zeros(ave_t_index_pts,ave_t_index);
DC_Current_Int = zeros(ave_t_index_pts,ave_t_index);
DC_Voltage_Int = zeros(ave_t_index_pts,ave_t_index);
AC_Current_Int = zeros(ave_t_index_pts,ave_t_index);
AC_Voltage_Int = zeros(ave_t_index_pts,ave_t_index);
WindSpeed1_Int = zeros(ave_t_index_pts,ave_t_index);
WindDir1_Int = zeros(ave_t_index_pts,ave_t_index);
WindDir2_Int = zeros(ave_t_index_pts,ave_t_index);

for i=1:1:ave_t_index
    Time_Int(:,i) = Time(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);
    DC_Current_Int(:,i) = DC_Current(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);
    DC_Voltage_Int(:,i) = DC_Voltage(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);
    AC_Current_Int(:,i) = AC_Current(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);
    AC_Voltage_Int(:,i) = AC_Voltage(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);
    WindSpeed1_Int(:,i) = WindSpeed1(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);
end
WindDir1_Int(:,i) = WindDir1(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);
WindDir2_Int(:,i) = WindDir2(ave_t_index_pts*i-(ave_t_index_pts-1):ave_t_index_pts*i);

for i=1:1:ave_t_index

    Time_avg (i) = Time_Int(ave_t_index_pts,i) + Ts;
    L = length(AC_Voltage_Int(:,i));
    % std(X,1) is form of standard deviation that computes RMS(X)
    DC_Current_avg (i) = mean(DC_Current_Int(:,i))*12.5;
    DC_Voltage_avg (i) = mean(DC_Voltage_Int(:,i))*12.5;
    DC_Power(i) = DC_Current_avg(i)*DC_Voltage_avg(i);
    AC_Current_avg (i) = std(AC_Current_Int(:,i),1)*12.5;
    AC_Voltage_avg (i) = std(AC_Voltage_Int(:,i),1)*12.666;
    AC_Power(i) = 3*AC_Current_avg(i)*AC_Voltage_avg(i);
    WindSpeed1_avg(i) = std(WindSpeed1_Int(:,i),1)*53.599;
    WindDir1_avg_Ratio1 = Ratio_1*WindDir1_Int(:,i);
    WindDir1_avg_Ratio2 = WindDir1_avg_Ratio1(:)-Ratio_2;
    [azimuthal_angle1(i),x1(i),y1(i)] = vane2angle(Vane_1_offset,WindDir1_avg_Ratio2);
    [azimuthal_angle2(i),x2(i),y2(i)] = vane2angle(Vane_2_offset,WindDir2_avg_Ratio2);
    NFFT = 2^nextpow2(Factor*L); % Next power of 2 from length of y
    Y = fft(AC_Voltage_Int(:,i),NFFT)/L;
    f = Fs/2*linspace(0,1,NFFT/2);
    max_num = max(2*abs(Y(1:NFFT/2)));
    RPM_index = find( 2*abs(Y(1:NFFT/2)) == max_num);
    RPM(i) = f(RPM_index)/8;
    RPS(i) = RPM(i)*60;
end

x1_scaled = WindSpeed1_avg.*x1;
y1_scaled = WindSpeed1_avg.*y1;

x2_scaled = WindSpeed2_Vel_cubic.*x2;
y2_scaled = WindSpeed2_Vel_cubic.*y2;
if plot_q == 1:

    disp('Plotting realtime data.....');

    figure(1)
    hold on
    title('Wind Speed Anemometer Comparison')
    plot(Time_avg,WindSpeed1_avg,'b','LineStyle','--')
    plot(xi,WindSpeed2_Vel_cubic,'r','LineStyle','-')
    legend('Wind Speed 1','Wind Speed 2')
    xlabel('Time (sec)')
    ylabel('Wind Speed (MPH)')
    grid on
    hold off

    figure(2)
    hold on
    title('Current Comparison')
    plot(Time_avg,DC_Current_avg,'b','LineStyle','--')
    plot(Time_avg,AC_Current_avg,'r','LineStyle','-')
    legend('DC Current','AC Current')
    xlabel('Time (sec)')
    ylabel('Current (Amps)')
    grid on
    hold off

    figure(3)
    hold on
    title('Voltage Comparison')
    plot(Time_avg,DC_Voltage_avg,'b','LineStyle','--')
    plot(Time_avg,AC_Voltage_avg,'r','LineStyle','-')
    legend('DC Voltage','AC Voltage')
    xlabel('Time (sec)')
    ylabel('Voltage')
    grid on
    hold off

    figure(4)
    hold on
    title('Power Comparison')
    plot(Time_avg,DC_Power,'b','LineStyle','--')
    plot(Time_avg,AC_Power,'r','LineStyle','-')
    legend('DC Power','AC Power')
    xlabel('Time (sec)')
    ylabel('Power (Watts)')
    grid on
    hold off

    figure(5)
    hold on
    title('Power and Wind Speed 1')
    [AX,H1,H2] = plotyy(Time_avg,AC_Power,Time_avg,WindSpeed1_avg,'plot');
    set(get(AX(1),'Ylabel'),'String','AC Power (Watts)')
    set(get(AX(2),'Ylabel'),'String','Wind Speed 1 (MPH)')
    xlabel('Time (sec)')
    set(H1,'LineStyle','--')
    set(H2,'LineStyle',':')
    grid on
    hold off
figure(6)
hold on
title('Power and Wind Speed 2')
[AX,H1,H2] = plotyy(Time_avg,AC_Power,xi,WindSpeed2_Vel_cubic,'plot');
set(get(AX(1),'Ylabel'),'String','AC Power (Watts)')
set(get(AX(2),'Ylabel'),'String','Wind Speed 2 (MPH)')
xlabel('Time (sec)')
set(H1,'LineStyle','--')
set(H2,'LineStyle':'')
grid on
hold off

figure(7)
hold on
title('Power and RPM')
[AX,H1,H2] = plotyy(Time_avg,AC_Power,Time_avg,RPM,'plot');
set(get(AX(1),'Ylabel'),'String','AC Power (Watts)')
set(get(AX(2),'Ylabel'),'String','RPM')
xlabel('Time (sec)')
set(H1,'LineStyle','--')
set(H2,'LineStyle':'')
grid on
hold off

figure(8)
hold on
title('Wind Direction Comparison')
plot(Time_avg,azimuthal_angle1,'b','LineStyle','--')
plot(Time_avg,azimuthal_angle2,'r','LineStyle','-')
legend('Vane 1','Vane 2')
xlabel('Time (sec)')
ylabel('Direction')
grid on
hold off

figure(9)
hold on
title('Generator Performance')
scatter(RPM,AC_Power)
xlabel('RPM')
ylabel('AC Power (Watts)')
grid on
hold off
end

if plot_ave == 1;

disp('Loading LabView Averaged data.....');

V = char(AVGFileName);
allfields = dlmread(V,'%t',1,0); %reads all columns from a tab delimited file
AVG_Time = allfields(:,1);
AVG_DC_Current = allfields(:,2);
AVG_DC_Voltage = allfields(:,3);
AVG_DC_Power = allfields(:,4);
AVG_AC_Current = allfields(:,5);
AVG_AC_Voltage = allfields(:,6);
AVG_AC_Power = allfields(:,7);
AVG_TurbineRPM = allfields(:,8);
AVG_WindSpeed1 = allfields(:,9);
AVG_WindSpeed2 = allfields(:,10);
AVG_WindDir1 = allfields(:,11);
AVG_WindDir2 = allfields(:,12);

AVG_Length = length(AVG_Time);
AVG_TimeCorr = zeros(1,AVG_Length);

for i=1:AVG_Length
    AVG_TimeCorr(i) = AVG_Time(i) - AVG_Time(1);
end

disp('Plotting realtime versus averaged data comparisons.....');

figure(10)
hold on
title('Wind Speed 1 Averaged Anemometer Comparison')
plot(Time_avg,WindSpeed1_avg,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_WindSpeed1,'r','LineStyle','--')
legend('Wind Speed 1','Wind Speed 1 Ave.')
xlabel('Time (sec)')
ylabel('Wind Speed (MPH)')
grid on
hold off

figure(11)
hold on
title('Wind Speed 2 Averaged Anemometer Comparison')
plot(xi,WindSpeed2_Vel_cubic,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_WindSpeed2,'r','LineStyle','--')
legend('Wind Speed 2','Wind Speed 2 Ave.')
xlabel('Time (sec)')
ylabel('Wind Speed (MPH)')
grid on
hold off

figure(12)
hold on
title('Averaged AC Current Comparison')
plot(Time_avg,AC_Current_avg,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_AC_Current,'r','LineStyle','--')
legend('AC Current','AC Current Ave.')
xlabel('Time (sec)')
ylabel('AC Current (Amps)')
grid on
hold off

figure(13)
hold on
title('Averaged AC Voltage Comparison')
plot(Time_avg,AC_Voltage_avg,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_AC_Voltage,'r','LineStyle','--')
legend('AC Voltage','AC Voltage Ave.')
xlabel('Time (sec)')
ylabel('AC Voltage')
grid on
hold off

figure(14)
hold on
title('Averaged AC Power Comparison')
plot(Time_avg,AC_Power,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_AC_Power,'r','LineStyle','--')
legend('AC Power','AC Power Ave.')
xlabel('Time (sec)')
ylabel('AC Power (Watts)')
grid on
hold off

figure(15)
hold on
title('Averaged Vane 1 Comparison')
plot(Time_avg,azimuthal_angle1,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_WindDir1,'r','LineStyle','--')
legend('Vane 1','Vane 1 Ave.')
xlabel('Time (sec)')
ylabel('Direction')
grid on
hold off

figure(16)
hold on
title('Averaged Vane 2 Comparison')
plot(Time_avg,azimuthal_angle2,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_WindDir2,'r','LineStyle','--')
legend('Vane 2','Vane 2 Ave.')
xlabel('Time (sec)')
ylabel('Direction')
grid on
hold off

figure(17)
hold on
title('RPM Comparison')
plot(Time_avg,RPM,'b','LineStyle','--')
plot(AVG_TimeCorr,AVG_TurbineRPM,'r','LineStyle','--')
legend('RPM','RPM Ave.')
xlabel('Time (sec)')
ylabel('RPM')
grid on
hold off

end

if file_create == 1

disp('Creating 0.5 second data file....');

M = zeros(length(AC_Power),12);
M(:,1) = Time_avg;
M(:,2) = DC_Current_avg;
M(:,3) = DC_Voltage_avg;
M(:,4) = DC_Power;
M(:,5) = AC_Current_avg;
M(:,6) = AC_Voltage_avg;
M(:,7) = AC_Power;
M(:,8) = RPM;
M(:,9) = WindSpeed1_avg;
M(:,10) = WindSpeed2_Vel_cubic;
M(:,11) = azimuthal_angle1;
M(:,12) = azimuthal_angle2;

dlmwrite(output, COND, '\t')

dlmwrite(output, M,'-append', 'roffset', 1, 'delimiter', '\t')

code concludes

disp(' ');
disp('End of Code.....');
disp(' ');
disp(' ');}
function [azimuthal_angle,x,y] = vane2angle(offset,WindDirVolts)
size = length(WindDirVolts);

for j = 1:size
    x(j) = cos(WindDirVolts(j));
    y(j) = sin(WindDirVolts(j));
end

x = mean(x);
y = mean(y);

offset_rad = (offset*pi) / 180;
if (x == 0) && (y == 0)
    angle = 0 + offset_rad;
elseif (x >= 0)
    angle = asin(y) + offset_rad;
elseif (x < 0)
    angle = -1*asin(y)+ pi + offset_rad;
else
    disp('invalid wind direction voltage')
end

if angle > 2*pi
    coor_angle = angle - 2*pi;
else
    coor_angle = angle;
end

degrees = (coor_angle * 180) / pi;

if degrees >= 0
    azimuthal_angle = degrees;
else
    azimuthal_angle = 360 + degrees;
end
clear all;
close all;
c1c;
format long e;

disp('');
disp('*******************************************************************************');
disp('WIND TURBINE 0.5 SECOND AVERAGED DATA PROCESSING');
disp('*******************************************************************************');
disp('');
disp('For every input, be aware to type capital letters where you have to...');
disp('');

%% Designate Constants
R = 4.571/2; % Rotor Radius in Meters

% Standard Atmospheric Conditions
rho_std = 1.225; % kg/m^3
Temp_std = 288.15; % degR
Baro_std = 1013.3; % mbar

%% User File Prompt and File Creation
[FileName,PathName,FilterIndex] = uigetfile('*txt','Select pre-processed data acquisition input file','MultiSelect','on');
master_directory = uigetdir('C:\Users\Brian\Desktop\WORK\Wind Turbine\Field Experiments\Input File Prep','Select Directory to Save Processed Data');
out = input('Enter base output file name for processing results: ','s');
output = [out,'_master.txt'];
output2 = [out,'_processing.txt'];
output3 = [out,'_A1_bin.txt'];
output4 = [out,'_A2_bin.txt'];
average_interval = input('Enter data resolution (averaging) interval in seconds: ');
average_interval_string = num2str(average_interval);
today = now;
V = datevec(today);
V1 = num2str(V(1));
V2 = num2str(V(2));
V3 = num2str(V(3));
mkdir(master_directory,['WT','V2,V3,V1,'_,average_interval_string,'sec_Processing']);
WT_Perf = input('Would you like to compare data with WT_Perf results {no(0) or yes(1)}: ');
ifWT_Perf == 1
    [WT_Perf_FileName,PathName,FilterIndex] = uigetfile('*txt','Select wind speed based WT_Perf output file (.oup)');
    [WT_Perf_FileName2,PathName2,FilterIndex2] = uigetfile('*txt','Select tip speed ratio based WT_Perf output file (.oup)');
end

%% Create Manufacturers Power Curve for Comparison
manu_windspd =
manu_power =
[23.0769; 146.1538; 238.4615; 353.8462; 438.4615; 515.3846; 623.0769; 776.9231; 915.3846; 1030.7692; 1207.6923; 1376.9231; 1600; 1784.6154; 1946.1538; 2161.5385; 2392.3077; 2630.7692; 2823.0769; 2938.4615; 3023.0769; 3107.6923; 3192.3077; 3253.8462; 3284.6154; 3307.6923; 3307.6923; 3307.6923; 3284.6154; 3238.4615; 3161.5385; 3069.2308; 2969.2308; 2830.7692; 2707.6923; 2592.3077; 2446.1538; 2307.6923; 2200; 2115.3846; 2053.8462];

%% Load Files

Num_files = length(FileName);

tempR = zeros(1,Num_files);
Press = zeros(1,Num_files);
rho = zeros(1,Num_files);

for i = 1:Num_files
    clear X;
    S = char(FileName(i));
    M = dlmread(S, '\t');
    tempR(i) = M(1,1) + 459.67 / 1.8;
    Press(i) = M(1,2)*33.864;
    rho(i) = rho_std*(Temp_std/tempR(i))*(Press(i)/Baro_std);
end
n = dlmread(S, '\t', 2, 0);
data_length = length(n);
Final_Time = data_length*0.5;
Ave_intervals = floor(Final_Time / average_interval);
Ave_points = average_interval / 0.5;

m = zeros(Ave_intervals,12);
points = 0;
for j = 1:Ave_intervals
    m(j,1) = n(points+Ave_points,1);
    m(j,2) = mean(n(points+1:j*Ave_points,2));
    m(j,3) = mean(n(points+1:j*Ave_points,3));
    m(j,4) = mean(n(points+1:j*Ave_points,4));
    m(j,5) = mean(n(points+1:j*Ave_points,5));
    m(j,6) = mean(n(points+1:j*Ave_points,6));
    m(j,7) = mean(n(points+1:j*Ave_points,7));
    m(j,8) = mean(n(points+1:j*Ave_points,8));
    m(j,9) = mean(n(points+1:j*Ave_points,9));
    m(j,10) = mean(n(points+1:j*Ave_points,10));
    m(j,11) = mean(n(points+1:j*Ave_points,11));
    m(j,12) = mean(n(points+1:j*Ave_points,12));
    points = points + Ave_points;
end
temp_size = size(m);
X(1:temp_size(1),:) = i;
X(1:temp_size(1),2:temp_size(2)+1) = m;
dlmwrite(output, X, 'delimiter', '	', '-append');
end

disp(' ');
disp('Successful Reading of Files. Wait for the "end of code" message....');
disp(' ');

%% Organize Matrices for Calculations
M = dlmread(output, '	');
cd([master_directory, '\WT',V2,V3,V1,'_',average_interval_string,'sec_Processing ']);
dlmwrite(output, M, 'delimiter', '	');

num = length(M);
M_index = M(:,1);
M_Time = M(:,2);
M_DC_Current = M(:,3);
M_DC_Voltage = M(:,4);
M_DC_Power = M(:,5);
M_AC_Current = M(:,6);
M_AC_Voltage = M(:,7);
M_AC_Power = M(:,8);
M_Turbine_RPM = M(:,9);
M_WindSpeed1 = M(:,10)*0.44704;
M_WindSpeed2 = M(:,11)*0.44704;
M_WindDir1 = M(:,12);
M_WindDir2 = M(:,13);

%% Calculate Wind Speed and Power under Atmospheric Corrections
j=1;
for i=1:1:num
    if (M_WindSpeed2(i) >= 2) && (M_WindSpeed1(i) >= 2)
        avgfields(j,:) = M(i,:);
        j=j+1;
    end
end

Index = avgfields(:,1);
Time = avgfields(:,2);
DC_Current = avgfields(:,3);
DC_Voltage = avgfields(:,4);
AC_Current = avgfields(:,6);
AC_Voltage = avgfields(:,7);
Turbine_RPM = avgfields(:,9);
WindDir1 = avgfields(:,12);
WindDir2 = avgfields(:,13);
temp_length = size(avgfields);
for i = 1:temp_length(1)
    for k = 1:Num_files
        if Index(i) == k
            DC_Power(i) = avgfields(i,5)*(rho_std/rho(k));
            AC_Power(i) = avgfields(i,8)*(rho_std/rho(k));
            % product of three times RMS AC Current and RMS AC Voltage already assumed included
            WindSpeed1(i) = avgfields(i,10)*0.44704*(rho(k)/rho_std)^(1/3);
            % Calculate normalized wind speed from standard sea-level air density
            WindSpeed2(i) = avgfields(i,11)*0.44704*(rho(k)/rho_std)^(1/3);
            % Calculate normalized wind speed from standard sea-level air density
        end
    end
end

dlmwrite(output2, avgfields, 'delimiter', 't');

%% Binning Section
threshold_low = 2;
threshold_high = 20;
increment = .5;
row_inc = 1;
row_inc2 = 1;
for i = 1:length(Time)
    for j=1:(threshold_high-threshold_low)/increment % this is the number of bins
        lowval = (threshold_low+(j*increment)-increment);
        highval = (threshold_low +j*increment);
        if WindSpeed1(i) >=lowval && WindSpeed1(i) < highval % this sets up the correct increments ie 4-4.5, 4.5-5 etc
            TimeBin{1,j}(row_inc,1) = Time(i);
            WindSpeedBin{1,j}(row_inc,1) = WindSpeed1(i);
            DCPowerBin{1,j}(row_inc,1) = DC_Power(i);
            ACPowerBin{1,j}(row_inc,1) = AC_Power(i);
            RPM_Bin{1,j}(row_inc,1) = Turbine_RPM(i);
            row_inc = row_inc+1; % increments what row the data is written to
        end
        if WindSpeed1(i) == threshold_high % Sets up the bin for the == case
            TimeBin{1,j}(row_inc,1) = Time(i);
            WindSpeedBin{1,j}(row_inc,1) = WindSpeed1(i);
            DCPowerBin{1,j}(row_inc,1) = DC_Power(i);
            ACPowerBin{1,j}(row_inc,1) = AC_Power(i);
            RPM_Bin{1,j}(row_inc,1) = Turbine_RPM(i);
            row_inc = row_inc+1;
        end
    end
if WindSpeed2(i) >= lowval && WindSpeed2(i) < highval
% this sets up the correct increments ie 4-4.5, 4.5-5 etc
    TimeBin2{1,j}(row_inc2,1) = Time(i);
    WindSpeedBin2{1,j}(row_inc2,1) = WindSpeed2(i);
    DCPowerBin2{1,j}(row_inc2,1) = DC_Power(i);
    ACPowerBin2{1,j}(row_inc2,1) = AC_Power(i);
    RPM_Bin2{1,j}(row_inc2,1) = Turbine_RPM(i);
    row_inc2 = row_inc2+1; % increments what row the data is written to
end

if WindSpeed2(i) == threshold_high
% Sets up the bin for the == case
    TimeBin2{1,j}(row_inc2,1) = Time(i);
    WindSpeedBin2{1,j}(row_inc2,1) = WindSpeed2(i);
    DCPowerBin2{1,j}(row_inc2,1) = DC_Power(i);
    ACPowerBin2{1,j}(row_inc2,1) = AC_Power(i);
    RPM_Bin2{1,j}(row_inc2,1) = Turbine_RPM(i);
    row_inc2 = row_inc2+1;
end

%% Ensemble Averaging Section
SizeStruct = size(TimeBin);
for i = 1:SizeStruct(1,2)
    U_avg_Bin(i) = mean(nonzeros(WindSpeedBin{1,i}));
    DCPower_avg_Bin(i) = mean(nonzeros(DCPowerBin{1,i}));
    ACPower_avg_Bin(i) = mean(nonzeros(ACPowerBin{1,i}));
    RPM_avg_Bin(i) = mean(nonzeros(RPM_Bin{1,i}));
    Count_Bin(i) = length(nonzeros(WindSpeedBin{1,i}));
    Time_Bin(i) = (Count_Bin(i)*average_interval)/60;
    if isempty (ACPowerBin{1,i}) == 1
        ACPowerBin{1,i} = NaN;
    end
    if isempty (DCPowerBin{1,i}) == 1
        DCPowerBin{1,i} = NaN;
    end
    if Time_Bin(i) <= 3
        U_avg_Bin(i) = NaN;
    end
end
DCPower_avg_Bin(i) = NaN;
ACPower_avg_Bin(i) = NaN;
RPM_avg_Bin(i) = NaN;
end

maxDCPower_avg_Bin(i) = max(nonzeros(DCPowerBin{1,i}));
minDCPower_avg_Bin(i) = min(nonzeros(DCPowerBin{1,i}));
stdDCPower_avg_Bin(i) = std(nonzeros(DCPowerBin{1,i}));
maxACPower_avg_Bin(i) = max(nonzeros(ACPowerBin{1,i}));
minACPower_avg_Bin(i) = min(nonzeros(ACPowerBin{1,i}));
stdACPower_avg_Bin(i) = std(nonzeros(ACPowerBin{1,i}));
end

SizeStruct = size(TimeBin2);
for i = 1:SizeStruct(1,2)
    U_avg_Bin2(i) = mean(nonzeros(WindSpeedBin2{1,i}));
    DCPower_avg_Bin2(i) = mean(nonzeros(DCPowerBin2{1,i}));
    ACPower_avg_Bin2(i) = mean(nonzeros(ACPowerBin2{1,i}));
    RPM_avg_Bin2(i) = mean(nonzeros(RPM_Bin2{1,i}));
    Count_Bin2(i) = length(nonzeros(WindSpeedBin2{1,i}));
    Time_Bin2(i) = (Count_Bin2(i)*average_interval)/60;
    if isempty (ACPowerBin2{1,i}) == 1
        ACPowerBin2{1,i} = NaN;
    end
    if isempty (DCPowerBin2{1,i}) == 1
        DCPowerBin2{1,i} = NaN;
    end
    if Time_Bin2(i) <= 3
        U_avg_Bin2(i) = NaN;
        DCPower_avg_Bin2(i) = NaN;
        ACPower_avg_Bin2(i) = NaN;
        RPM_avg_Bin2(i) = NaN;
    end
    maxDCPower_avg_Bin2(i) = max(nonzeros(DCPowerBin2{1,i}));
    minDCPower_avg_Bin2(i) = min(nonzeros(DCPowerBin2{1,i}));
    stdDCPower_avg_Bin2(i) = std(nonzeros(DCPowerBin2{1,i}));
    maxACPower_avg_Bin2(i) = max(nonzeros(ACPowerBin2{1,i}));
    minACPower_avg_Bin2(i) = min(nonzeros(ACPowerBin2{1,i}));
    stdACPower_avg_Bin2(i) = std(nonzeros(ACPowerBin2{1,i}));
end

%% Calculate and apply Biasing Effect Correlation Coefficient
corr_coeff_matrix = corrcoef(AC_Power,WindSpeed1);
corr_coeff = corr_coeff_matrix(2,1);
U_bar = mean(WindSpeed1);
U_corr = U_avg_Bin - (1-corr_coeff)*(U_avg_Bin-U_bar);
corr_coeff_text = num2str(corr_coeff, 3);

corr_coeff_matrix2 = corrcoef(AC_Power,WindSpeed2);
corr_coeff2 = corr_coeff_matrix2(2,1);
U_bar2 = mean(WindSpeed2);
U_corr2 = U_avg_Bin2 - (1-corr_coeff2)*(U_avg_Bin2-U_bar2);
corr_coeff_text2 = num2str(corr_coeff2, 3);

%% Calculate Annual Energy Production from Measured Power Curve

number_bins = length(U_avg_Bin);
AEP = 0;
for i = 1:number_bins
    F_V(i) = 1 - exp((-pi/4)*(U_avg_Bin(i) / 3));
end
for i = 2:number_bins
    if (isnan(F_V(i)) == 0) && (isnan(F_V(i-1)) ==0)
        AEP = AEP + (F_V(i) - F_V(i-1))*0.5*(ACPower_avg_Bin(i-1)+ACPower_avg_Bin(i));
    end
end
AEP = (8760 * AEP)/1000;
AEP_string = num2str(AEP, 6);

number_bins = length(U_avg_Bin2);
AEP2 = 0;
for i = 1:number_bins
    F_V2(i) = 1 - exp((-pi/4)*(U_avg_Bin2(i) / 3));
end
for i = 2:number_bins
    if (isnan(F_V2(i)) == 0) && (isnan(F_V2(i-1)) ==0)
        AEP2 = AEP2 + (F_V2(i) - F_V2(i-1))*0.5*(ACPower_avg_Bin2(i-1)+ACPower_avg_Bin2(i));
    end
end
AEP2 = (8760 * AEP2)/1000;
AEP_string2 = num2str(AEP2, 6);

%% Prepare and Output Bin Information Data File
M1 = [U_avg_Bin; U_corr; ACPower_avg_Bin; RPM_avg_Bin; Count_Bin; Time_Bin];
M2 = [U_avg_Bin2; U_corr2; ACPower_avg_Bin2; RPM_avg_Bin2; Count_Bin2; Time_Bin2];

dlmwrite(output3, M1, 'delimiter', '\t');
dlmwrite(output4, M2, 'delimiter', '\t');

%% Output and Save Wind Turbine Performance Plots

% Non Dimensional Quantities
Cp_AC = ACPower_avg_Bin./(.5*rho_std*U_corr.^3*pi*R^2);
Cp_DC = DCPower_avg_Bin./(.5*rho_std*U_corr.^3*pi*R^2);

omega = RPM_avg_Bin./60*2*pi; % rad/sec
lambda = omega*R./U_corr;

Cp_AC2 = ACPower_avg_Bin2./(.5*rho_std*U_corr2.^3*pi*R^2);
Cp_DC2 = DCPower_avg_Bin2./(.5*rho_std*U_corr2.^3*pi*R^2);

omega2 = RPM_avg_Bin2./60*2*pi; % rad/sec
lambda2 = omega2*R./U_corr2;

Kp_AC = Cp_AC./lambda.^3;
Kp_AC2 = Cp_AC2./lambda2.^3;

CT = ACPower_avg_Bin./(.5*rho_std*U_corr.^3*pi*R^2);
CT2 = ACPower_avg_Bin2./(.5*rho_std*U_corr2.^3*pi*R^2);

% Dimensional Quantities
Torque = ACPower_avg_Bin./omega;
Torque2 = ACPower_avg_Bin2./omega2;

{PLOT COMMANDS NOT INCLUDED: SEE CODE}

cd([master_directory,'\WT',V2,V3,V1,'_','average_interval_string','sec_Processing ']);
save workspace;
cd(master_directory);
disp(' ');
disp('end of code....');
disp(' ');}
Appendix J

Wortmann Airfoil Information
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Appendix K

WT_Perf Simulation Input Parameters

--- WT_Perf Input File -----------------------------------------------
WT_Perf Test07 input file. Southwest Whisper (Dimen, Metric, Space, Old AF, PROP-PC, Cp Analysis).
Compatible with WT_Perf v3.00f

--- Input Configuration -----------------------------------------------
True  Echo: Echo input parameters to "<rootname>.ech"?
True  DimenInp: Turbine parameters are dimensional?
True  Metric: Turbine parameters are Metric (MKS vs FPS)?

--- Model Configuration -----------------------------------------------
5  NumSect: Number of circumferential sectors.
1000  MaxIter: Max number of iterations for induction factor.
1.0e-7  ATol: Error tolerance for induction iteration.
1.0e-6  SWTol: Error tolerance for skewed-wake iteration.

--- Algorithm Configuration -----------------------------------------------
True  TipLoss: Use the Prandtl tip-loss model?
True  HubLoss: Use the Prandtl hub-loss model?
True  Swirl: Include Swirl effects?
True  AdvBrake: Use the advanced brake-state model?
True  IndProp: Use PROP-PC instead of PROPX induction algorithm?
True  ADrag: Use the drag term in the axial induction calculation.
True  TIDrag: Use the drag term in the tangential induction calculation.

--- Turbine Data -----------------------------------------------
2  NumBlade: Number of blades.
2.25  RotorRad: Rotor radius [length].
0.442  HubRad: Hub radius [length or div by radius].
0.0  PreCone: Precone angle, positive downwind [deg].
0.0  Tilt: Shaft tilt [deg].
0.0  Yaw: Yaw error [deg].
9.14  HubHt: Hub height [length or div by radius].
30  NumSeg: Number of blade segments (entire rotor radius).

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<th>RElm</th>
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<th>Chord</th>
<th>AFfile</th>
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1.677  4.298  0.09361  2  TRUE
1.738  4.023  0.08899  2  TRUE
1.798  3.767  0.08438  2  TRUE
1.858  3.528  0.07976  2  TRUE
1.918  3.305  0.07514  2  TRUE
1.979  3.096  0.07053  2  TRUE
2.039  2.900  0.06591  2  TRUE
2.099  2.716  0.06129  2  TRUE
2.160  2.541  0.05668  2  TRUE
2.220  2.375  0.05206  2  TRUE

--- Aerodynamic Data ---------------------------------------------
1.2231  Rho:      Air density [mass/volume].
1.4639e-5  KinVisc:   Kinematic air viscosity
0.0  ShearExp: Wind shear exponent (1/7 law = 0.143).
False  UseCm:    Are Cm data included in the airfoil tables?
2  NumAF:   Number of airfoil files.

*airfoils/SWWP/rectangle.dat*  AF_File:  List of NumAF airfoil files.
*airfoils/SWWP/Wortmannfx60.dat*

--- Output Configuration -----------------------------------------

True  TabDel: Make output tab-delimited (fixed-width otherwise).
False  KFact:  Output dimensional parameters in K (e.g., kN instead of N)
True  WriteBED: Write out blade element data to “<rootname>.bed”?
False  InputTSR: Input speeds as TSRs?
*mps*  SpdUnits: Wind-speed units (mps, fps, mph).

--- Combined-Case Analysis --------------------------------------

0  NumCases:  Number of cases to run. Enter zero for parametric analysis.
WS or TSR  RotSpd  Pitch  Remove following block of lines if NumCases is zero.
--- Parametric Analysis (Ignored if NumCases > 0) ----------------

3  ParRow: Row parameter (1-rpm, 2-pitch, 3-tsr/speed).
1  ParCol: Column parameter (1-rpm, 2-pitch, 3-tsr/speed).
2  ParTab: Table parameter (1-rpm, 2-pitch, 3-tsr/speed).
True  OutPwr: Request output of rotor power?
True  OutCp:  Request output of Cp?
True  OutTrq: Request output of shaft torque?
True  OutFlp: Request output of flap bending moment?
True  OutThr: Request output of rotor thrust?
0, 0, 0  PitSt, PitEnd, PitDel: First, last, delta blade pitch (deg).
200, 600, 100  OmgSt, OmgEnd, OmgDel: First, last, delta rotor speed (rpm).
2, 20, 1  SpdSt, SpdEnd, SpdDel: First, last, delta speeds.