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Small Wind Research Turbine

Final Report

D. Corbus and M. Meadors

Technical Report
NREL/TP-500-38550
October 2005

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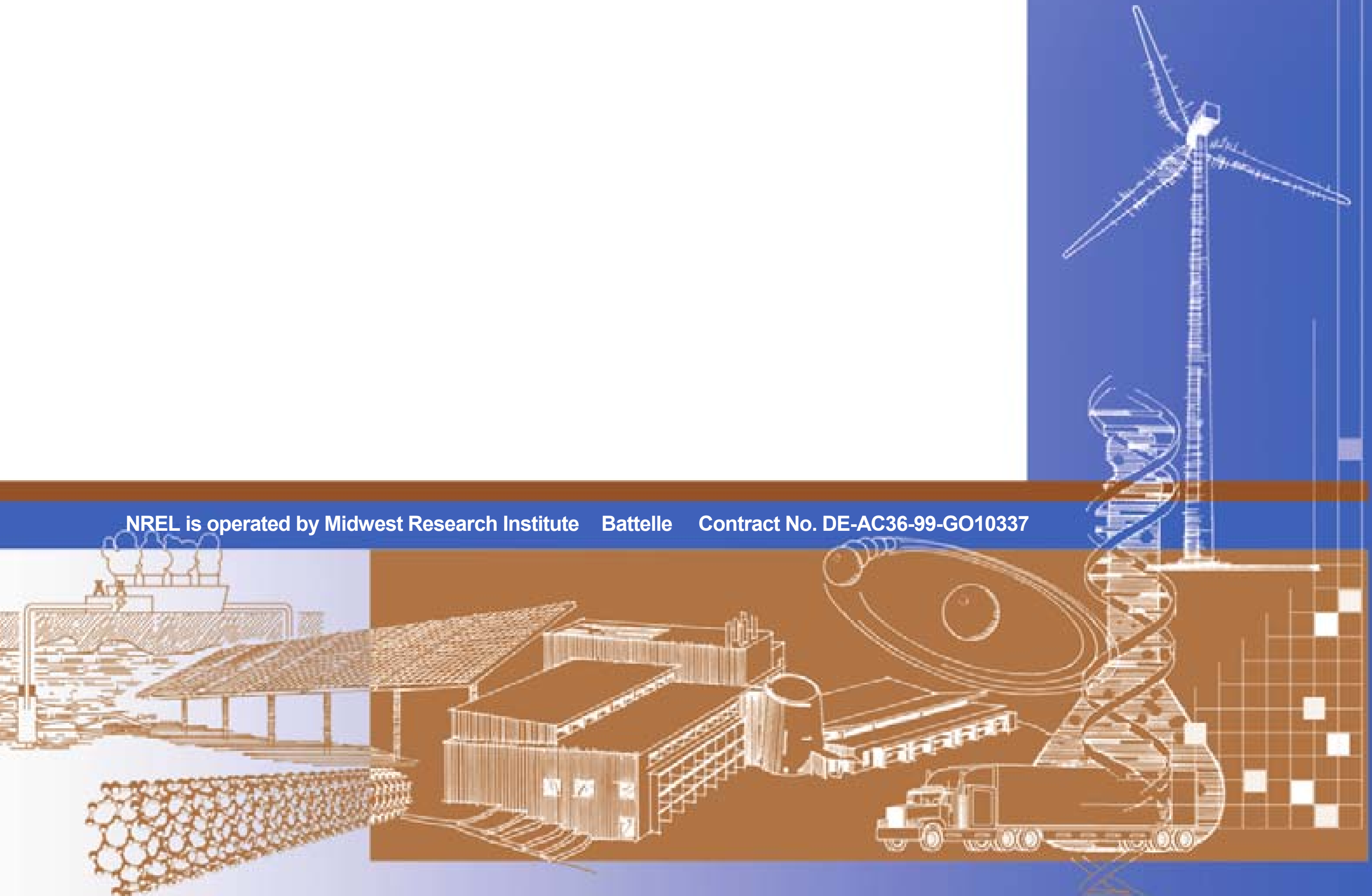

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Prepared under Task No. WER5.3101

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Introduction

Many small wind turbines use furling, whereby the rotor either tilts and/or yaws out of the wind to protect itself from overspeed during very high winds. In the past, most small wind turbine designers used trial and error approaches that often used variable geometry test platforms to vary furling offsets. Although recent advances in understanding furling have resulted in furling being incorporated into wind turbine aeroelastic simulation models, to date there has been a limited amount of test data available for validation of small furling wind turbine models [1]. Acquiring good test data for a small furling wind turbine was a recommended action of the National Wind Technology Center (NWTC) Furling Workshop held in July of 2000 [2] and has been mentioned in previous papers on furling [3]. The Small Wind Research Turbine (SWRT) project was initiated to provide reliable test data for model validation of furling wind turbines and to help understand small wind turbine loads. The measurements of thrust and furling are of particular importance to the model validation effort and are unique to this test.

The SWRT is a Bergey Excel 10-kilowatt (kW) turbine that was modified in several ways, including addition of a shaft-bending, torque, and thrust sensor in line with the shaft; modification of the nose cone and nacelle to allow for data acquisition system (DAS) components; and customization of the tower adapter with load cells on the top of each tower leg. The turbine rotor axis is offset from the yaw axis, and in high winds, the turbine furls horizontally out of the wind during rotor thrust and aerodynamic moments.

The FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code, which was developed and is distributed by the National Renewable Energy Laboratory's (NREL's) NWTC, is the primary aeroelastic simulator used by the U.S. wind industry to model small wind turbines. The recent upgrades to FAST allow users to simulate lateral offset and skew angle of the rotor shaft from the yaw axis, rotor-furling and tail-furling degrees-of-freedom (DOFs), up- and down-furl stops, and tail inertia and tail fin aerodynamic effects [4,5]. Because the location and orientation of the furling DOFs are user-specified, the simulator is flexible enough to model virtually any furling wind turbine configuration. FAST's built-in features allow for the determination of full-system modes, including furling, of an operating or stationary turbine. These enhancements to the FAST code were validated using the data sets from the SWRT test described herein [6].

This report will familiarize the user with the scope of the SWRT test and support the use of these data. In addition to describing all the testing details and results, the report presents an analysis of the test data and compares the SWRT test data to simulation results from the FAST aeroelastic simulation model.

Test Site

The test site chosen for the SWRT is site number 1.4 at the National Wind Technology Center approximately 8 km south of Boulder, Colorado. The site is located in complex terrain at an approximate elevation of 1,850 m above sea level. Winter winds are dominant at this site with a prevailing direction of 292 degrees from true north. The wind turbine was unobstructed by other wind turbines or structures.

The turbine was installed in May 2003 and preliminary testing was conducted until January 2004. The testing for the data sets described in this paper was started in January 2004 and concluded in June 2004.

Wind Turbine System Description

Test Turbine Description

The SWRT is a modified Bergey EXCEL 10-kW turbine that furls horizontally out of the wind. The tail boom attaches with a hinge and bumper arrangement to the rotor/generator/main-frame assembly, and there is a lateral offset between the yaw axis and the rotor axis. The axis of the hinge pivot joint is inclined laterally at a small angle to the vertical yaw axis and produces a gravity restoring moment. A main-frame stop keeps the tail boom from furling more than about 68 degrees. There is a lateral offset between the yaw axis and the rotor axis. As the wind speed increases, so do the thrust and aerodynamic normal force on the nominally aligned vertical tail at the end of the tail boom. Furling occurs when the rotor moments exceed the gravity restoring moment. The furl damper provides very little resistance to furling but a high resistance to unfurling.

The Bergey EXCEL is a three-bladed upwind turbine with a rated output of 10 kW at 13.0 m/s. The EXCEL uses a permanent magnet alternator to produce three-phase variable frequency output at a nominal 240-volts. The three-phase output is then rectified to DC power and converted to single-phase 240-volt 60-hz AC power by the Gridtek inverter. The turbine blades are constant chord and made from pultruded fiberglass, and the direction of rotation is counter-clockwise. The turbine nacelle and shaft have an eight-degree tilt, and the SWRT turbine is installed on a Rohn SSV, 24.4 m. (80 ft.), freestanding lattice tower. The SWRT was modified in several ways to allow for the installation of test instrumentation. One significant modification was the turbine main shaft was shortened approximately 0.18 m. (7 in.) to allow for installation of a 0.18 m (7 in.) load fixture in-line with the non-rotating shaft to measure shaft loads.

Table 1 summarizes the SWRT configuration and basic operational data. It should be noted that because the SWRT (Figure 1) was modified, the test results in this report are not necessarily representative of the Bergey EXCEL turbine.

Table 1. Test Turbine Configuration and Operational Data

General Configuration:	
Make, Model, Serial Number	Bergey WindPower, EXCEL-S, 2002 726
Rotation Axis (H / V)	Horizontal
Orientation (upwind / downwind)	Upwind
Number of Blades	3
Rotor Hub Type	Rigid
Rotor Diameter (m)	Configuration A/B – 5.6 m; Configuration C – 6.7 m
Hub Height (m)	25.0 m (82 ft)
Performance:	
Rated Electrical Power (kW)	10 kW
Rated Wind Speed (m/s)	13.0
Cut-in Wind Speed (m/s)	3.1
Cut-out Wind speed (m/s)	none
Rotor/Blades:	
Swept Area (m^2)	CONFIGURATION A/B – 26.4; Configuration C – 35.3.
Direction of Rotation	Counterclockwise viewed from upwind
Rotor speed	0-400 rpm (500 unloaded)
Power Regulation (active or passive)	Passive
Blades	Pultruded vinylester E-glass
Airfoil	Configuration A/B- SH3052, constant chord; Configuration C – SH3055, constant chord
Tower:	
Type	Rohn SSV (freestanding lattice)
Height (m)	24.4 m (80 ft)
Control / Electrical System:	
Controller: Make, Type	Bergey Gridtek inverter
Electrical Output: Voltage	Nominal 240-volt AC
Yaw System:	
Wind Direction Sensor	Tail vane keeps turbine pointed into the wind

Figure 1. Small wind research turbine at the National Wind Technology Center

Electrical Layout

The test configuration consists of the turbine mounted on its tower, a data shed containing the Gridtek inverter, instrumentation, the meteorological tower, and associated wiring and junction boxes. The turbine is installed on a Rohn SSV, 24.4-meter, freestanding lattice tower. At the base of the tower is a three-pole disconnect rated for 100 amps and 600 volts that is used as a down-tower service switch in light winds to brake the turbine by shorting the three phases of the turbine together. This is followed by a three-phase fused disconnect. The wire run from the base of the tower to the data shed is approximately 20.3 meters of #6 AWG wire. Note that the turbine brake cannot be used to stop the turbine in winds above about 8 m/s, and that the turbine cannot be left with the brake on for long periods of time because the rotor torque may overcome the braking torque of the generator (i.e., the short-circuited electrical torque).

Figure 2 shows the Gridtek inverter and the disconnect switches inside the data shed, and Figure 3 shows the downtower service brake and down-tower turbine disconnect. Appendix A contains a 1-line electrical schematic of the installed turbine. The turbine may also be connected to a resistive load bank located in the Hybrid Power Test Bed.

Figure 2. Gridtek inverter and disconnects

Figure 3. Downtower disconnect

Pre-test Turbine Characterization

To supply inputs for aeroelastic models of the SWRT, the turbine tail assembly and main frame were weighed and center of gravities (Cgs) were determined. Tests were also conducted to calculate the inertia about the tail axis and the yaw axis. Tail damper properties were measured and all turbine geometries noted. A modal test was conducted for a blade to determine mode shapes for flap and edge. This data, as well as all turbine related parameters, including airfoil data, is contained in Appendix B.

Instrumentation and Data Acquisition

Measured Parameters

Table 2 shows a list of the measured parameters for the test, including which data acquisition module (DAM) and channel the parameter is measured on and the manufacturer and model number of the sensor. Figure 4 is a schematic of the turbine that shows the location of sensors and DAS equipment on the turbine. Figures 5-8 are photos showing the different DAS components on the turbine.

Table 2. Measured Parameters and Sensor List

DAM #	Channel	Parameter	Sensor	Make	Model
1	1	B1edge bend	Full Bridge Str	Micro Meas	WK-09-250BF-10C
	2	B1 flap bend	Full Bridge Str	Micro Meas	WK-09-250BF-10C
	3	B2 edge bend	Full Bridge Str	Micro Meas	WK-09-250BF-10C
	4	B2 flap bend	Full Bridge Str	Micro Meas	WK-09-250BF-10C
	5	B3 edge bend	Full Bridge Str	Micro Meas	WK-09-250BF-10C
	6	B3 flap bend	Full Bridge Str	Micro Meas	WK-09-250BF-10C
	7	Rotor position	Encoder	Mich. Scientif	SR10MW/E512
	8	Rotor velocity	Encoder	Mich. Scientif	SR10MW/E512
2	1	Shaft 0 bend	Full Bridge Str	Sensor Dev.	Custom Design
	2	Shaft 90 bend	Full Bridge Str	Sensor Dev.	Custom Design
	3	Thrust	Full Bridge Str	Sensor Dev.	Custom Design
	4	Torque	Full Bridge Str	Sensor Dev.	Custom Design
	5	Wind speed Tail	Sonic anno	Campbell Sc	CSAT3
	6	Wind speed Tail	Sonic anno	Campbell Sc	CSAT3
	7	Wind speed Tail	Sonic anno	Campbell Sc	CSAT3
	8	Furl	Rotary Variable Inductance Transduc	Schaevitz	RVIT-15-120i
3	1	Tower Top -1	Force sensor	Sen. Dev	10191
	2	Tower Top -2	Force sensor	Sen. Dev	10191
	3	Tower Top -3	Force sensor	Sen. Dev	10191
	4	Atmos Pressure	Presurre	Vaisala	PTB101B
	5	Yaw position	Encoder	Mich. Scienti	SR10MW/E512
	6	Yaw velocity	Encoder	Mich. Scienti	SR10MW/E512
	7	Wind direction	Wind vane	Met One	020
	8	Spare	-	-	
4	1	Wind Sp. –Hub U	Sonic Anno	Kaijo	DA 310
	2	Wind Sp. –Hub U	Sonic Anno	Kaijo	DA 310
	3	Wind Sp. –Hub U	Sonic Anno	Kaijo	DA 310
	4	Wind Sp.- hub	Anno conv to v	Met One	010C
	5	Wind Sp.- Mid-tow	Anno conv to v	Met One	010C
	6	Wind Sp.- 3 Meter	Anno conv to v	Met One	010C
	7	Atmos Temp	Temp	Met One	T-200 RTD
	8	AC Power	Watt Transducer	OSI	P-143E

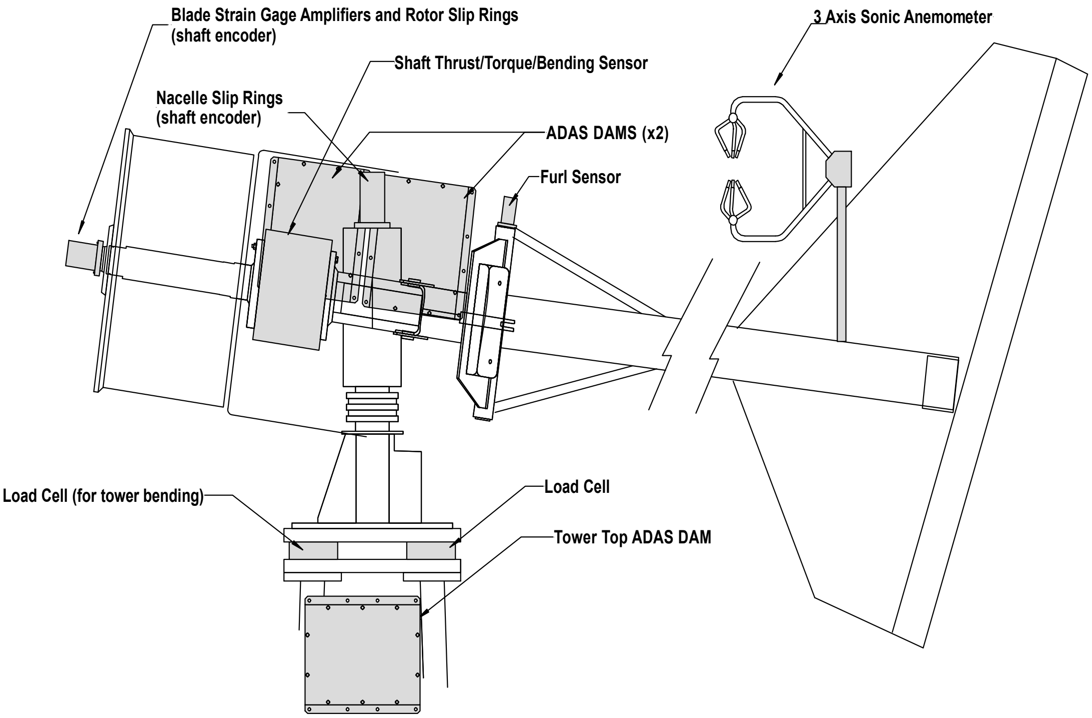

Figure 4. Location of turbine sensors and DAS equipment

Figure 5. SWRT showing blade strain gages and rotor slip rings

Figure 6. SWRT showing ADAS, DAMS, and Nacelle J-box

Figure 7. SWRT showing shaft sensor, furl sensor, and tower-leg load cells

Figure 8. Sonic tail anemometer

Turbine and Tower Sensor Descriptions

Blade Strain Gages

Blade flap and edge bending moments are measured in one location on each of the three blades. Blade bending is measured with respect to the blade chord on each blade. The gages are configured as two full Wheatstone bridges. Each bridge is comprised of two two-element rosettes. The rosettes are installed in pairs, with each pair in a given bridge diametrically opposed on the blade. Each bridge has four active arms. Diagrams of the strain gauge locations are shown in Appendix C.

Flap and edge signals are measured on all blades and then amplified on the hub before being sent over slip rings to the nacelle DAS where they are digitized.

Thrust, Shaft Bending, and Torsion Moments

The shaft load fixture was built specifically for the SWRT test to measure thrust, shaft 0- and 90-degree bending, and torque. Figure 9 is a picture of the shaft load fixture, opened to show the four strain-gauged posts that carry all of the rotor loads. The shaft sensor is located on the nonrotating shaft (i.e., fixed frame) approximately 0.51 m (20.35 in) from the rotor's center. Detailed calibration data for the sensor, including the coefficients for the 4 by 4 crosstalk calibration matrix, may be found in Appendix C.

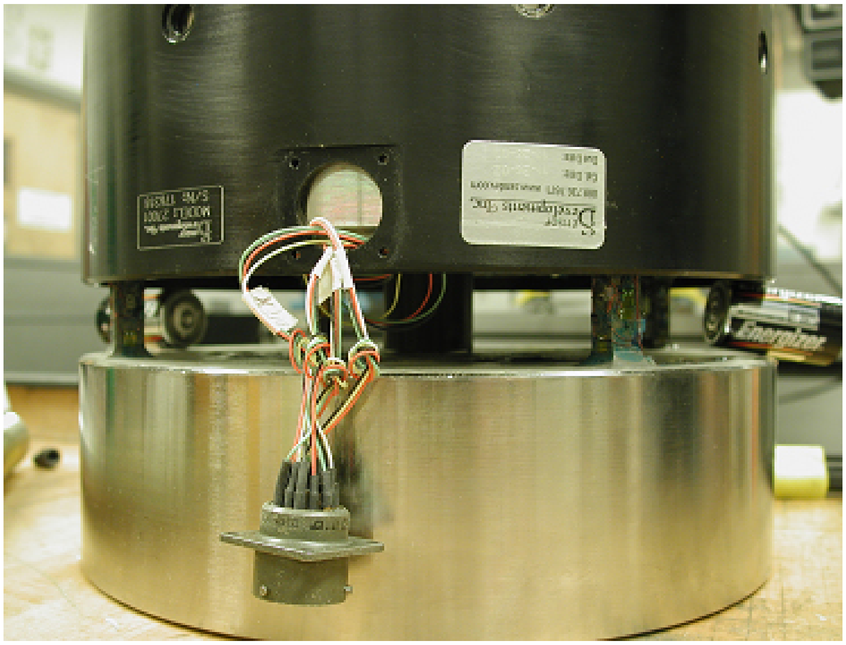

Figure 9. SWRT shaft sensor

Tower Bending Moments

Tower loads were measured with load cells at the top of each of the three feet of the lattice tower. The vector sum of the loads is used to determine the tower bending moment. Data on the load cells can be found in Appendix C. Because of time and budget constraints, this data was never reduced to actual tower top bending loads, therefore, the only data currently available is the raw data measured in volts from the output of each tower-top load cell.

Power Output

A Watt transducer was used to measure the variable-voltage power from the turbine upstream of the inverter. Calibration data and specifications for the Watt transducer can be found in Appendix C.

Rotor Speed and Azimuth

Rotor speed and azimuth were measured using a high-speed, optical shaft encoder. The encoder, mounted on a slip ring, receives the signals from the rotating hub frame and sends them to the nacelle. The encoder outputs 512 pulses per rotor revolution. The hub azimuth and rotor speed are analog signals. Because the turbine rotates counterclockwise, rotor azimuth is positive in the counterclockwise direction with 0 degrees corresponding to blade 1 when it is vertical and pointing up. Specifications for the sensor may be found in Appendix C.

Yaw Position and Velocity

Yaw position and velocity were also measured using a high-speed, optical shaft encoder. The encoder is smiliar to the rotor speed and azimuth encoder and comes mounted on a slip ring that was used to get the signals from the rotating nacelle frame to the tower. The encoder outputs 512 pulses per rotor revolution. The yaw position signal is an analog signal. Yaw position is defined as positive in a counterclockwise direction from true north as shown in Figure 10. Specifications for the sensor may be found in Appendix C.

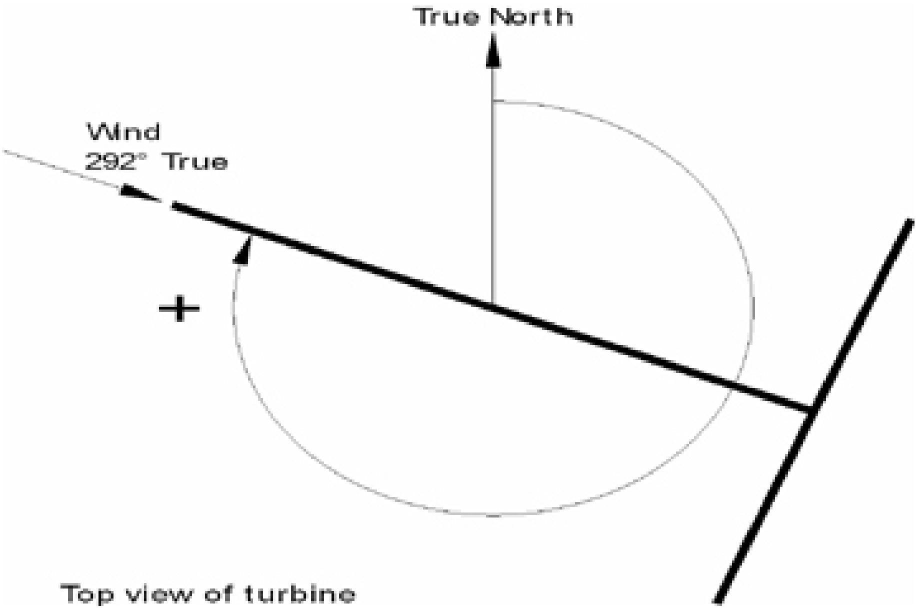

Figure 10. Yaw angle convention

Furl Angle

Furl angle was measured with a rotary variable inductance transducer (RVIT) mounted on the tail hinge pin of the turbine. The sensor range is from 0 to 120 degrees, but the furling angle is approximately 0 to 68 degrees. Calibration procedures and specifications for the sensor may be found in Appendix C.

Tail Wind Speed

A sonic anemometer is located on the tail of the wind turbine just upwind of the tail fin at approximately 3.26 m (10.7 ft.) from the rotor plane at the centerline of the shaft. Specifications for the sensor may be found in Appendix C.

Meteorological Tower Sensors

A sonic anemometer was located at hub height (24.4 m [80 ft]) on a meteorological tower (Figure 11) located 19.8 m (64.9 ft) upwind from the turbine and at a height of 24.4 m (80 ft). The distance from the sonic anemometer to the turbine was 3.5 rotor diameters for Configurations A and B and 3 rotor diameters for Configuration C. The sonic anemometer also recorded the temperature. In addition to the sonic anemometer, a barometric pressure sensor was located in the up-tower junction box. Adjacent to the up-tower junction box was a wind vane that was used as a secondary measurement device with the primary wind direction derived from the sonic anemometer data. Three mechanical anemometers were located on the meteorological tower at heights of 23.4 m (76 ft), 13.7 m (45 ft), and 3.0 m (9.8 ft). Specifications and calibration data for the meteorological sensors can be found in Appendix C.

Also mounted on the meteorological tower was a Panasonic WV-CL830 camera with a Pelco model PT570P pan and tilt control. A Panasonic video monitor and recorder was used to record video footage of the turbine.

In addition to the meteorological data described, data for the inflow analysis used the gradient Richardson number (N_{Ri}) for height of 2-80 m that was obtained from a meteorological tower at the NWTC and included in the data sets for the SWRT.

Figure 11. Sonic anemometer mounted on a meteorological tower

Data Acquisition System

Zond's Advanced Data Acquisition System (ADAS), a distributed multi-source, synchronous, multi-channel data recorder, recorded the test data by employing remote Data Acquisition Modules (DAMs) that can record the data near the source of the measurement. A personal computer system performed all set-up, programming, data display, and downloading duties. All channels were synchronized and data acquisition occurred simultaneously without multiplexing. Data was sampled at 160 Hz and a 40 Hz 6-pole low-pass Butterworth filter filtered all data except the rotor and yaw position channels. Ten-minute records were stored.

Four DAMs with individual channel programming that included gain and filter set points were used. Two DAMs were located on the turbine's nacelle. A third was located adjacent to the uptower junction box and the fourth at the base of the meteorological tower. Both analog and digital signal conditioning cards were used in the DAM setup. Sensor and bridge excitation and offset adjustment is standard on all analog cards. Digitized data from the DAMs were sent by fiber optic cable to a Smartport inside the test data shed and then to the host computer. Table 3 outlines the important specifications for the ADAS data acquisition system.

The ADAS II software was written by Louis Manfredi to expand the features of the ADAS hardware. It is a general purpose data acquisition program with special features that increase its utility for field data acquisition in wind turbine test programs. Although it uses the Zond DAMs as the front end, it provides a variety of features that were not included in the original software. The program is written in Labview^{tm}, a graphical programming language written by National Instruments Inc. Specific features of the ADAS II software include:

- Setup files – To take advantage of the program's versatility, a number of application-specific control settings can be stored to file or use throughout a test or for future tests.
- File readability – All of the files generated by the program (data files and setup files) are written in tab and carriage return delimited ASCII.
- Configuration information – Every data file stored by the program can be stored in engineering units, with a record of the signal name, units, calibration history, etc. stored in an associated header file.
- Calculated channels – In addition to measured data, the program can store calculated data that is derived from the measured data using formulae supplied by the user.
- Real-time display – The program can display real-time data as it is being collected in several strip-chart style forms and in one digital format. The update rate for real-time display can be up to 10 Hz.
- Stand-alone operation – The program can trigger the DAMs to store data at a high rate (up to 160 Hz.) in their internal memories automatically or at the user's request. The data is later downloaded to the host computer, where it can be scaled, formatted, and stored to disk files.
- Automatic triggering – The program has an elaborate automatic triggering utility that allows the user to specify a matrix of test conditions under which data should be collected. When operated in this mode, the program will trigger stand-alone storage, interrogate the DAMs for the statistics of the resulting data set, and only download the data set if it is needed to fill the user specified test matrix.
- Automatic calibration – The program has a calibration feature that allows the user to perform a full calibration, a zero check, or a calibration check.

The computer used for the loads test was a 200 MHz Pentium based PC using the Windows 95 operating system. The computer has a 20 Gigabyte hard drive and data retrieval was performed over a wireless LAN system with data stored on the NWTC certification server.

Table 3. ADAS Specifications

ADAS Module Specifications:	
Calibration	7 level calibration on analog cards at ±± 10 volt scale, 5 level at ± volt, other scales calibrated by checking mid-scale values.
Master Processor	Motorola 68332, 17 MHz, 32 bit CPU
Memory	4 megabytes
Recording Time Available	27 min. @160 Hz, 54.6 min. @ 80 Hz., 3.64 hours @ 20 Hz., 72.8 hours @ 1 Hz, and 182 days at 1 minute averages
Communications	Hard wire RS-422 like protocol, 19,200 baud Radio telemetry, spread spectrum modulation, 19,200 baud
Data Download Times	For one eight-channel module, 9 minutes per 1 megabyte
Environmental Range	-25 to +70° C, 0 to 100% humidity including condensing atmosphere
Size	16.3 X 20.3 X 28.9 cm
Weight	With 8 analog cards, 10 kg
Number of Channels per Module	8
Number of Modules per Host	14 (112 channels total)
Data Acquisition	Simultaneous for all channels
Excitation Voltage	User selectable: 1,2,4,5,6,7,9,and 10
Excitation Accuracy	± 500 micro volt initial accuracy
Excitation Voltage Tempco	± ppm/degree C max
Sample Rate	User selectable: 160,80,40,32,20,10,8,5,4,2,and 1 Rates selectable as averages: 1,2,4,5,10,30 seconds,1,5,10 min.
Analog Card Specifications:	
Overall Card Accuracy	± 0.1% typical, ± .4% max. at ±.05 and .025 Volt range
Card Gain Temperature Coefficient	± 15ppm/deg C typical, 60ppm/deg C max
Card Nonlinearity	± .015% typical, ± .02% max
Anti-Alias Filter Type	6-pole Butterworth
Anti-Alias Filter Cut Off Frequency	-3dB @ 20 Hz
Anti-Alias Nyquist Cutoff	-72.25dB @ 80 Hz
Anti-Alias filter DC Offset	400 microvolts max
Channel AC Bandwidth	DC to 20 Hz.
Excitation Driver	Current: 100 milliamps max, Offset: 175 microvolts max.
D to A Converter	True 12 bit integration type, Integration period = 3.125 ms
Sampling Rate	160 Hz. Fixed, other rates chosen by master processor via DSP
Amplifier	FET input
Overvoltage Protection	± 100 VDC
Input Set-Up	Full differential, single ended or disabled
User Selectable Gain	1,2,10,20,100,200, and 400
Input Range (based on user selectable gain)	±10, ±5, ±1, ±10, ±.5, ±.1, ±.05,and ±.025V

Calibration Procedures

The test engineer must follow defined procedures to perform calibrations. Whenever possible, the measurement chain from the sensor output through the data acquisition system is calibrated by generating known sensor outputs and recording the corresponding readings in the data acquisition system, i.e., an “end-to-end” calibration. Several points provide data for linear interpolation, and the slope and offset values of a linear transducer can then be determined. This form of calibration is used for the blade strain gages, the furl sensor, and the secondary wind vane. However, it is not feasible for a number of instruments because manufacturer calibrations are required, as in the case of the shaft sensor or the AC wattmeter. In these cases, calibration coefficients were obtained through the manufacturer or a certified calibration laboratory.

The strain gages were calibrated by applying a known load. A jig was attached to each blade to isolate the loads in both the flap and edge directions. Weights were used to apply a moment, which was measured by the strain gages. A least-squares regression analysis provided slope calibration coefficients. The zero offsets were determined by rotating the rotor slowly in low wind conditions and taking the average signal of the sine wave that resulted from the gravity moment due to the shaft tilt. A detailed description of the calibration procedures may be found in Appendix C, as well as the coefficients for the crosstalk matrix. Two sets of calibrations were conducted; one for each set of blades tested.

The calibration for the shaft sensor for thrust, shaft 0 and 90 degree bending, and torque was conducted by the manufacturer, Sensor Developments, in a special load cell jig. The shaft sensor was then installed on the top of one section of the tower in the high bay at the NWTC and isolated loads were applied with a special jig. This calibration was performed to verify the manufacturer’s calibration process. Details of the manufacturer’s calibration process may be found in Appendix C, including the 4 by 4 crosstalk matrix and the post-test calibration of the sensor. Offsets for the shaft sensor, which is located on the non-rotating shaft, were obtained by taking “zero” files in low wind conditions with the turbine not rotating.

With the exception of the furl sensor, it was impossible to perform a full-path calibration *in-situ.* For example, the cup anemometers required a known wind velocity and were thus calibrated by the manufacturers in a wind tunnel. Manufacturer calibrations generally provide both slope and offset values. In some cases, such as the optical-position encoders, the offset was determined by placing the transducer in a known position and noting the associated count value on the ADAS. Although the sonic anemometers as “first principal” instruments did not need calibration, their speed was correlated to the mechanical wind anemometer as a final check. Other calibration procedures are described in Appendix C.

A database of resulting calibration coefficients was maintained and applied to raw data values to produce engineering unit data files. Because all the measured channels were linear, only slope and offset calibration coefficients were applied.

The SWRT calibration procedures were established to ensure that all recorded data values were within the stated error limits. Uncertainty analysis results for selected measured channels used during the testing are presented in Table 4. Total estimated uncertainty values listed in the table are expressed in engineering units and represent random and bias error components. The uncertainty is also expressed in terms of full-scale error. Error analysis and calibration procedures specific to wind turbine field-testing are described in McNiff and Simms [7].

Table 4. Uncertainty Analysis for Selected SWRT Measured Channels

Measurement	Units	Measurement Range	Total Estimated Uncertainty	% Full Scale Error
Shaft Yaw Bending	N-m	± 2910	± 38.5	1.3
Shaft Tilt Bending	N-m	± 2910	± 38.6	1.3
Shaft Torque	N-m	± 450	± 21.6	4.8
Shaft Thrust	N	± 5450	± 87.0	1.6
Wind Speed	M/S	0 to 37	± 0.5	1.3
Tail Furl	Degrees	± 60	± 0.9	1.4

Calculated Channels

Calculated channels were used for a wide range of parameters based on the measured data. For example, shaft thrust, 0 and 90 degree bending, and torque were calculated based on the four by four crosstalk matrix from the sensor calibration. Similarly, blade flap and edge bending were calculated using the results from the 2 by 2 crosstalk matrix.

A sonic anemometer measured wind velocity and direction in the u, v, and w orthogonal component directions. These vector components were transformed into magnitude and direction during post-processing using vector relations. Thirteen calculated channels were derived from the meteorological sonic anemometer data and the N_{Ri} to characterize the inflow. Yaw error was calculated from the sonic wind direction and the yaw position sensor and a positive yaw error is defined as yaw position minus wind direction as shown in Figure 12. Yaw error was corrected for the 4-degree shim angle. Equations and descriptions for all calculated channels are shown in Appendix D.

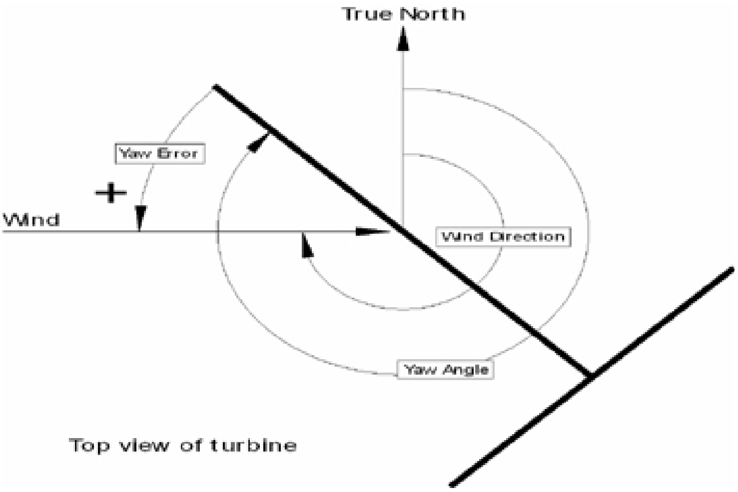

Figure 12. Yaw error angle convention

Turbine Configurations

Data were collected for three turbine configurations, A, B, and C, as summarized in Table 5 [8]. Configuration A and B differ by the lateral offset distance between the rotor centerline and the yaw axis, which was 0.106 m in Configuration A and 0.083 m in Configuration B (a 22%

change). The change in the lateral offset for Configuration A was implemented by placing a 4-degree shim between the alternator and the shaft sensor. Figure 13 shows a schematic of the shim and the change in the lateral offset. Note that the shim was placed upstream of the shaft sensor. The yaw position signal was corrected for this four degree lateral offset by adding four degrees to the measured yaw position.

Hysteresis in the inverter controller software for torque control resulted in some scatter in the torque-RPM curves (see Figure 34 of RPM versus Torque). For model validation data sets, scatter in the torque-RPM curve is undesirable, so for each configuration a limited number of data sets were taken with a fixed resistance load that reduced the torque-RPM scatter. See Appendix C for more information and plots of torque versus RPM with the resistor load.

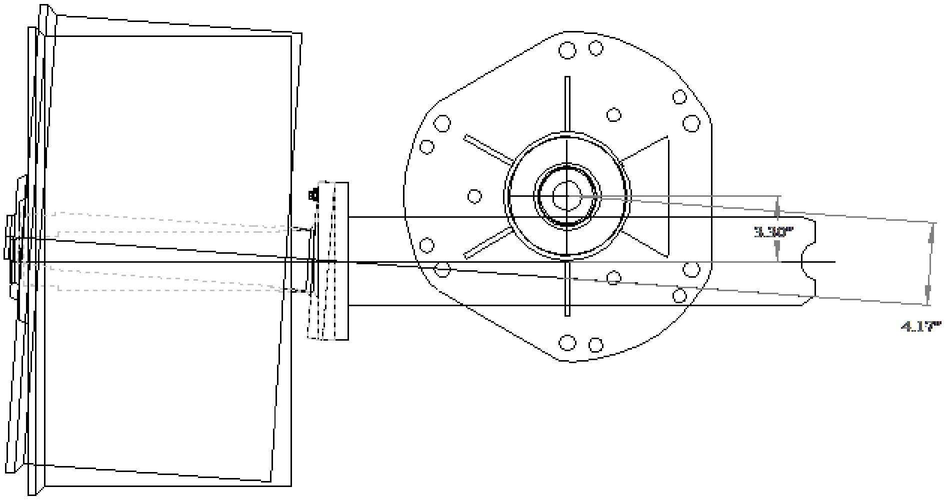

Figure 13. Lateral offset with and without 4-degree shim

Configuration C had a greater swept area (about 20%) than Configurations A and B and different blade pitch.

Table 5. SWRT Configurations

Configuration	A	B	C
Lateral Offset (m)	0.106	0.083	0.083
Airfoil Shape	SH3052	SH3052	SH3055
Rotor Radius (m)	2.90	2.90	3.35
Blade Chord (m)	0.213	0.213	0.2794
Blade Pitch (degrees)	11.44	11.44	9.5
Blade Swept area (m^2)/ rotor diameter (m)	26.4/5.8	26.4/5.8	35.3/6.7

In addition to all configurations running with a shaft tilt of 8 degrees, they ran at an average yaw error of between 13 and 23 degrees, resulting in a significantly skewed wake.

A total of 514 10-minute data sets were collected; 200 for configuration A, 78 for B, and 236 for configuration C. An additional 248 2-minute data sets were collected for configuration B prior to the ten-minute data sets and were used for data verification during turbine start up. As a result of the data validation , some channels were removed from the data sets. For example, the yaw position and the calculated yaw error channels were removed from some of the data sets because of a problem with instrumentation. The data sets for the test are summarized in Appendix C.

The number of test records for each configuration was affected by unexpected test results. For example, the test was started with the SH3052 blades without a shim as the baseline configuration, but the turbine did not furl at a low-enough wind speed, and the inverter went off-line from high-power or voltage faults. To get the turbine to furl at lower wind speeds and, hence, prevent over-power and voltage fault conditions, first a 2-degree, then a 4-degree lateral shim was introduced. However, this did not prevent the faults, as the turbine would not always furl fast enough in high wind conditions. The inverter torque-RPM curve in the software was finally changed to minimize the inverter faults, but some data with high wind speed inverter faults needed to be excluded from the final data sets. Another drawback to the inverter controller for this experimental testing was that it would unload the turbine in very low winds, so data sets below 5 m/s were missing. Although this is not important for furling data, it can be important for characterizing turbine operation. All final configurations were run with the same inverter torque-RPM curve.

Changing the blade configuration was prematurely introduced into the test matrix because the strain gages for the flap signals on the first set of blades reached the rated cycle life of between 10^6 and 10^7 cycles. The high average rotation speed of the turbine, coupled with the fact that the turbine does not have a brake so it is always spinning, resulted in the high number of cycles within 1 year of testing. The degradation of the strain gages may have been exacerbated by blade flutter from the unloaded operation of the turbine during inverter fault conditions and special test conditions. The strain gauge failure is the reason why Configuration B has only 78 test records.

Data Analysis

The Crunch software [9] was created at the NWTC to perform the following tasks:

1. Read in the ASCII data files.
2. Convert strain-gauge data to engineering units using the zeros and calibration matrices described earlier.
3. Perform calculated channel calculations as mentioned above.
4. Calculate the minimums, means, maximums, and standard deviations of all parameters output by Crunch for all 10-minute blocks. The data is also analyzed in several other ways including power spectral densities (PSDs), azimuth averaging, and time series data.

Turbine Dynamics

Power spectral densities (PSDs) were measured with the turbine operating at different rotor speeds [10]. The PSDs showed one per revolution (1P) and 3P in all shaft and blade signals at different magnitudes, as seen in Figures 14 and 15 from a 15 m/s average wind speed file. Of particular interest was the first mode tower frequency showing up in the thrust. Figure 16 shows a plot of PSDs for Configuration A at an average wind speed of 17.3 m/s, when the turbine blades were in and out of flutter. The high shaft and blade response at approximately 34 hz is from blade flutter. It is close to the first torsional frequency of the blades and corresponds to a 6P frequency. The blades did not flutter like this in Configuration C.

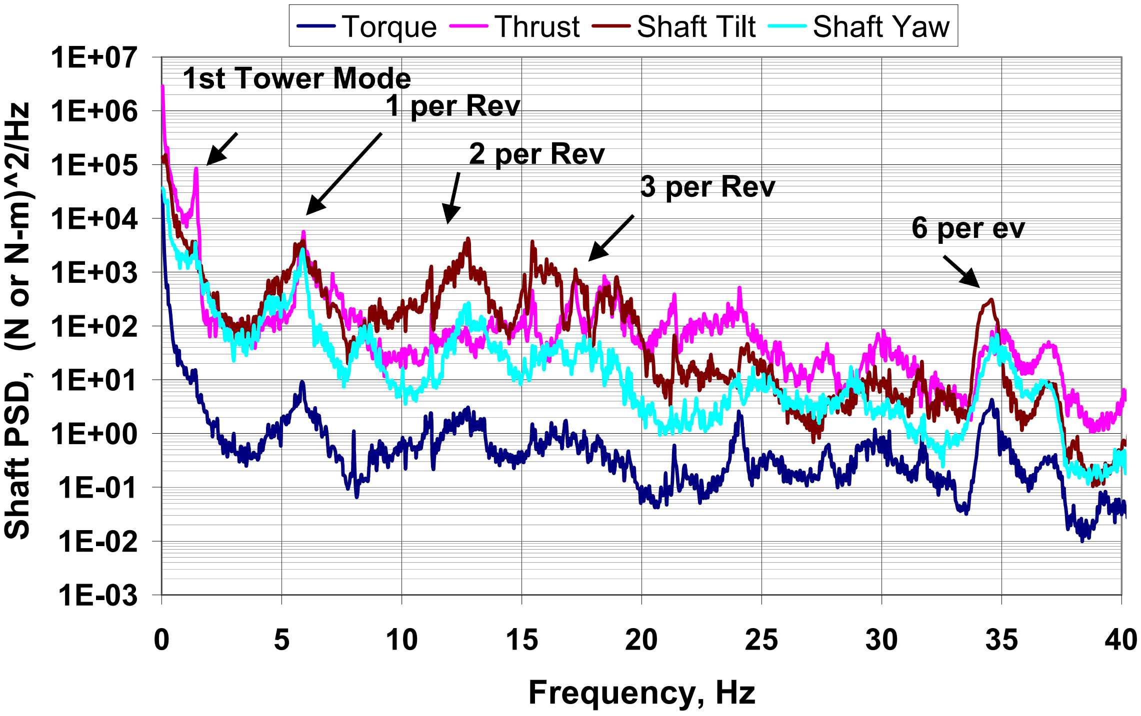

Figure 14. PSD of shaft measurements

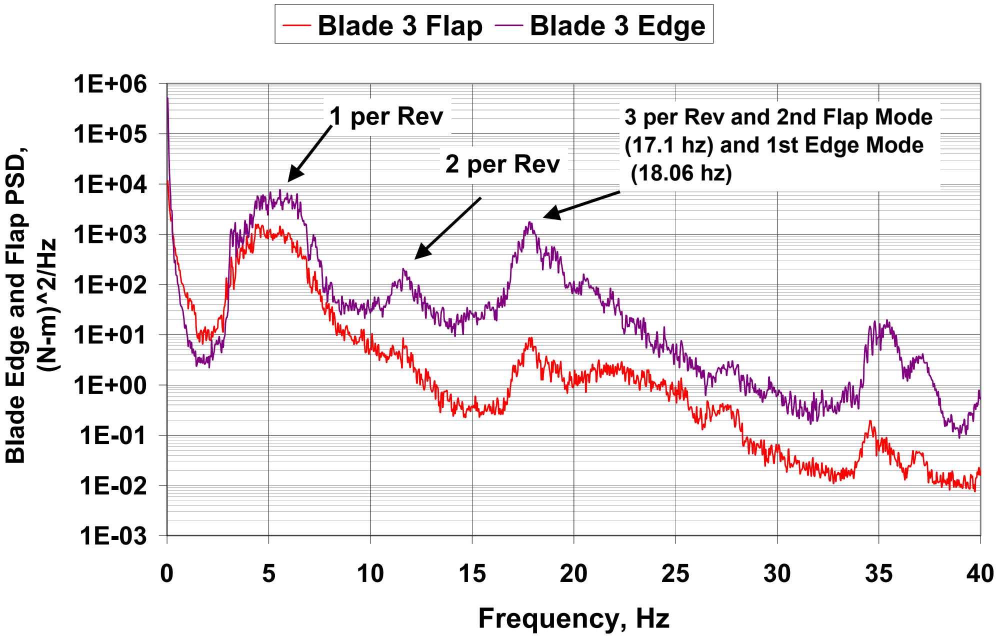

Figure 15. PSD of blade 3 edge and flap moments

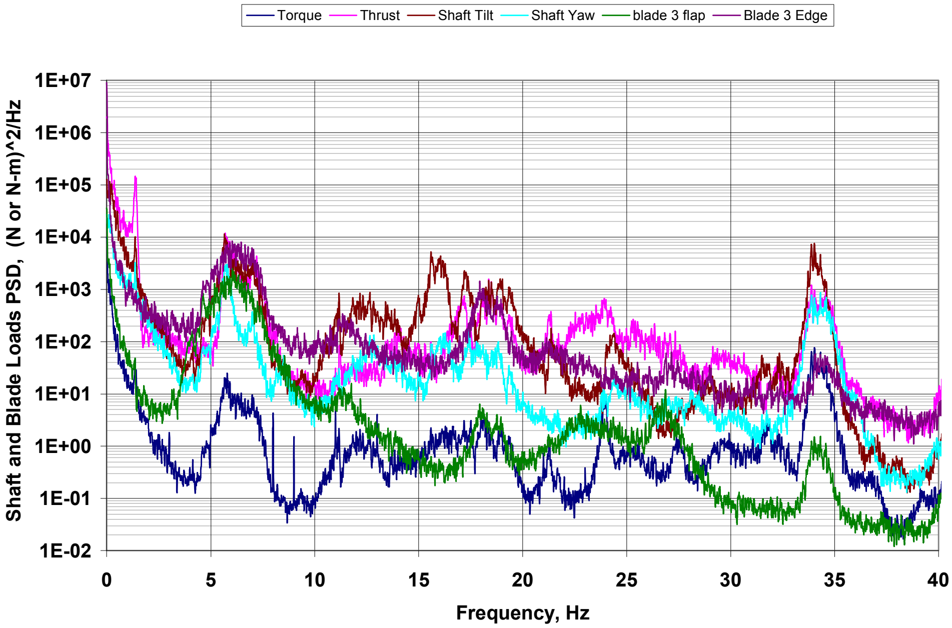

Figure 16. PSD at 17.3 m/s showing the effects of blade flutter at 34 hz

10-Minute Data Sets

Figures 17 through 20 show scatter plots of furl, yaw rate, electrical power, and rotor speed for Configuration A. The data show mean, maximum, and minimums plotted against mean wind speed. The average yaw error for Configuration A is between 15 and 20 degrees depending on wind speed. Because of space limitations, only scatter plots for Configuration A are shown, but comparisons between the configurations are shown later in this paper. The plots give a good overview of the operating characteristics of the SWRT: high rotor speeds, up to 500 RPM, with high maximum yaw rates and mean yaw errors.

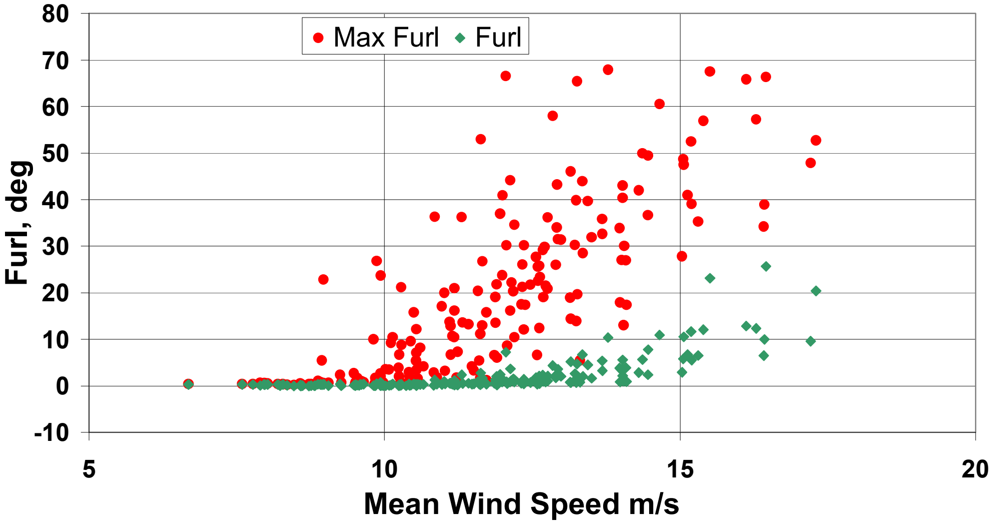

Figure 17. Furl versus mean wind speed

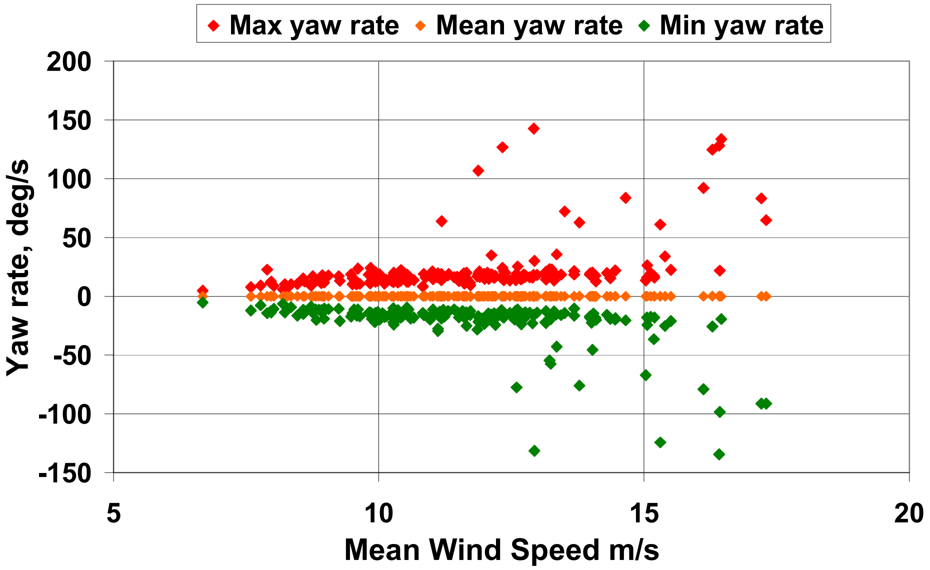

Figure 18. Yaw rate versus mean wind speed

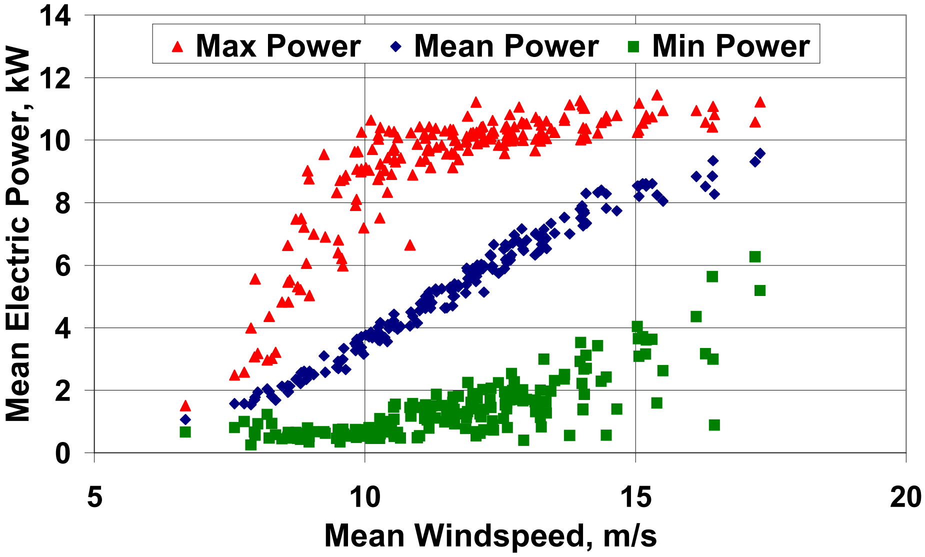

Figure 19. Electrical power versus mean wind speed

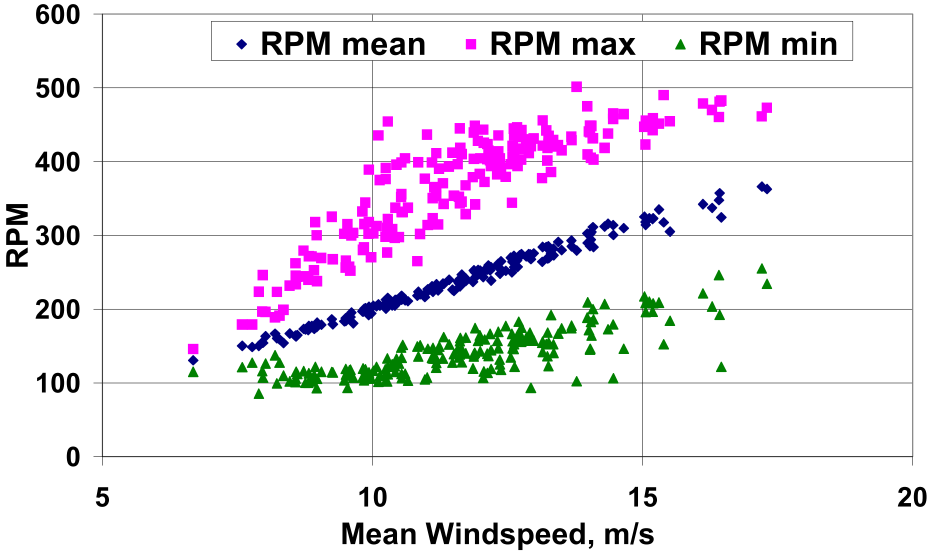

Figure 20. Rotor speed versus mean wind speed

Figures 21 through 23 show similar scatter plots from the same data set for shaft thrust and torque. Also shown is a plot of mean furl versus mean thrust. There is a significant amount of scatter in the plots of both mean furl versus mean wind speed and mean furl versus mean thrust.

Edge-Bending Moments

Test results showed a large discrepancy between the sum of the three edge-bending moments when adjusted for strain gauge location and the torque signal. At rated wind speed, the sum of the three edge signals was 300% to 500% greater than the torque. Yet, analysis of the blade signals during "slow rolls" of the rotor showed good agreement between test data and the predicted in-plane and out-of-plane blade-bending moments from gravity loads, which were significant because of the 8-degree shaft tilt.

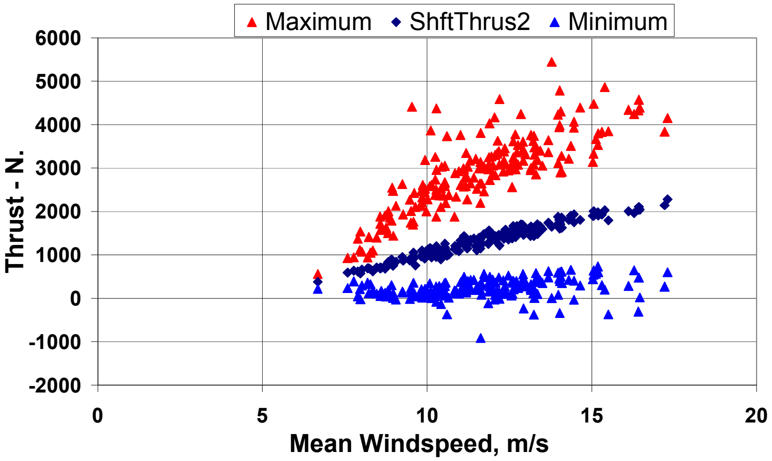

Figure 21. Thrust versus mean wind speed

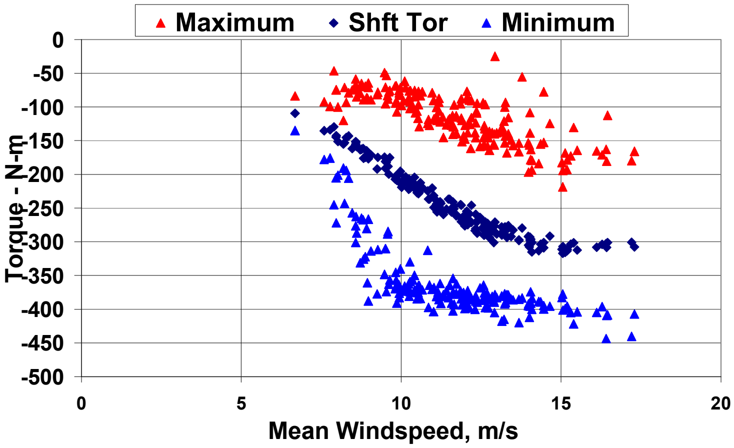

Figure 22. Torque versus mean wind speed

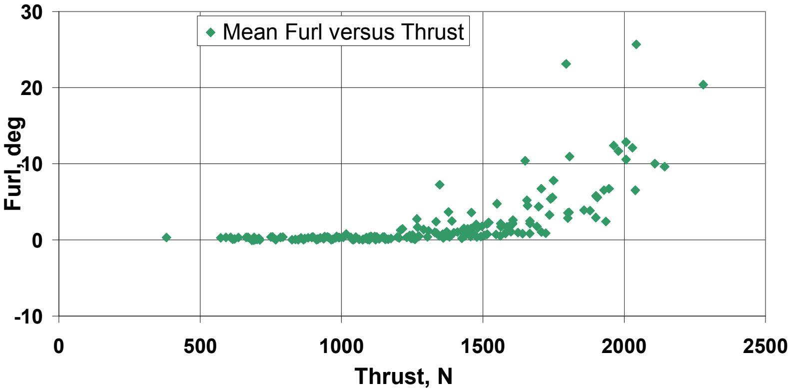

Figure 23. Furl versus thrust

The reason for the discrepancy was that there was a small moment arm, or chordwise offset, between the blade Cg and the centerline of rotation and between the blade Cg and the edge gauge neutral axis, as shown in Figure 24. Although care was taken to align the edge gages along the neutral axis, with a complex airfoil shape there will always be some offset from the neutral axis, which creates a moment arm. As a result of the high speed of the rotor, centrifugal loading acts on this moment arm, so that the edge aerodynamic moments can be relatively small compared to the total edge-bending moment, especially at higher rotor speeds. The error in the edge-bending moment from centrifugal loading caused by the offset between the edge gauge neutral axis and the center of rotation is a test phenomena that has been largely overlooked to date in many test procedures. This effect will be more apparent with smaller turbines that operate at higher RPMs but may also have some effect on larger turbines.

To calculate aerodynamic edge-bending moments, testing was conducted with the rotor unloaded and correlations between the square of rotor RPM and edge-bending moments were developed as shown in Figure 25 for two of the blades. This correlation was then slightly adjusted for the friction losses that are included in the unloaded torque test data by using dynamometer data of torque versus RPM for the unloaded condition. Figure 26 shows a scatter plot of the measured blade three edge moment without any correction. Figure 27 shows a scatter plot of the flap moment for blade three of the SWRT. Flap-bending response is relatively flat with increase in wind speed and decreases at the higher wind speeds as a result of centrifugal stiffening of the blades at the high rotor speeds.

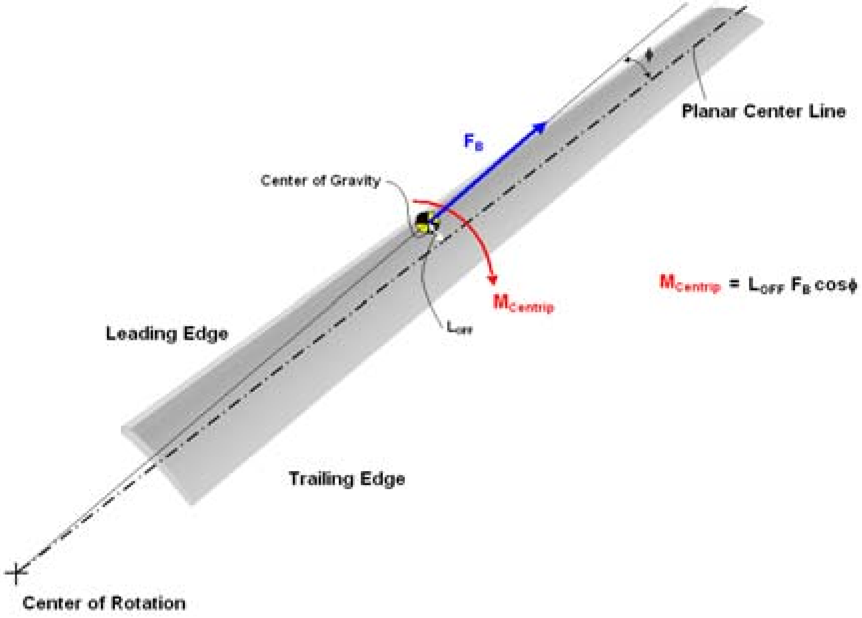

Figure 24. Moment arm between Blade Cg and center of rotation for edge-bending moments

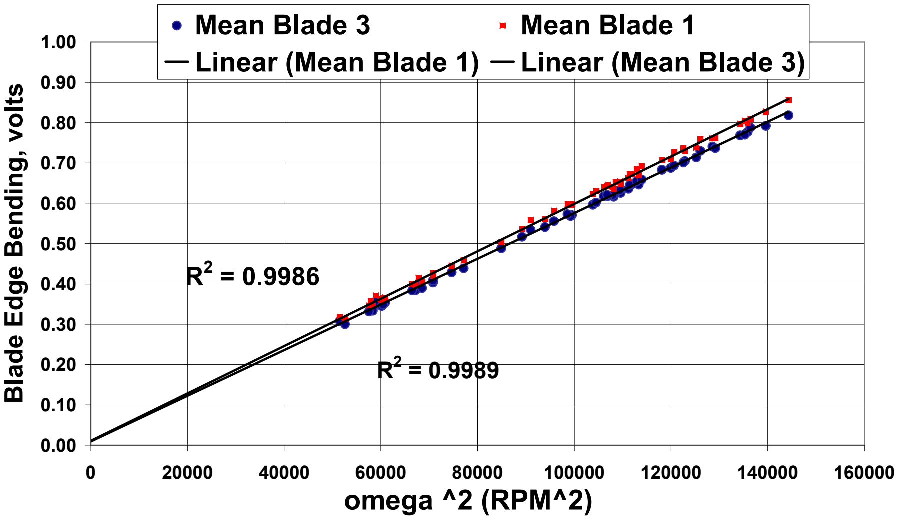

Figure 25. Edge bending versus RPM squared for unloaded operation

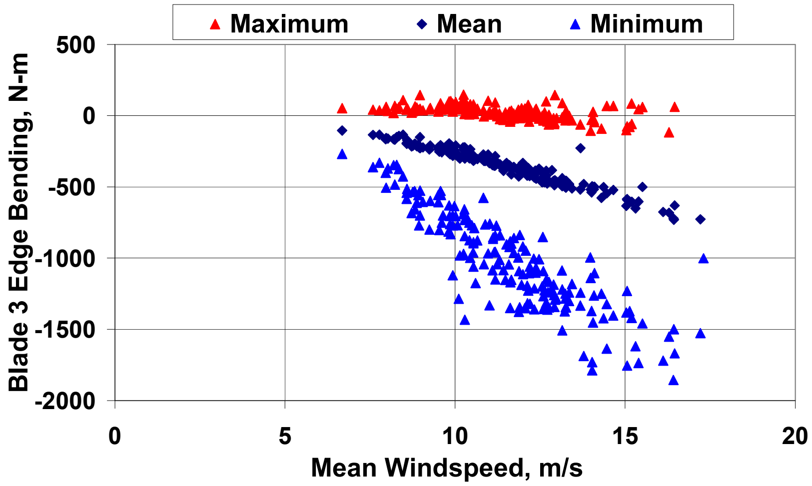

Figure 26. Edge-bending moment versus mean wind speed

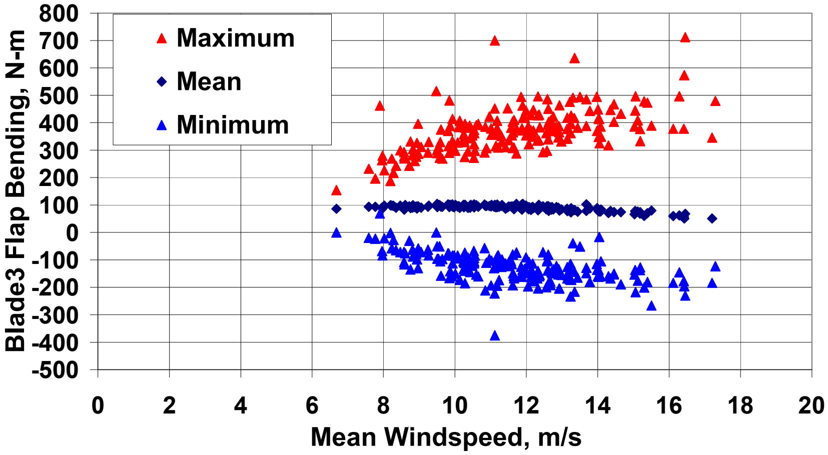

Figure 27. Flap-bending moment versus mean wind speed

Time Series Data

Because furling is a transient phenomena, analysis of time-series data can be more useful than that of 10-minute mean data. In the time-series data, thrust and furl are often correlated but not always. For example, the second furling event of about 14 degrees shown in Figure 28 occurs when the thrust is relatively low and the rotor speed is decreasing, whereas the large furling event of 36 degrees occurs when the thrust is high and the rotor speed is increasing immediately preceding the furl, as would be expected. Yaw error changes occur rapidly and affect furl.

Calculated channels for shaft thrust and shaft 0- and 90-degree bending moments are used to calculate the center of thrust angle (CenThrAng) and center of thrust length (CenThrLen) as follows:

$$\text{CenThrAng} = \text{ArcTan2 (shaft tilt moment/thrust, shaft yaw moment/thrust)} \quad \textbf{(1)}$$

$$\text{CenThrLen} = \text{Sqrt [(shaft tilt moment/thrust)}^{2} + \text{(shaft yaw moment/thrust)}^{2}\text{]} \quad \textbf{(2)}$$

These equations are only valid when inertial forces can be ignored during steady-state operation with negligible yaw rate, otherwise the gyroscopic forces on the shaft have too large an effect and invalidate the equations. Figure 29 shows a time-series furling event with a low yaw rate before the furling event and how CenThrLen plots in relationship to furling. Additional data analysis, using equations (1) and (2), is needed to characterize the effect of aerodynamic thrust on furling behavior during low yaw rates.

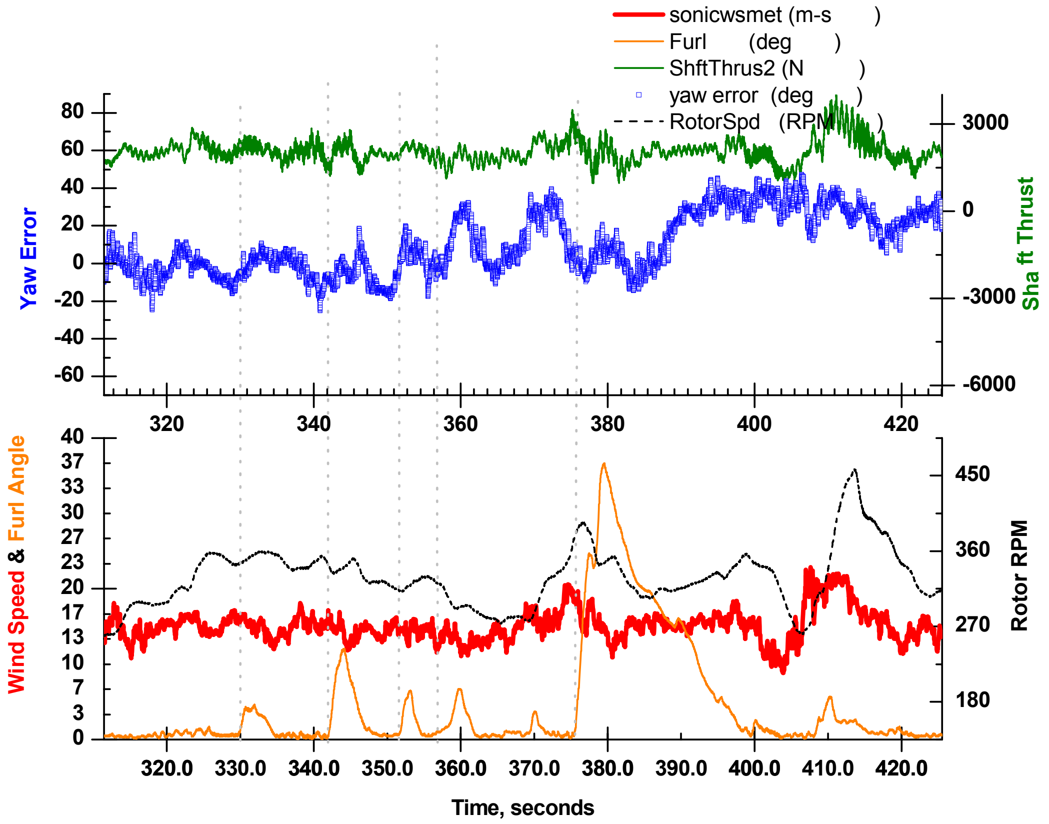

Figure 28. Time series furling events

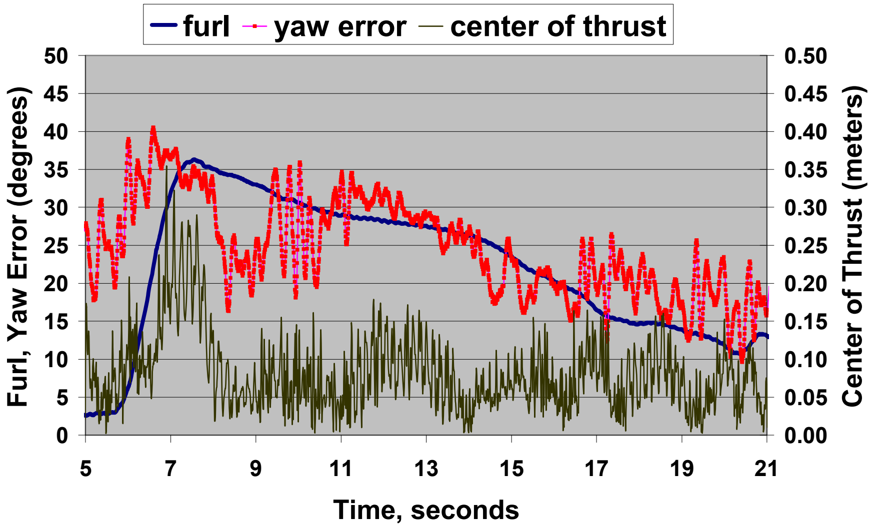

Figure 29. Furling with center of thrust

Comparison of Data Sets

A comparison of 10-minute scatter plots for the different configurations shows the effect of parameter changes between the configurations. Figure 30 shows the ratio of 10-minute mean meteorological tower wind speeds to tail wind speeds for Configuration A and C plotted against wind speed. The greater solidity (about 16% greater) and 33% greater swept area of Configuration C results in a significantly reduced tail wind speed as compared to Configuration A. Because the data are for a very narrow power coefficient (Cp) range, the ratios for a given configuration do not change much with wind speed until the higher wind speeds where the turbine is furled a large percentage of the time and the sonic tail anemometer is partially out of the wake. Rotor speeds for Configuration C are about 25 RPM greater than that of A and B until furling.

Figure 31 shows a comparison of 10-minute mean furling versus wind speed for configuration A, B, and C. The data show only those data points with furl greater than 1.5 degrees and is fitted with a third-order polynomial resulting from the high degree of scatter. The data show that Configuration C furls the most, predominantly because of the higher thrust resulting from the higher solidity of the blades and larger swept area; followed by A with a 4-degree shim, lower solidity, and shorter blades; and then B with the same blades as A but without the shim.

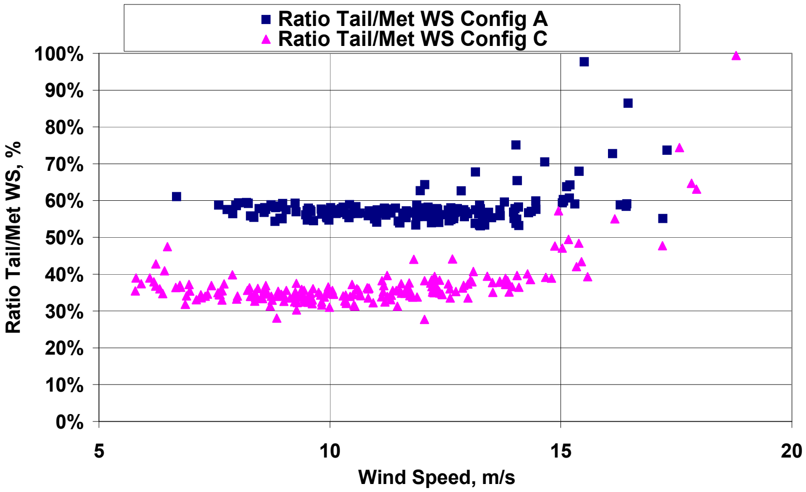

Figure 30. Ratio of tail/met wind speed versus wind speed

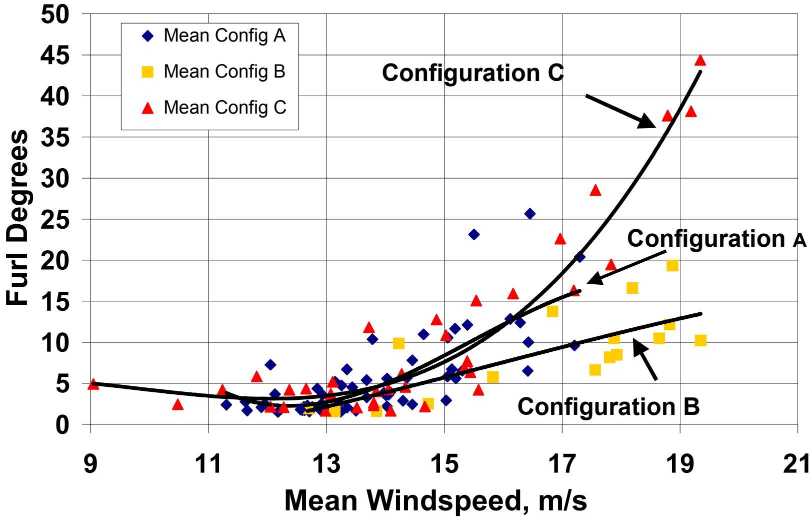

Figure 31. Furl versus wind speed for different configurations

Figures 32 through34 show the data for mean electric power and rotor speed versus mean wind speed and mean torque versus rotor speed for the different configurations. Figures 35 through 37 show data for thrust, shaft-yaw moment, and shaft-tilt moment for the different configurations. Configuration C has a significantly higher thrust and higher yaw and tilt moments. The data for Configurations A and B are similar and hard to differentiate. (The coordinate system conforms to the International Electrotechnical Commission [IEC] standard, so the x-axis is parallel to the main shaft and positive downwind; the z-axis is perpendicular to the main shaft and positive up; and x-y-z form a right-hand system. The shaft tilt moment [My] is the moment about the y-axis and shaft yaw moment [Mz] is the moment about the z-axis. Note that the overhang moment for shaft tilt is not included in the data.)

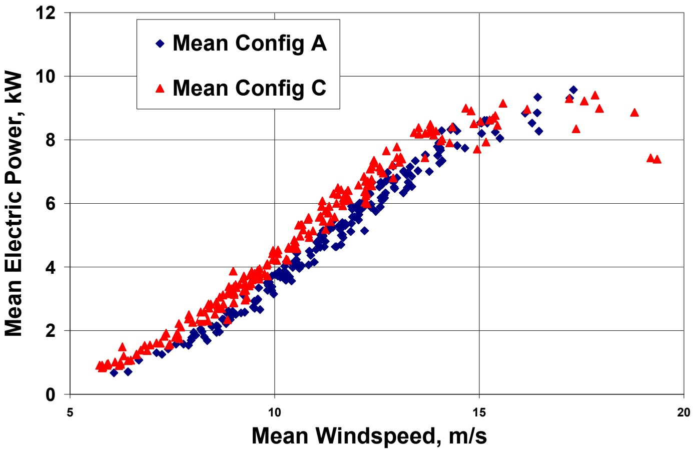

Figure 32. Shaft electric power versus wind speed for different configurations

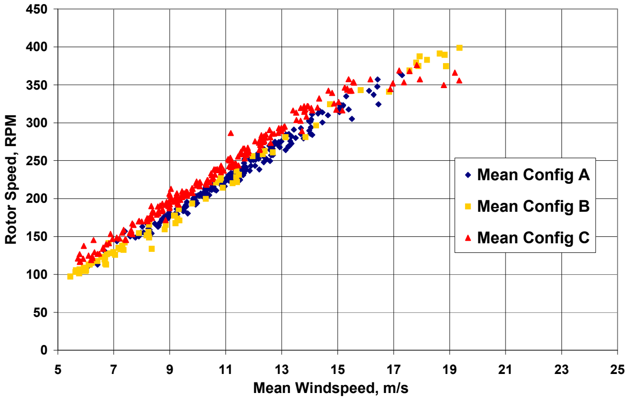

Figure 33. Shaft RPM versus wind speed for different configurations

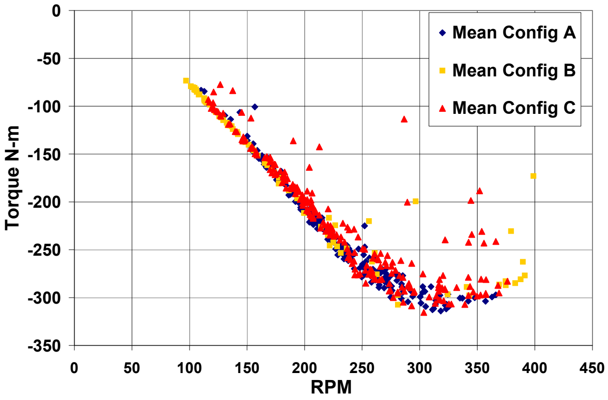

Figure 34. Shaft torque versus RPM for different configurations

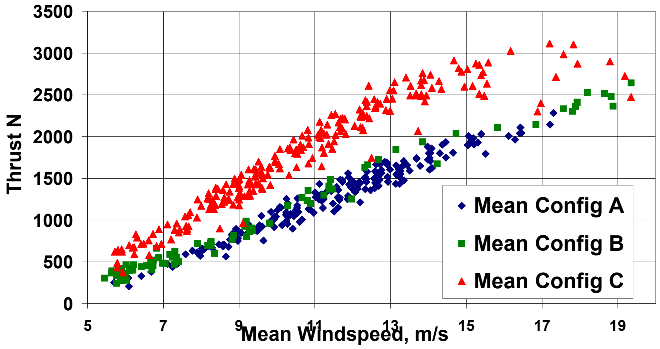

Figure 35. Shaft thrust versus RPM for different configurations

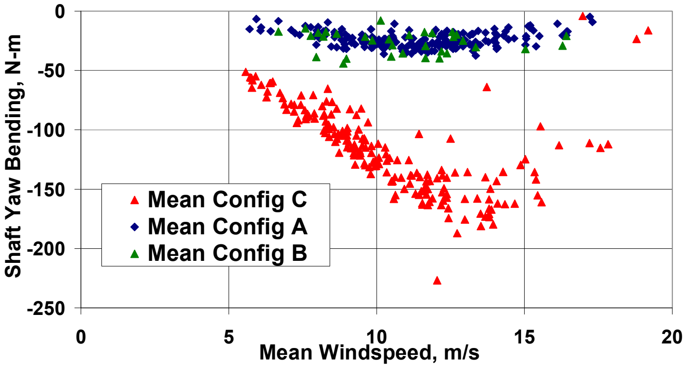

Figure 36. Shaft yaw moment versus wind speed for different configurations

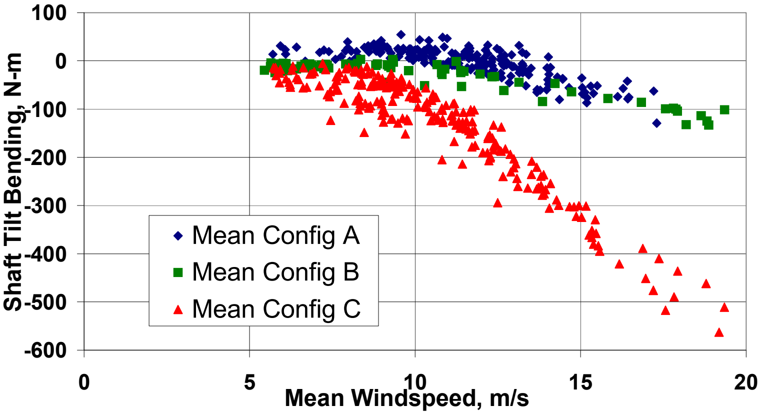

Figure 37. Shaft tilt moment versus wind speed for different configurations

Correlation Between Inflow and Furling

Inflow Data Processing Equations

In recent years, significant work has been conducted showing the relationship between inflow parameters and fatigue loads for wind turbines [11, 12]. To better understand the relationship between coherent or organized turbulence and the potential impact on furling, calculated channels were developed for several different inflow parameters based on the data obtained by the sonic anemometer on the meteorological tower.

The following inflow parameters were calculated for each data set.

$$u_{f_H}(t_i) = |\, u_{p_1}(t_i)\cos\beta + u_{p_2}(t_i)\sin\beta \,| \qquad \textbf{(3)}$$

$$u_{f_1}(t_i) = u_{f_H}(t_i)\cos\phi + u_{p_3}(t_i)\sin\phi \qquad \textbf{(4)}$$

$$u_{f_2}(t_i) = -\,u_{p_1}(t_i)\sin\beta + u_{p_2}(t_i)\cos\beta \qquad \textbf{(5)}$$

$$u_{f_3}(t_i) = -u_{p_H}(t_i)\sin\phi + u_{p_3}(t_i)\cos\phi \qquad \textbf{(6)}$$

where u_{f_1}, u_{f_2}, and u_{f_3} are wind vectors rotated from those measured in the sonic probe coordinate system ($p_{1,2,3}$) to ones aligned with the flow ($f_{1,2,3}$) and in the direction of the mean shearing stress, and

$$\beta = \arctan(\overline{u_{p_2}} \,/\, \overline{u_{p_1}}) \qquad \textbf{(7)}$$

$$\phi = \arctan(\overline{u_{p_3}} \,/\, \overline{u_{p_H}}) \qquad \textbf{(8)}$$

where u_{p_1} and u_{p_2} are the horizontal velocity components measured along the sonic probe x-axis and y-axis, respectively, and u_{p_3} is the vertical velocity component measured along the sonic probe z-axis. The turbulent or fluctuating (i.e., zero-mean) component velocities (i.e., longitudinal, transverse or crosswind, and vertical velocities) for which only the longitudinal (i.e., streamwise) component is aligned with the flow vector u_{f_1} with a non-zero mean, are defined as

$$u'(t_i) = u_{f_1}(t_i) - \overline{u_{f_1}} = u_{f_1}(t_i) - \frac{1}{N}\sum_{i=1}^{N} u_{f_1}(t_i) \qquad \textbf{(9)}$$

$$v'(t_i) = u_{f_2}(t_i) \qquad \textbf{(10)}$$

$$w'(t_i) = u_{f_3}(t_i) \qquad \textbf{(11)}$$

The turbulent Reynolds stress components are

$$u'w'(t_i) = u'(t_i) \cdot w'(t_i) \qquad \textbf{(12)}$$

$$u'v'(t_i) = u'(t_i) \cdot v'(t_i) \qquad \textbf{(13)}$$

$$v'w'(t_i) = v'(t_i) \cdot w'(t_i) \qquad \textbf{(14)}$$

and the mean shearing stress or friction velocity is defined as

$$u^* = \sqrt{|\overline{u'w'}|} \qquad \textbf{(15)}$$

and the turbulence kinetic energy (TKE) is

$$\text{TKE} = 0.5 * [(u')^2 + (v')^2 + (w')^2] \quad \textbf{(16)}$$

and coherent TKE (CoTKE) = $0.5 * \text{SQRT}\,[(u'w')^2 + (u'v')^2 + (v'w')^2]$. **(17)**

In addition to the inflow parameters listed in equations 3 through 17, the gradient N_{Ri} for a height of 2 m – 80 m was obtained from a meteorological tower at the NWTC and included in the data sets for the SWRT. The N_{Ri} can be useful in explaining turbulence because it represents the ratio of turbulence generation by buoyancy (i.e., thermal) to wind shear (i.e., mechanical) forces. A negative N_{Ri} value represents unstable or convective conditions, a value of zero represents neutral, and positive values signify a stable flow.

A correlation analysis was conducted to determine whether inflow parameters have a significant impact on furling. Using the inflow parameters described in equations 9 through 17, a single variable correlation analysis was performed for each test configuration that yielded a list of variables that are highly correlated to furl angle. A multivariate correlation was then performed on each test configuration to determine how sensitive the variables are to furl. A summary of the multivariate regression is provided below. It should be noted that the results presented here are preliminary and that correlation analyses such as these should be investigated further to show specific cause and relationship between physical parameters.

Configuration A: The highest correlation (correlation coefficient, r^2, is 0.65) was obtained between furl and the combination of coherent turbulent kinetic energy (CoTKE), standard deviation of the vertical wind component of the inflow (w'), and mean wind speed.

Configuration B: The highest correlation (correlation coefficient, r^2, is 0.72) was obtained between furl and the combination of maximum CoTKE, maximum wind speed, and wind speed.

Configuration C: The highest correlation (correlation coefficient, r^2, is 0.79) was obtained between furl and w', local friction velocity u*, wind speed, and rotor speed. The introduction of rotor speed made the correlation coefficient change dramatically and, even though it is a machine variable, it was left in. When it was taken out, the r value went down significantly.

Configuration B, the configuration that is hardest to furl, is most sensitive to the maximum wind speed and maximum CoTKE. The same configuration without the shim (i.e., A) furls easier and is sensitive to the mean CoTKE and mean wind speed, as well as w'. Configuration C, the easiest to furl configuration, is not sensitive to CoTKE. These results can be partially explained when taking into consideration the different geometries of the turbine, but the results should still be considered preliminary and are shown here for anyone interested in further pursuing the effects of inflow on turbine furling.

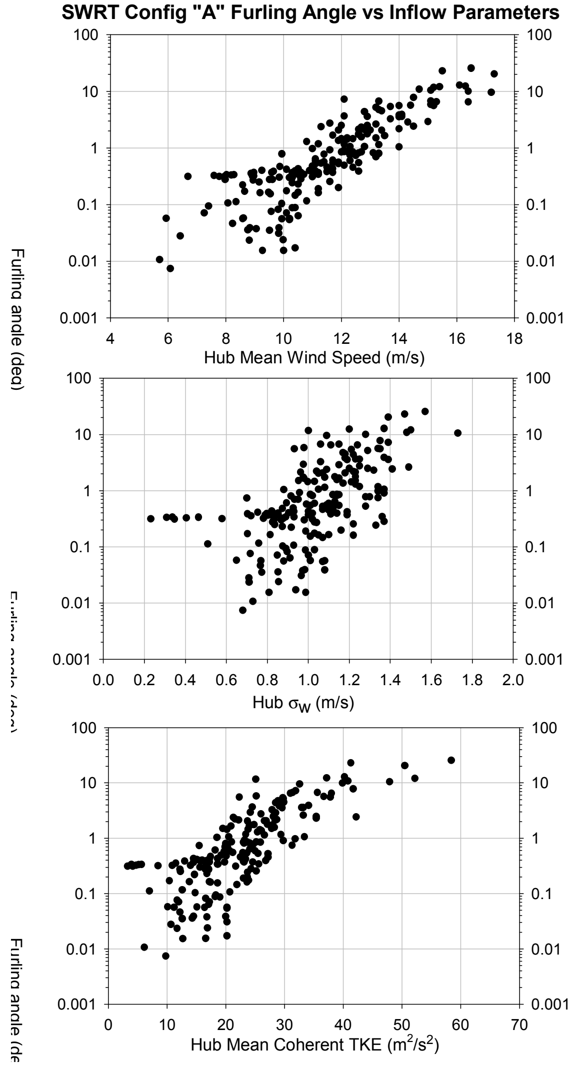

Figure 38. Furling and inflow

Figure 38 shows plots of furling versus wind speed, w', and CoTKE, and Figure 39 shows a plot of furling versus N_{Ri} for Configuration A. Note that the maximum furling occurs at about a N_{Ri} of 0.13. This is indicative of a site with a lot of coherent turbulence. The maximum load response from another test turbine at the NWTC, the Advanced Research Turbine (ART), is also shown on the graph for comparison. Note that the turbulence at this site is different because it is in a slightly different location.

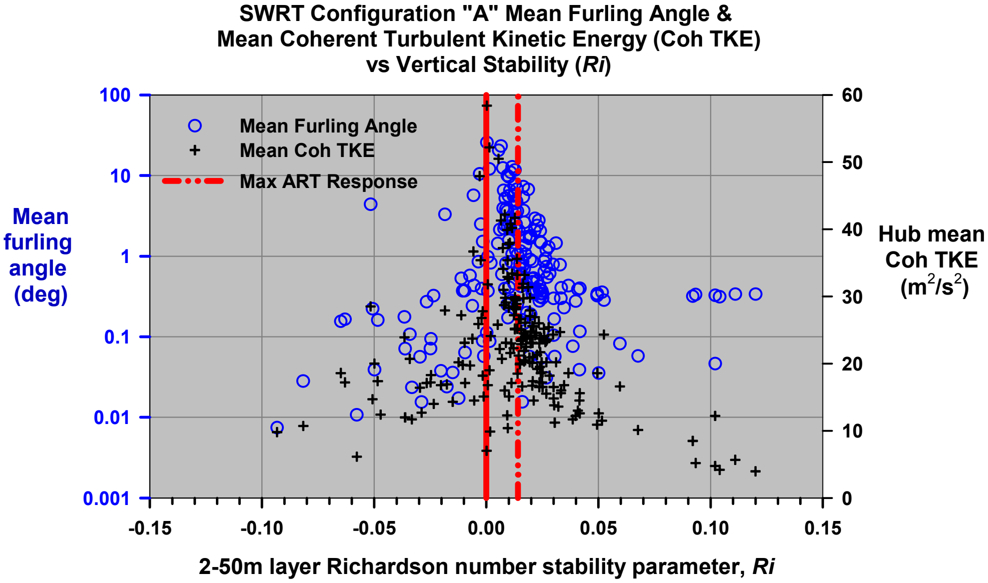

Figure 39. Furling versus N_{Ri}

Figure 40 shows plots of the RMS CoTKE and RMS w' (vertical gust velocity variance) versus frequency, cycles/minute, and wavelength in rotor diameters. The data are for two different time series plots from Configuration A with a wind speed of 14 m/s for both but different turbulence parameters. In one file, the mean 10-minute furl is zero, whereas the other is 4 degrees. The mean wind directions for the two files are within 1 degree of each other. CoTKE and w' were chosen as the variables to plot based on the correlation analysis. Mean wind speed, the other highly correlated variable, is the same for both files. The data show some effect of coherent turbulence and w' on furling, although the difference in furling is only four degrees and could be considered insignificant. The data also show a range of time for when the maximum energy is occurring and indicates the wavelength of the maximum CoTKE and w' in relation to the rotor diameter (this was calculated by dividing by the mean wind speed).

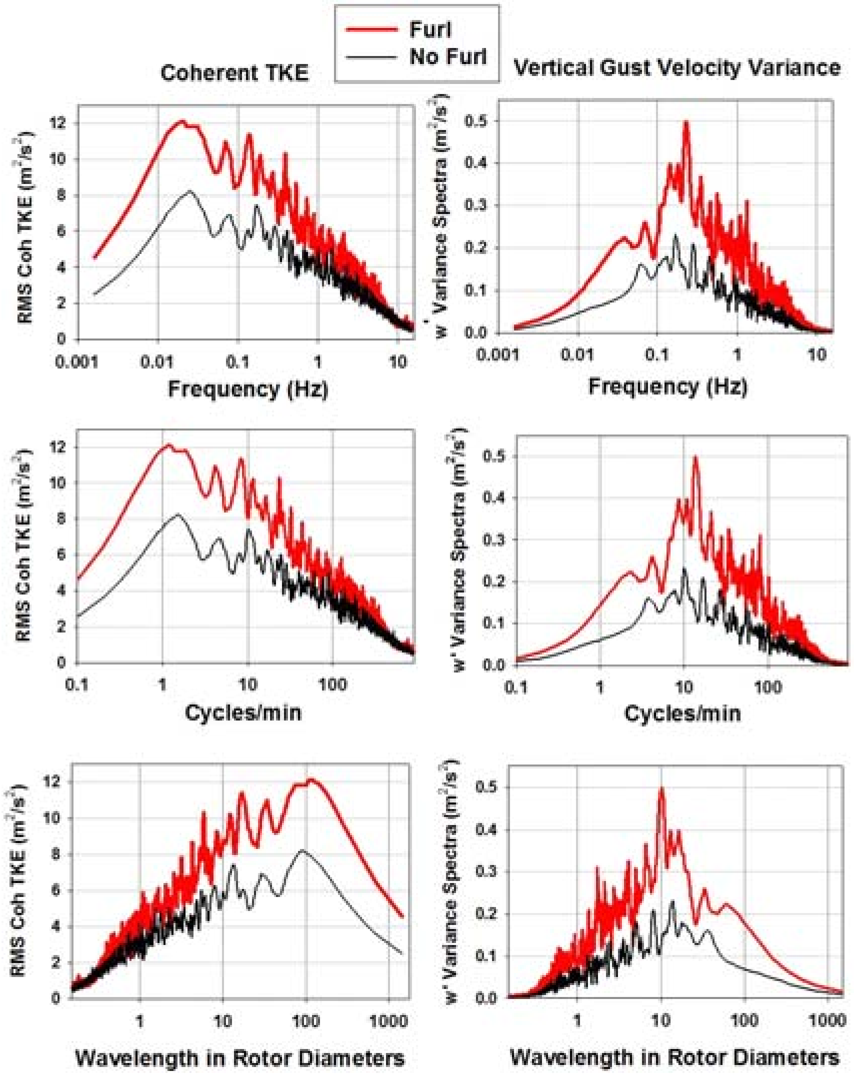

Figure 40. CoTKE and vertical gust variance for two files with the same wind speed but slightly different furl

SWRT Modeling

Overview

FAST (Fatigue, Aerodynamics, Structures, and Turbulence) [4] and ADAMS® (Automatic Dynamic Analysis of Mechanical Systems, "ADAMS" is used to imply "ADAMS®" throughout this report) [13] are two of the primary design codes used by the U.S. wind industry and the two most promoted by NREL's National Wind Technology Center (NWTC). FAST is a relatively simple, structural-response, HAWT-specific code written and distributed by the NWTC. The more complex ADAMS code is a commercially available, general purpose, multibody-dynamics code from MSC.Software Corporation for calculating multi-body dynamic forces [1] that is adaptable for modeling wind turbines. It is more difficult to use than FAST and the software is expensive, whereas FAST is available free of charge. Both FAST and ADAMS use the AeroDyn aerodynamic subroutine package developed by Windward Engineering LLC [14] to calculate aerodynamic forces.

The FAST and ADAMs models of the SWRT were developed using geometric, aerodynamic, and mass properties measured at the NWTC or provided by Bergey Windpower. The models include blade flexibility, a variable-speed generator with a torque-speed look-up table, tail furling with nonlinear user-defined springs and dampers, and free yaw.

The approach to modeling the SWRT consisted of the following: (1) upgrading the FAST model to include furling, which is described briefly below and more in-depth in reference [6]; (2) validating the FAST model by constructing an ADAMS model of the SWRT and comparing the two results for furling cases; (3) running simulations with the FAST model and comparing them to the SWRT test data, and finally, (4) including torsional blade stiffness in the ADAMs model and re-running the simulations performed in step (3) in ADAMs. This last step was necessary because after lengthy data analysis and comparisons between FAST SWRT simulations and test data, it was determined that the "live twist" of the blade was having a significant impact on rotor performance. Torsional stiffness cannot currently be modeled in FAST, so the ADAMS model was used for the final simulations and the torsional stiffness of the blade was input into the model.

Comparison of SWRT ADAMS and FAST Model with SWRT Test Data

The SWRT tests provided a unique opportunity to validate both the FAST and ADAMS aeroelastic models that include furling. Direct comparison of time series was useful in that it provided a highly detailed view of a small amount of data. Comparisons of summary statistics are valuable because they provide a view of a large quantity of data, albeit in much less detail. The first modeling results described below are for FAST modeling without the elastic twist of the blade tip (i.e., live twist).

Statistics were compared by running the FAST model with turbulent wind conditions simulated by TurbSim [15]. TurbSim can simulate coherent turbulent structures with temporal and spatial scaling that reflect the actual turbulence at site 1.4 at the NWTC [16]. For our analysis, we used an 8 x 8 grid of points across the rotor disc and specific inflow data measured and/or calculated for each TurbSim file for the following: gradient N_{Ri}, power law exponent, friction or shear velocity, and the cross correlation coefficients for the turbulent or fluctuating (i.e., zero mean) component velocities (i.e., longitudinal, transverse or crosswind, and vertical velocities, U', V', and W').

Figures 40 – 43 compare statistics for 186 10-minute test records and 310 10-minute simulations. All of these results are for Configuration A with an inverter load.

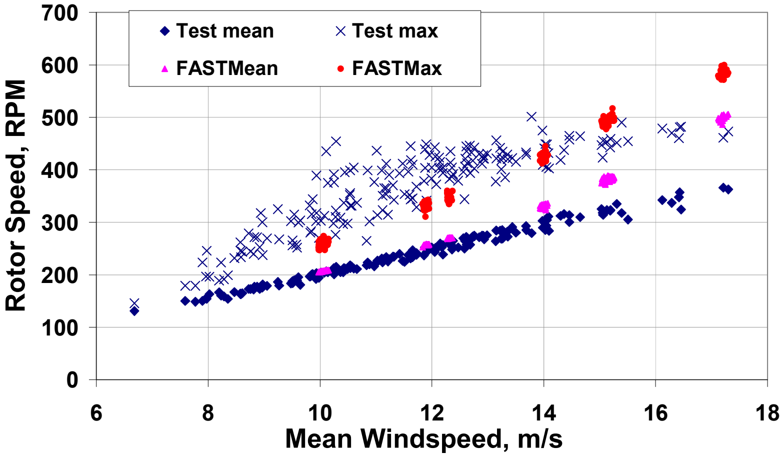

Figure 41. 10-Minute mean and maximum values of rotor RPM, Configuration A

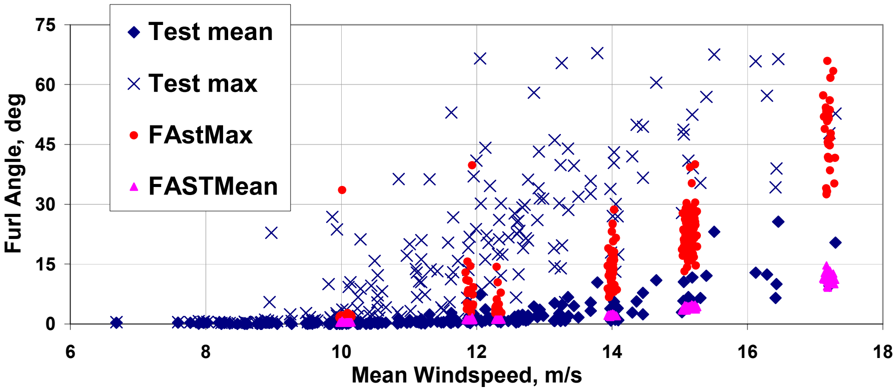

Figure 42. 10-Minute mean and maximum values of tail furl for Configuration A

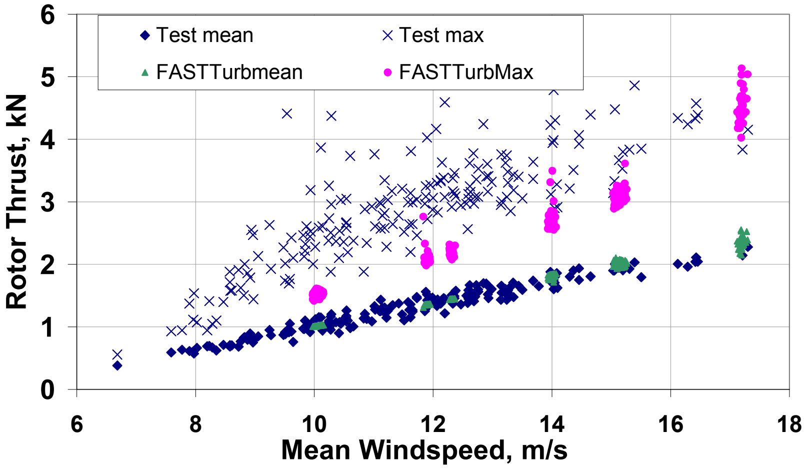

Figure 43. 10-Minute mean and maximum values of thrust for Configuration A

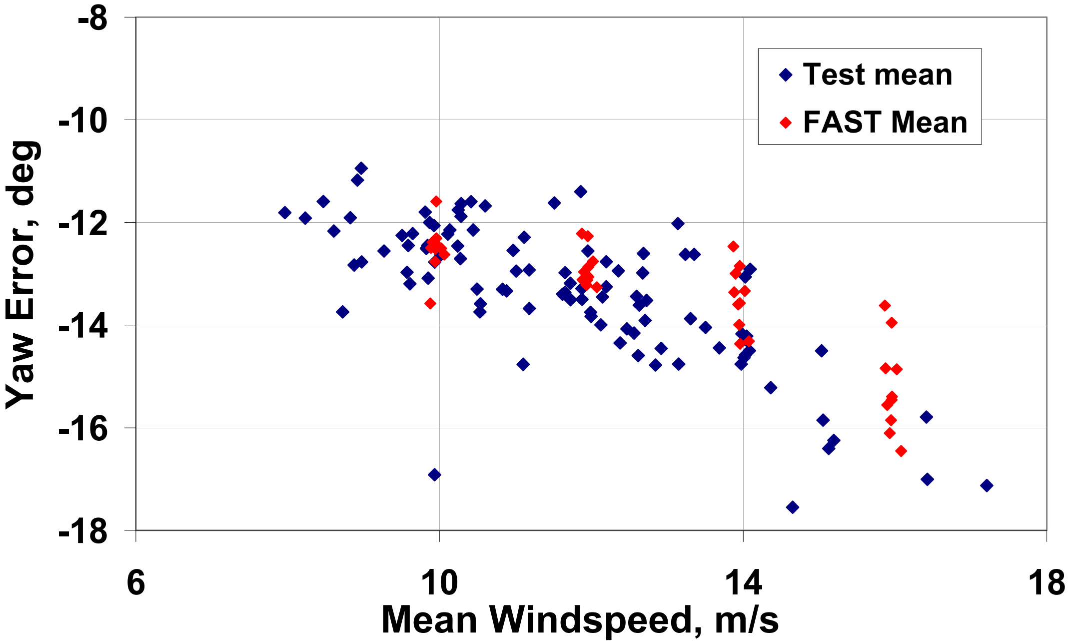

Figure 44. Mean yaw error for Configuration A

Time series comparisons for the SWRT modeled with FAST showed results similar to the summary statistics shown above; rotor RPM was severely over predicted at higher wind speeds but thrust was modeled accurately. This modeling was conducted for all three turbine configurations with the same results. Various approaches were tried to understand why the FAST model predicts rotor speeds much higher than measured in high winds. In low winds, the predictions were quite good. Both the airfoil tables and the alternator torque-speed curve were adjusted in various ways. Unrealistically large changes were required to improve the agreement in high winds, but then the accuracy in low winds was compromised. The reason for the discrepancy was finally discovered to be the elastic twist of the blade, which increases with rotor speed (or wind speed).

Because the FAST program cannot model blade elastic torsion motion, an ADAMS model was created from the FAST model that includes the blade torsion degrees of freedom (DOF). The torsional stiffness of the blades was measured and input into the ADAMS model. The aerodynamic pitching moment was added to the airfoil tables so the ADAMS model includes both aerodynamic and inertial causes of blade twisting. There were no other changes to the model. Therefore, the only substantial reason for difference between the FAST and ADAMS predictions is live blade twist.

ADAMS and Fast predict blade motions differently. ADAMS uses 6 DOF per blade element, and there are 15 elements per blade for a total of 90 DOF per blade. Fast has 3 DOF per blade (2 flapwise and 1 edgewise) plus a polynomial mode shape for each DOF.

ADAMS also requires blade torsional stiffness values, chordwise center of gravity (Cg) offsets, and the option of using the center of mass (Cm) values in the airfoil tables. Fast does not allow for any of these. The ability of the blade to twist (and therefore change the angle of attack) in the ADAMS model, resulted in better correlation with the test data. The torsional stiffness of the

SH3055 blade is 6500 Nm, and the c.g. offset is 0.017 m (towards the trailing edge) from the quarter chord. Appendices E and F show the model inputs for both the FAST and ADAMS models.

Figures 45-50 show the results of the summary statistics for Configuration C provided by Craig Hansen. These results were generated using the original 'untuned' airfoil and alternator data. They therefore represent the accuracy of predictions that would be done during a design if airfoil and alternator properties were available from wind tunnel or bench testing and blade elastic properties were known from Finite Element Analysis (FEA) or testing.

The statistics were compared by running the ADAMS model with simulated turbulent wind conditions generated by SNWind v1.22. An 8 x 8 grid of points was used across the rotor disc and three components of time-varying wind were generated at each grid point. The turbulence was generated with statistics that match the IEC Category-A conditions. Site-specific turbulent inputs were not used in this analysis.

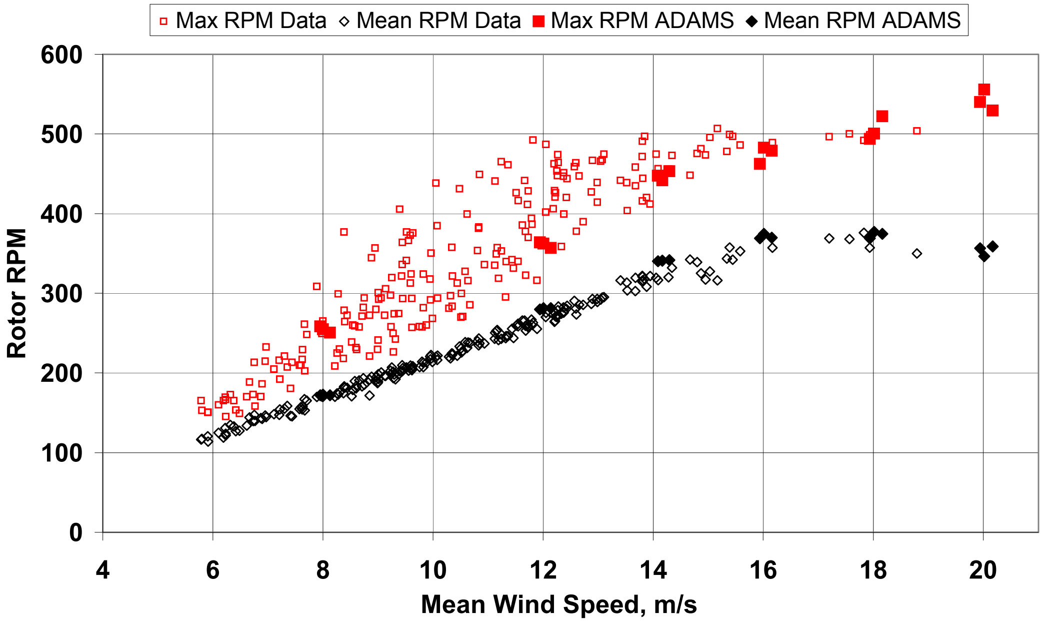

Figure 45. 10-Minute mean and maximum values of rotor RPM for Configuration C

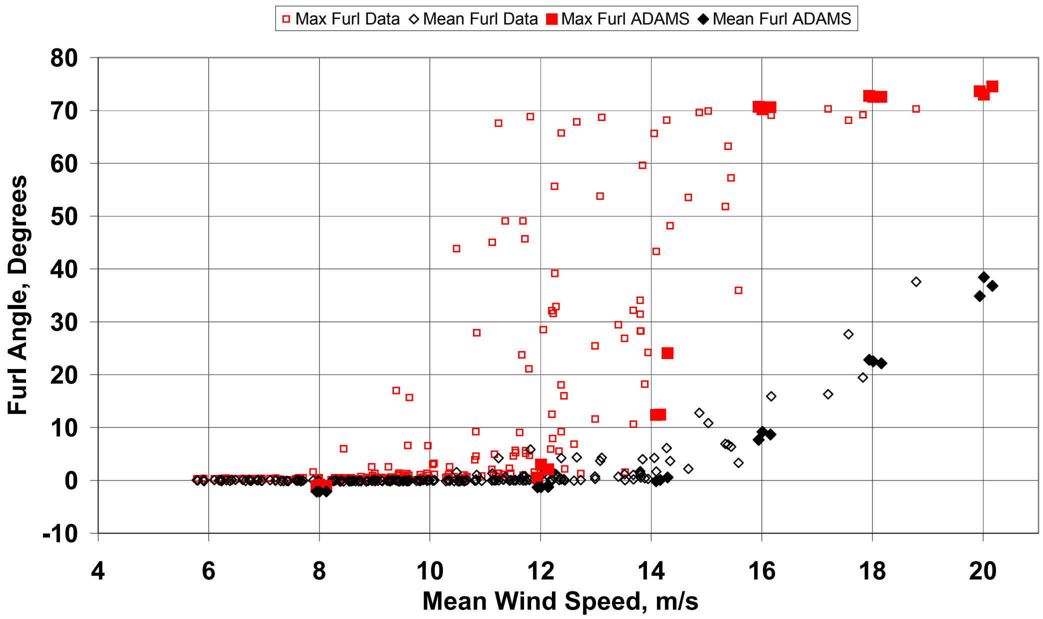

Figure 46. 10-Minute mean and maximum values of tail furl for Configuration C

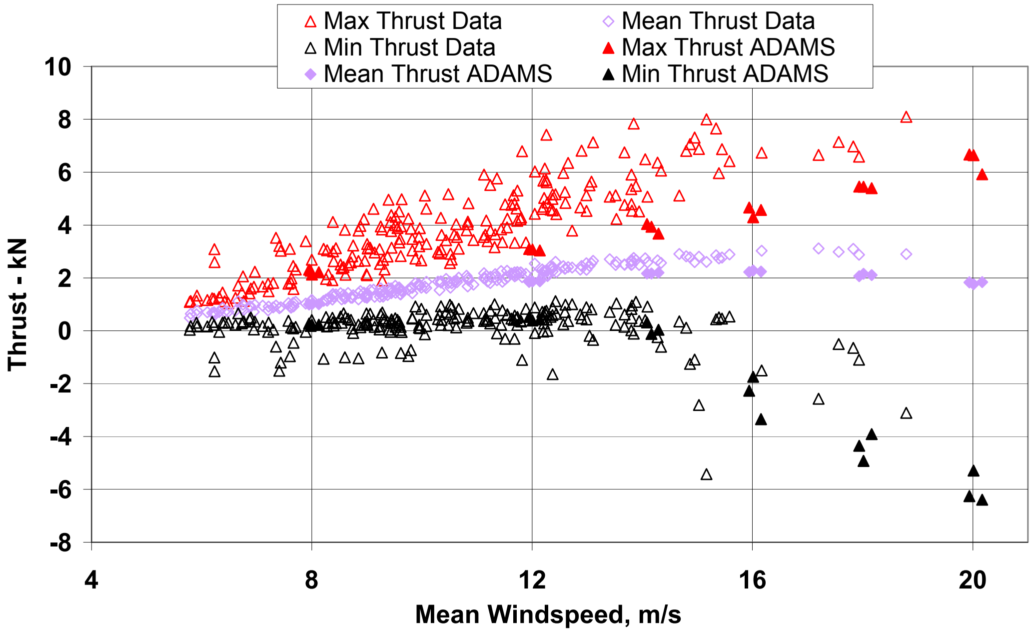

Figure 47. 10-Minute mean, minimum, and maximum values of thrust for Configuration C

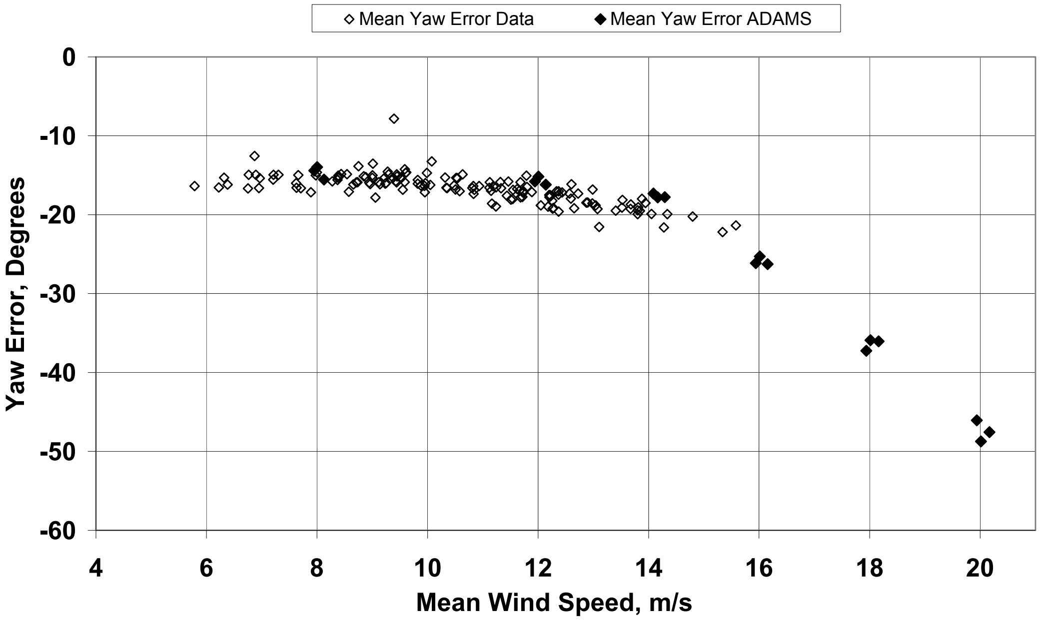

Figure 48. 10-Minute mean values of yaw error for Configuration C

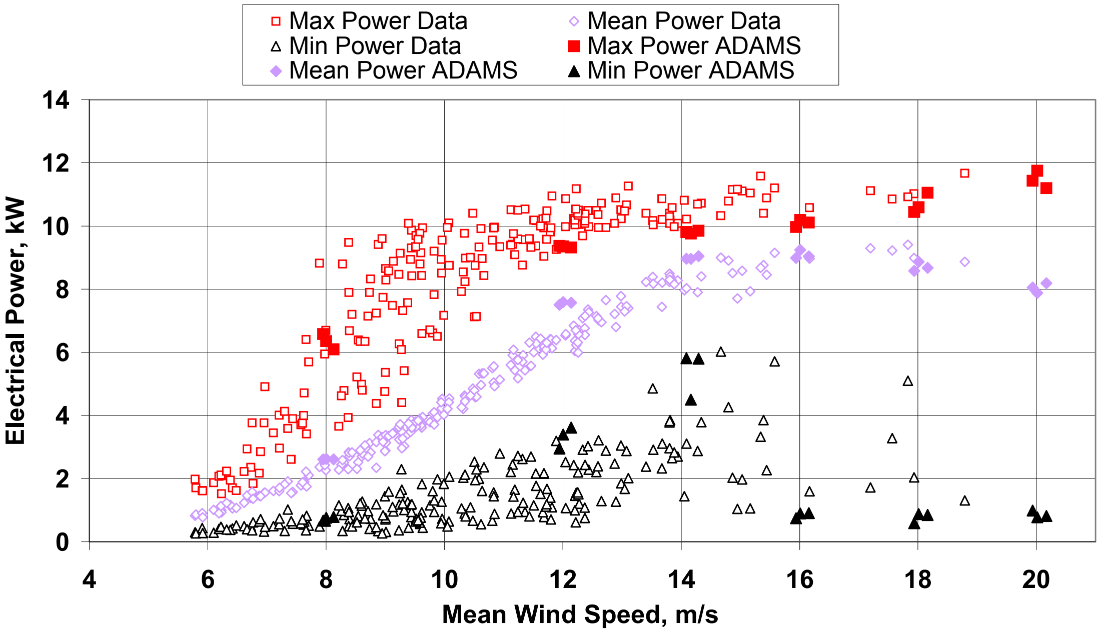

Figure 49. 10-Minute mean, maximum, and minimum values of electric power for Configuration C

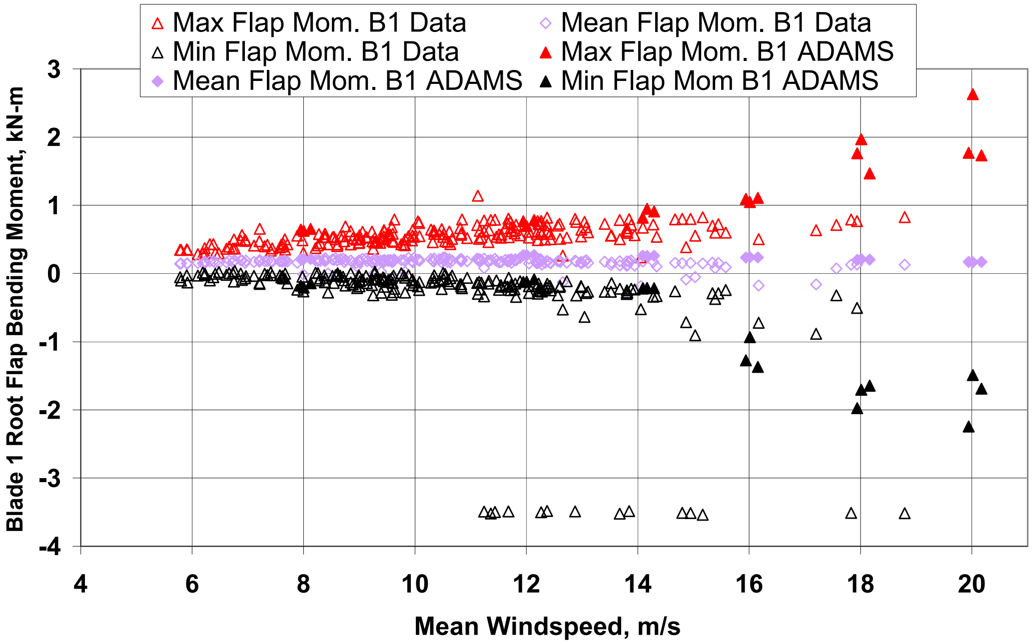

Figure 50. 10-Minute mean, maximum, and minimum values of Blade 1 flap bending for Configuration C

The summary statistics for Configuration C do not include the site-specific turbulence inputs that were included in the Configuration A FAST summary statistics shown previously. Configuration C statistics use the IEC Category A turbulence conditions. Figure 51 shows the actual turbulence intensities for the test data as compared to the IEC test case.

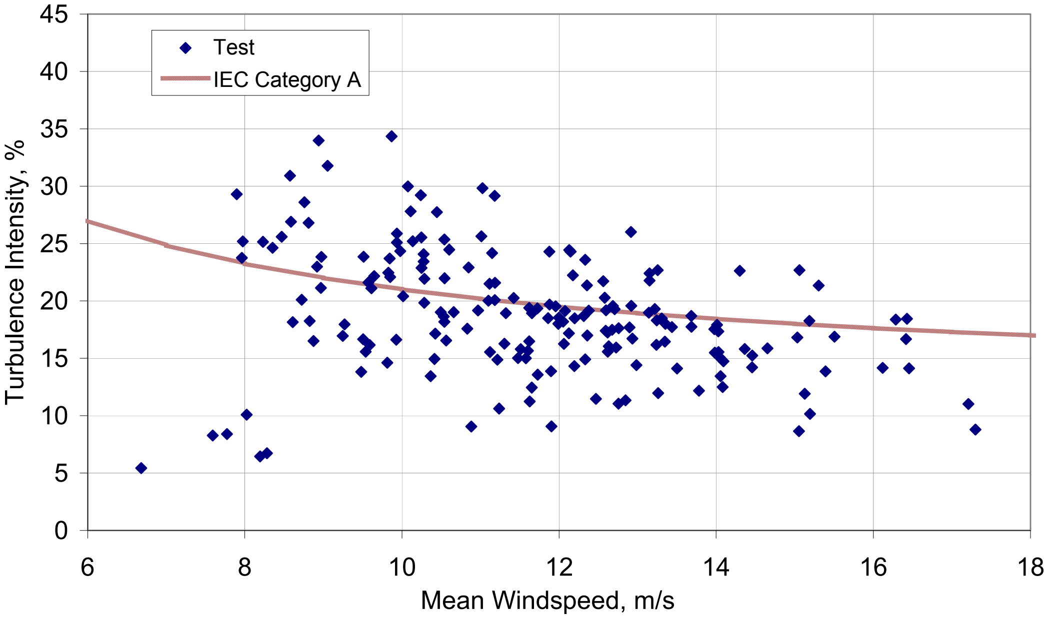

Figure 51. IEC Category A and test data turbulence intensities.

Time series comparisons are made by driving the ADAMS model with measured wind data. Measurements of the hub-height horizontal and vertical wind speeds and the wind direction are used for the comparisons. Measurements of instantaneous horizontal wind shear were not available. Horizontal wind shear is known to be an important driver of yaw and furling motions [17], but it is difficult to measure. Driving a model with "hub-height" wind data misses small-scale turbulence effects but captures the large-scale, slow variations in wind characteristics.

Figure 52 is a plot of blade elastic twist versus rotor RPM and Figure 53 is a time series plot of blade elastic twist for the SWRT that shows the large amount of live twist during one 10-minute time series file with an average wind speed of 16.2 m/s. Figures 54-57 show the same time series file for various parameters. The FAST modeling results without torsional stiffness are also shown. The results demonstrate the importance of blade live twist to modeling, especially for the RPM. Modeled sensitivity analyses show the importance of the aerodynamic pitching moment to the blade live twist.

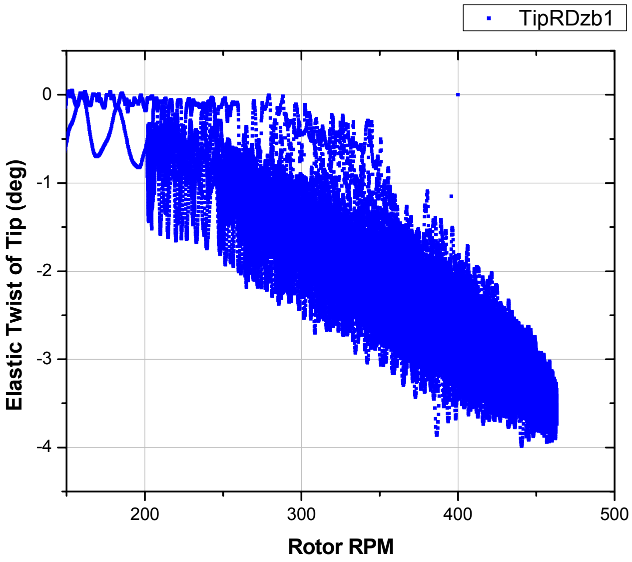

Figure 52. Elastic twist versus rotor RPM for one 10-minute test of Configuration C

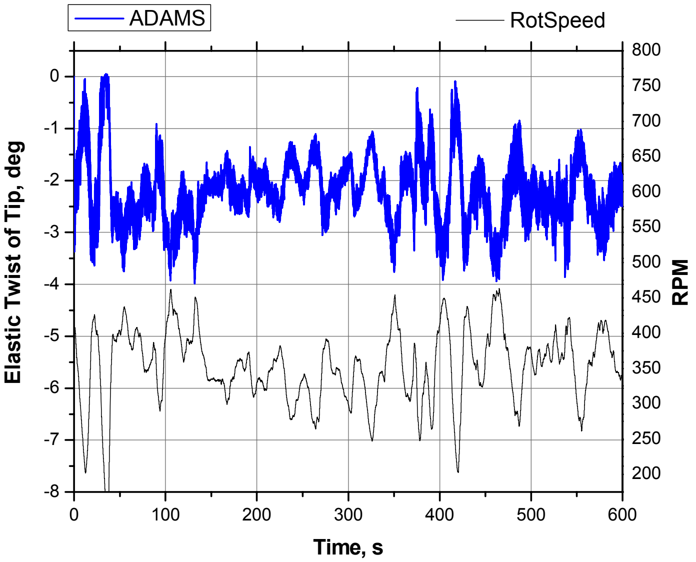

Figure 53. Elastic twist of blade tip and rotor RPM versus time for same 10-minute test (negative twist is toward feather)

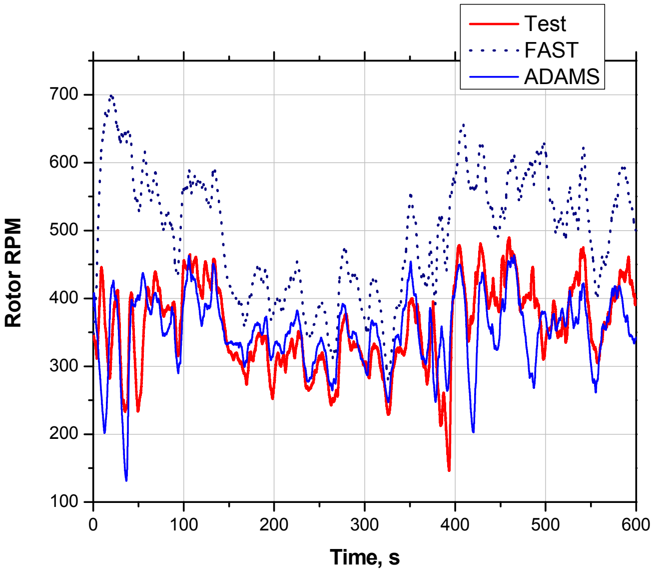

Figure 54. Rotor RPM versus time for same 10-minute test

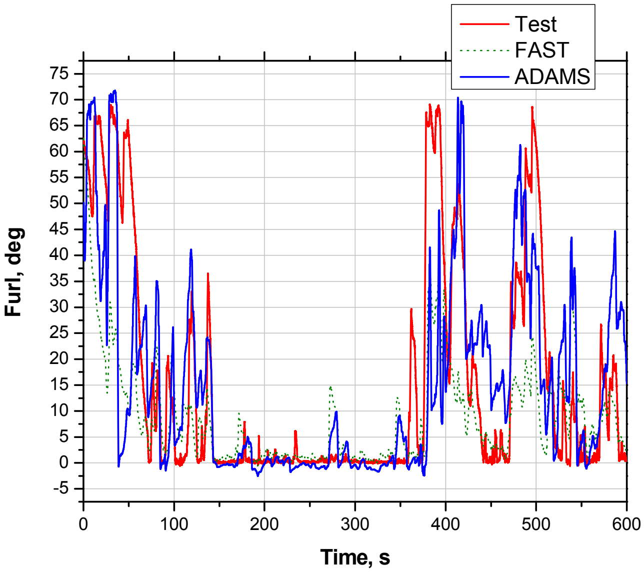

Figure 55. Rotor furl versus time for same 10-minute test

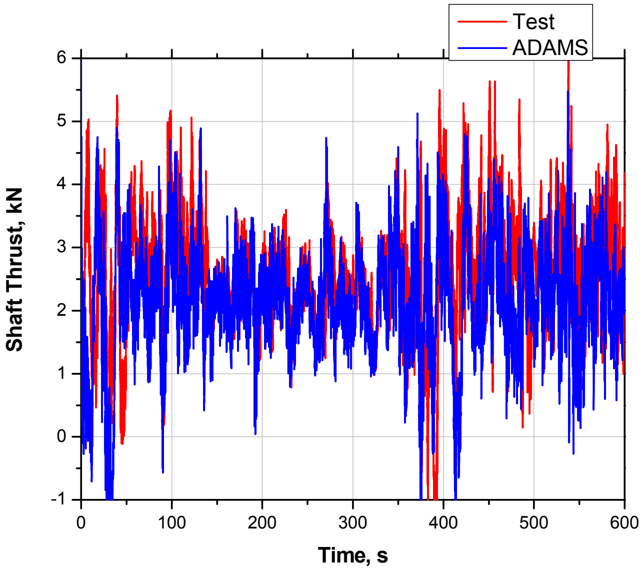

Figure 56. Rotor thrust versus time for same 10-minute test

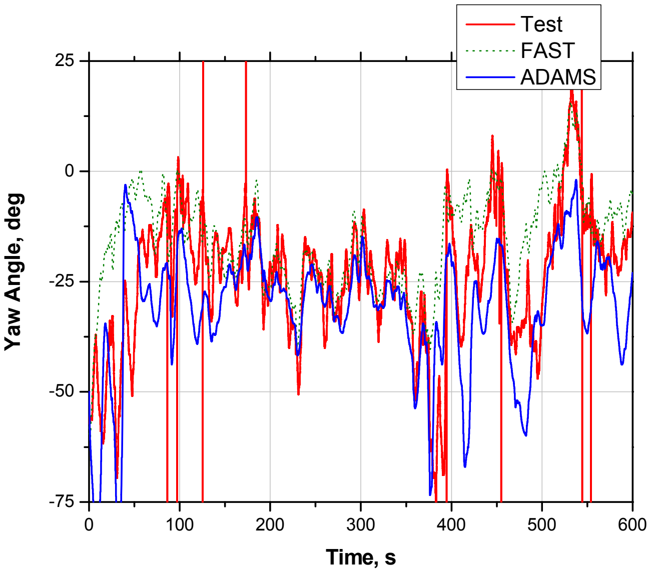

Figure 57. Yaw error versus time for same 10-minute test

Fast Furling Model

Jason Jonkman of NREL recently upgraded the FAST code to include furling effects [6]. The upgrades include a lateral thrust offset and skew angle of the rotor shaft from the yaw axis, rotor-furling and tail-furling degrees-of-freedom (DOFs), up- and down-furl stops, and tail fin aerodynamics and inertia. The location and orientation of the new furling DOFs are completely user-specified, making the simulator flexible enough to model many furling wind turbine configurations.

For example, to model a wind turbine with tail-furling like the SWRT, the new tail-furl DOF should be enabled and the rotor-furl DOF locked. The angular motion of the tail boom and fin through the tail-furl DOF then takes place about a tail-furl axis defined by input parameters TFrlPntxn, TFrlPntyn, TFrlPntzn, TFrlSkew, and TFrlTilt. Inputs TFrlPntxn, TFrlPntyn, and TFrlPntzn locate an arbitrary point on the tail-furl axis relative to the tower-top. Inputs TFrlSkew and TFrlTilt then define the angular orientation of the tail-furl axis passing through this point. Note that the tail is modeled as a rigid body with lumped tail-boom and tail-fin point masses and a moment of inertia specified about the tail-furl axis.

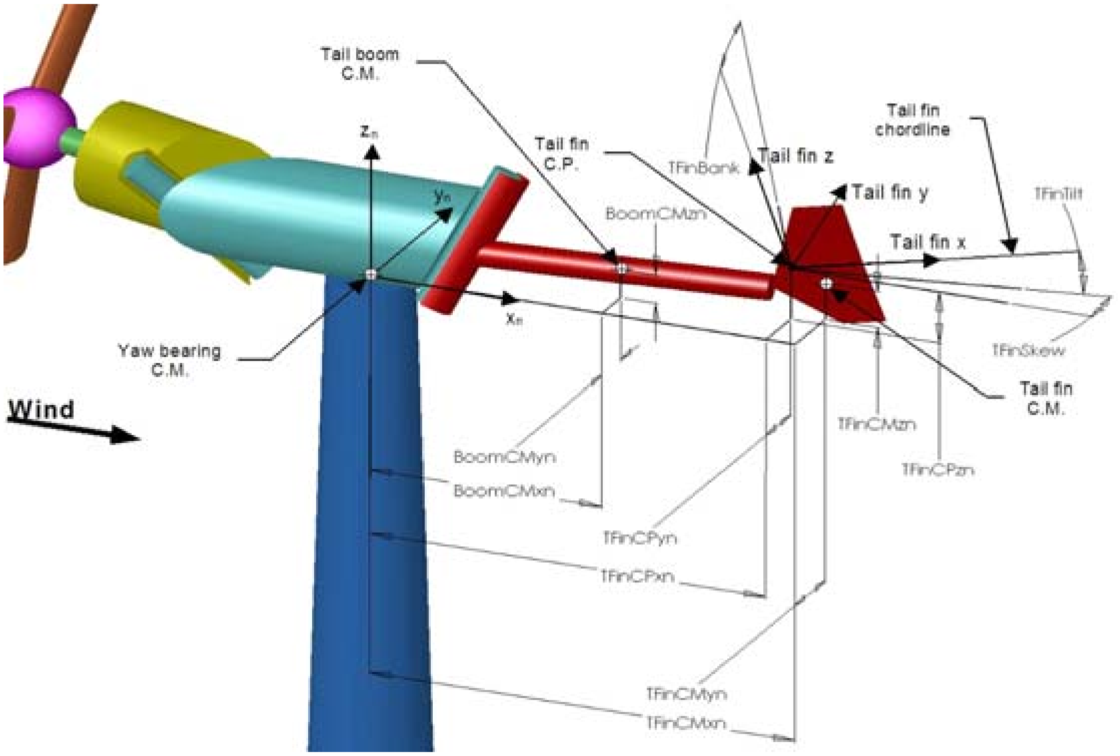

Figure 58. Tail-furling mass and configuration properties in FAST

The structural dynamic equations of the motions of the full system now include all of the inertia forces (gyroscopic, Coriolis, etc.) that result from furl motion. These equations do not require that the furl motions remain small because small angle assumptions were *not* used in their derivations. A FAST user does not need to worry about the complexity of the equations of motion because they are built within the code; a user need only be concerned with defining the configuration of the system properly.

The furling hinges can be ideal with no friction. A standard model is also available that includes a linear spring, linear damper and Coulomb damper, as well as up- and down-stop springs, and up- and down-stop dampers. FAST models the stop springs with a linear function of furl deflection. The furl stops start at a specified angle and work as a linear spring based on the deflection past the stop angle. The furl dampers are linear functions of the furl rate and start at the specified up-stop and down-stop angles. These dampers are bidirectional, resisting motion equally in both directions once past the stop angle. Hooks for interfacing user-defined furl springs and dampers are also available.

A simple tail fin aerodynamics model has been implemented in FAST. Hooks for interfacing user-defined models are also available. By accessing information from AeroDyn, the simple model computes the relative velocity of the wind-inflow and its angle of attack relative to the tail-fin chordline and uses an AeroDyn airfoil table chosen by the user to determine the lift and drag forces acting at the tail-fin center-of-pressure. To account for the velocity deficit in the rotor wake, the wind velocity at the tail-fin center-of-pressure is decreased by the average rotor induced velocity in the direction of the rotor shaft. The chordline and plane of the tail fin may be skewed, tilted, and banked relative to the tail boom as shown in Figure 58.

To verify the correct implementation of the newly added furling dynamics, response predictions from FAST were compared to those of ADAMS using models of the SWRT. Data on the validation of the FAST model may be found it Jonkman and Hansen [6]. It should be noted that, because blade torsional stiffness cannot currently be modeled in FAST, the torsional stiffness inputs to the ADAMs model assumed an infinitely stiff blade and the variances between the FAST and ADAMS models from live blade twist did not show up in the comparison of furling dynamics between the models.

Conclusions

The SWRT test has provided modelers with a unique data set to help the small wind turbine community understand small wind turbine behavior. A better understanding of small wind turbine dynamics, including furling and thrust, was a result of the test. Analysis of the SWRT test data shows the complex interaction of thrust, center of thrust, yaw rate, RPM, and how these variables relate to furl. The SWRT data sets provide a unique set of data for validating aerodynamic models for a turbine that operates at a significant yaw error, has high yaw rates, is in and out of stall quickly, and operates at higher RPMs. Analysis and comparison of FAST and ADAMS model simulations and test data for the SWRT has resulted in a better understanding of small wind turbine modeling, as well as a FAST furling model that can be used by engineers to better design small furling wind turbines. The SWRT modeling has shown the importance of including blade torsion in the modeling, which can only be done with the ADAMS model at this time. Future changes to the FAST model should include the ability to model blade torsion.

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Appendix A – SWRT Electrical Layout

Site 1.4 One-Line Electrical Diagram for BWC Installation

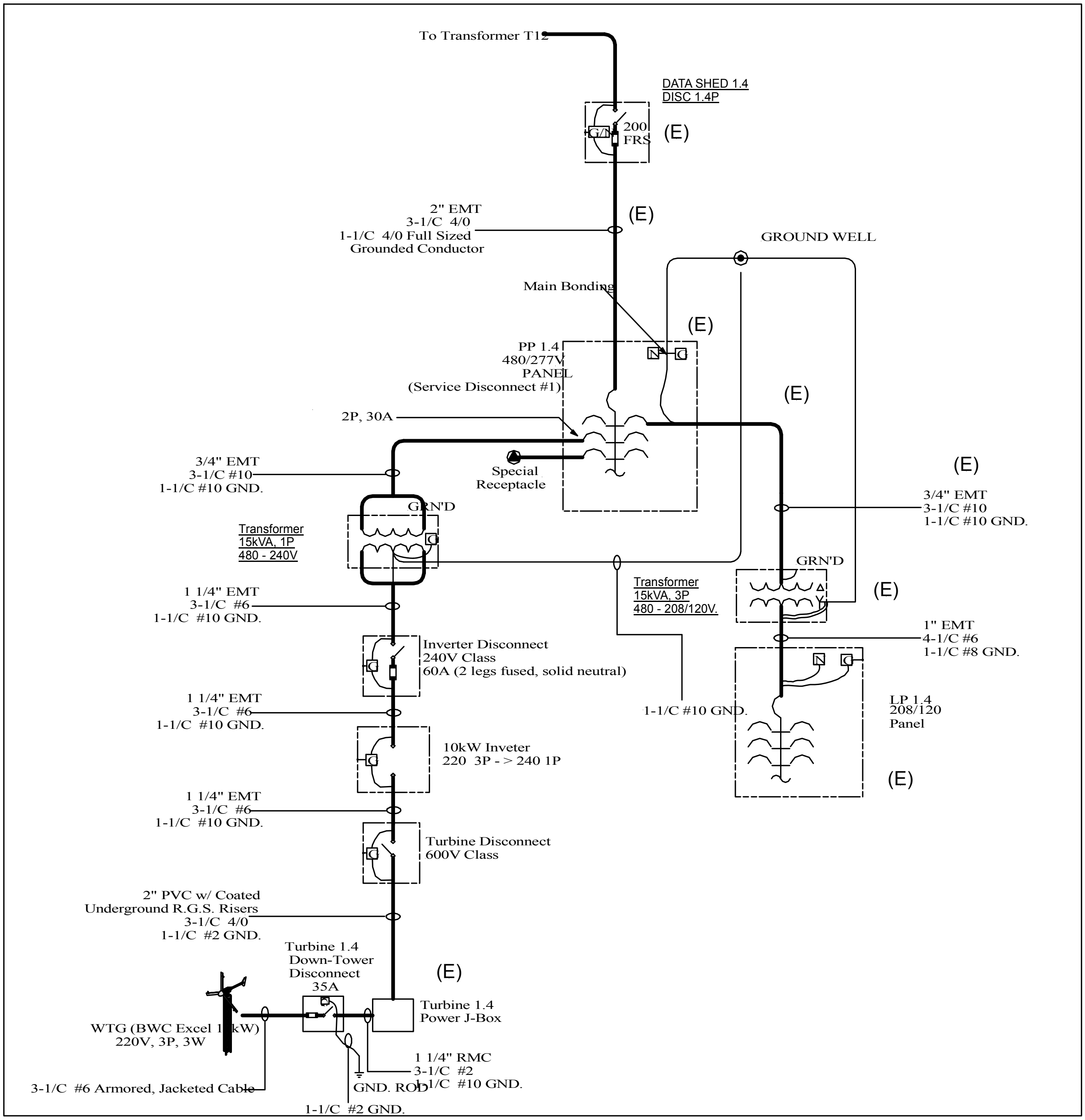


Figure A-1. SWRT Electrical Layout

Appendix B – Additional SWRT Turbine Parameters

Table B-1. Tail Assembly Properties

Weight	86.81 kg. (191.0 lb)
CG (loaded w/ vane and instrumentation (anno, anno box, cables)	1.46 m. (57.5 in.) with respect to tail hinge pin
Yaw axis to hinge (tail)	0.323 m (12.74”)
Angles of hinge	8 (in line with shaft)
Tail boom start angle (parallel to rotor axis)	0 degrees
Tail boom end angle	68 degrees
Tail size	1577 sq. inches (projected area including flap)
Distance from rotor to thrust sensor	20.3 “

Mass moment of inertia from Bifilar pendulum tests

If the bifilar pendulum cables are of length h and separated by a distance D (centered on the center of gravity of the part) then the mass moment of inertia about the c.g. is

$$I_{cg} = \frac{WD^2}{4\omega_n^2 h}$$

The weight of the part is W and the natural frequency is measured as in rad/s.

The SI units are N-m-s^2 = kg-m/s^2-m-s^2 = kg-m^2

Furl damper characteristics

The furl damper was tested by applying a known weight and measuring the time required to travel a known distance. From the time and distance an average speed was calculated. Then a power-law curve was fit in Excel to the weight (or force) vs. speed data.

This was repeated for both the furling and unfurling directions of motion.

Table B-2. Nacelle and Magnet Can Weights and Moment of Inertias

Mass (Nacelle, generator, and tower adapter)	415	kg
Mass (Nacelle and generator)	370	kg
Inertia (about yaw axis)	81	kgm^2
Inertia (about CG)	39	kgm^2
Mass (mag. Can)	110	kg
Inertia (about rotor axis)	7.135	kgm^2
Inertia (perpendicular to rotor axis)	4.63003	kgm^2
CG (from yaw axis)	23.085	in
CG (from yaw axis)	0.58636	m
CG (from yaw axis measured horizontally)	0.592	m
Mass (nacelle minus mag can and tower adapter)	260	kg
CG (from yaw axis)	9.082	in
CG (from yaw axis)	0.231	m
CG (from yaw axis measured horizontally)	0.233	m
I (about CG)	25.04	kgm^2

Table B-3. Tail Furl Damper Properties

Raw data:			
weight	time	weight	vel
lbs	sec	kN	m/s
10	46.2	0.0445	0.0000
20	10.1	0.0890	0.0000
25	7.25	0.1112	0.0000
30	5.3	0.1334	0.0000
weight	time	weight	vel
lbs	sec	kN	m/s
150	63	0.6672	0
200	36.5	0.8896	0
250	25.1	1.112	0
Summary:			
	Vel	Force	
furl	0.0054	0.044	
	0.0246	0.089	
	0.0342	0.111	
	0.0468	0.133	
unfurl	0.0039	0.667	
	0.0068	0.890	
	0.0099	1.112	

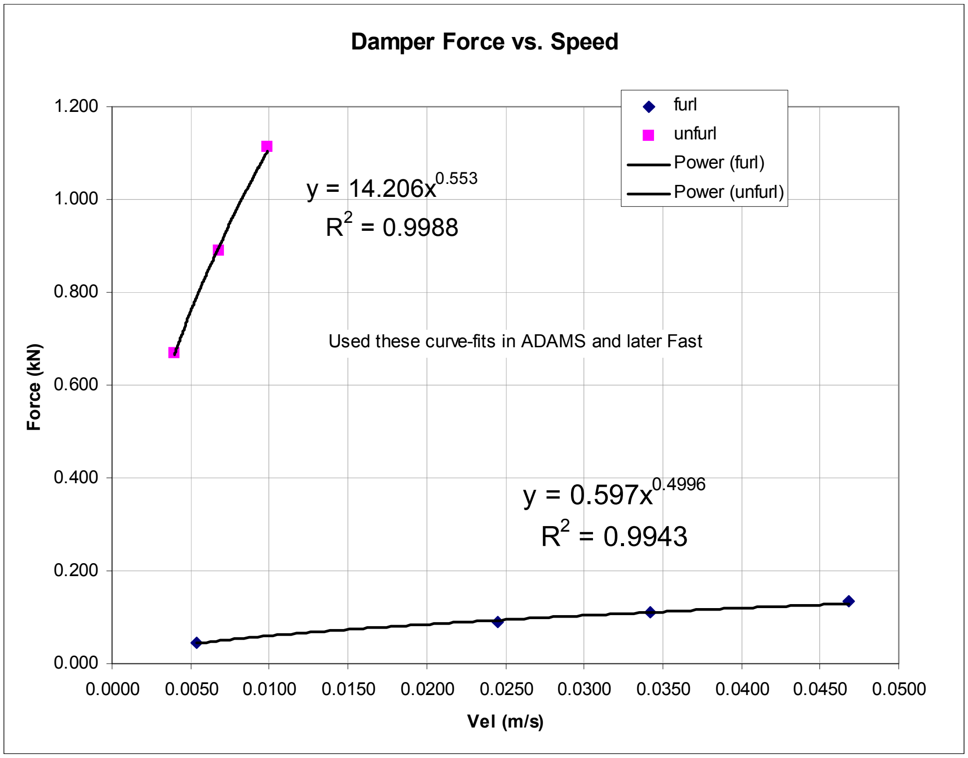
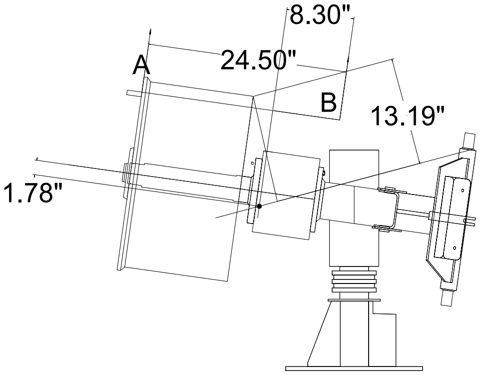


Figure B-1. Tail furl damper force versus velocity

Procedure for Determining Cg of SWRT Turbine

Note: X-axis is along shaft, Y-axis is side to side, Z is up and down.



1) Determine X axis Cg. Hang turbine from load cells – S.N. – 94572 front load cell (1),103940 back load cell (2), distance D = 24.5”,

   A= front face of magnet can
   B= on shaft axis between thrust sensor and yaw axis
   A= 315.3 lbs, B= 605.6 lbs, D= 24.5”

315*A=605*B
315*(24.5-B)=605*B
7717.5 – 315B=605 B
B=8.3.

2) Determine Y axis Cg. Hang turbine with load cells at X-axis Cg determined above with two load cells. Load cell A is on DAS side of turbine on DAS unistrut making an angle of 3.7 degrees with vertical, Load cell B is on the shaft axis 0 degrees vertical
Load cell A = 361.5 lbs (360 lbs *cos 3.7 deg), Load cell B = 550 lbs. D= 7.625.
Note that two load cells = total weight of turbine (361.5 + 550 = 912 lbs)

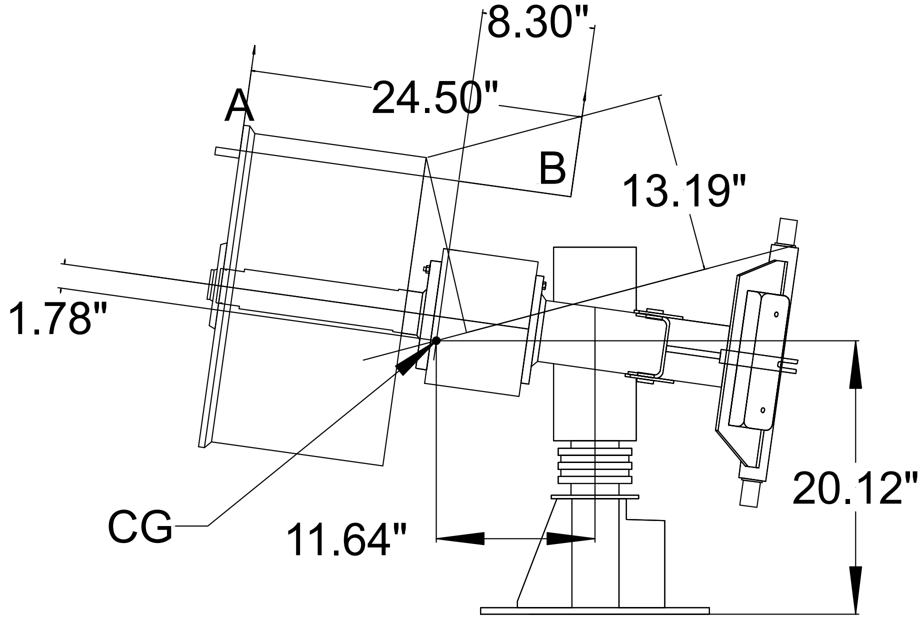
361.5*A = 550*B
361.5* (7.625-B) = 550*B
2756.4 – 361.5B = 550B
B = 3.0” away from shaft toward yaw axis.

By combining steps 1 and 2 we find the CG with respect to the Y and X axis.

3) Determine Cg along Z axis.

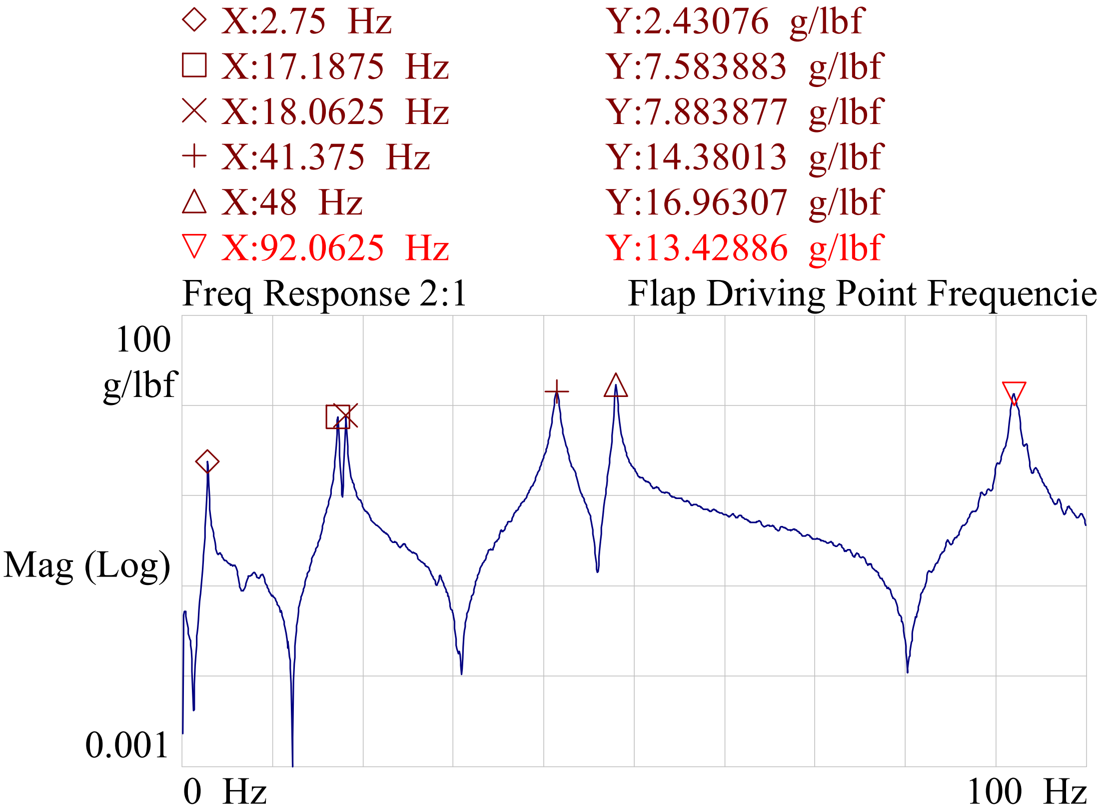
Hang turbine from tail hinge straight down. Measure point straight down from vertical hang point to determine Cg with respect to Z axis. Point is measured 13.19” from top of back edge of rotor can.

Intersection of plane determined by Cgs in X-Y space with plane from vertical hang from tail hinge (Z) determines Cg in X-Y-Z space. Diagram below shows Cg in Y-Z space, located 11.64” from yaw axis at 1.78” below the shaft centerline (and 3.0” away from shaft toward yaw axis).



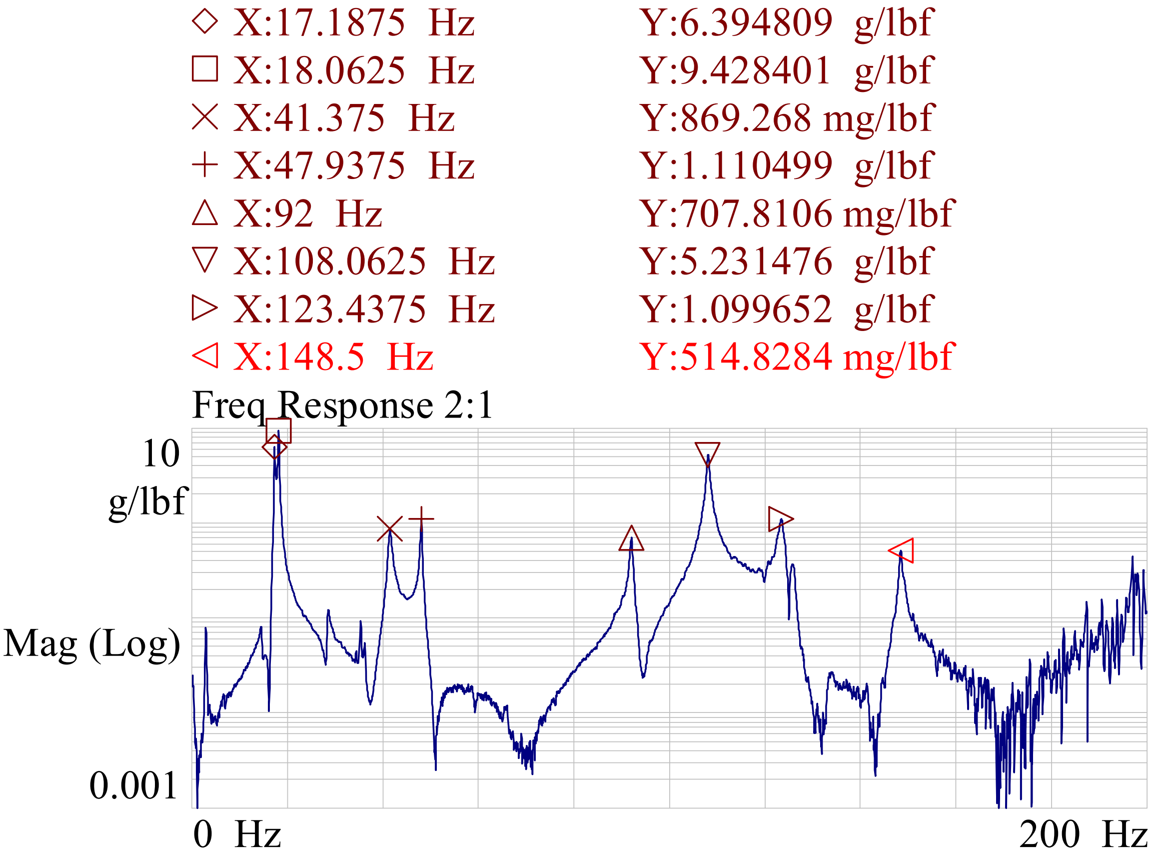
SWRT Bergey SH3052 Blade Modal Survey

Flap bending frequencies measured from driving point taken at LE of blade tip:



1. 2.75 Hz, First Flap Bending
2. 17.19 Hz, Second Flap Bending
3. 18.06 Hz, First Lag Bending
4. 41.38 Hz, First Torsion
5. 48 Hz, Third Flap Bending
6. 92.06 Hz, Fourth Flap Bending

Lag bending frequencies measured from driving point taken at LE of blade tip:


◇ X:17.1875 Hz Y:6.394809 g/lbf
□ X:18.0625 Hz Y:9.428401 g/lbf
× X:41.375 Hz Y:869.268 mg/lbf
+ X:47.9375 Hz Y:1.110499 g/lbf
△ X:92 Hz Y:707.8106 mg/lbf
▽ X:108.0625 Hz Y:5.231476 g/lbf
▷ X:123.4375 Hz Y:1.099652 g/lbf
◁ X:148.5 Hz Y:514.8284 mg/lbf

7. 108.06 Hz, Second Lag Bending coupled with Second Torsion
8. 123.44 Hz, Second Torsion coupled with Second Lag Bending
9. 148.5 Hz, Fifth Flap Bending

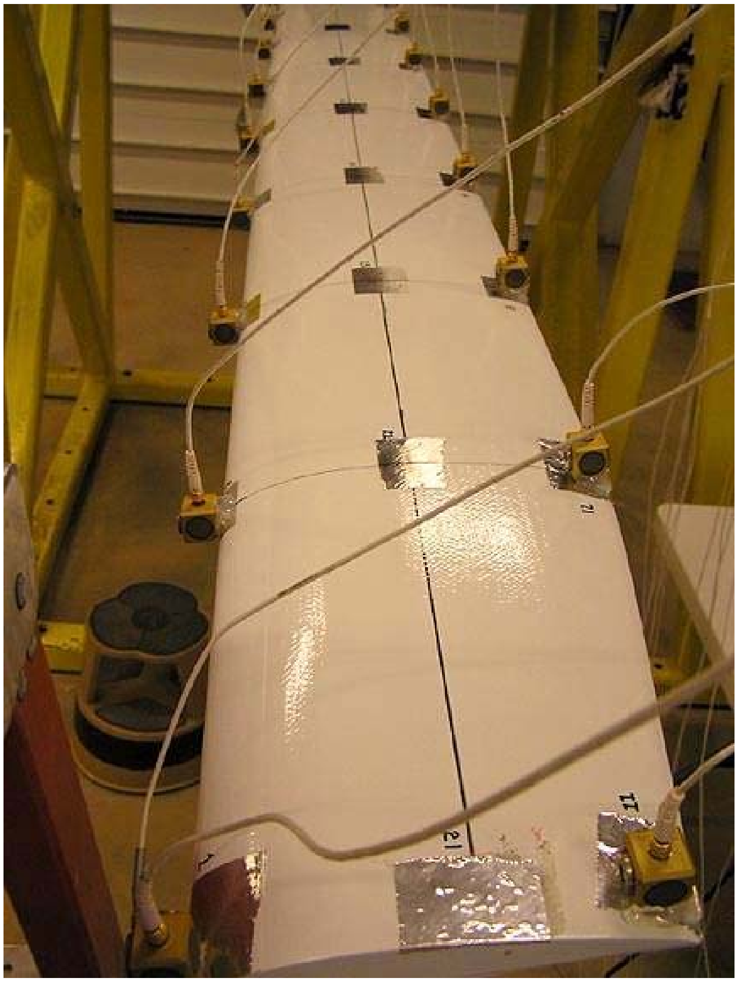
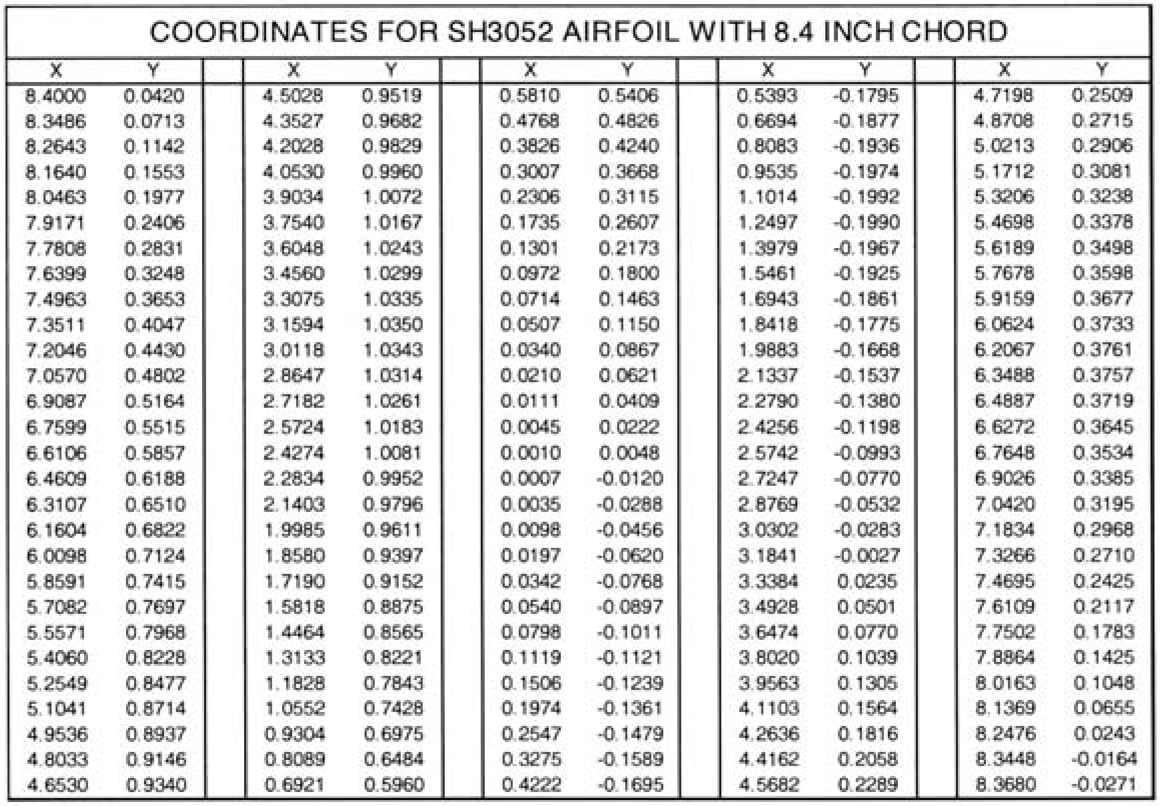


Figure B-2. Blade modal test

Table B-4. SH3052 Blade Data and Bifilar Pendulum Test Results

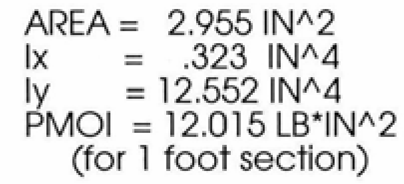
Blade weight	133.22-N (29.95-lbs)
Blade mass	13.584-Kg (0.9309-slugs)
Radial distance to C.G. measure from blade root end	1.231-m (48.47-in)
Cordwise distance to C.G. measure from leading edge of blade	0.0778-m (3.06-in)
Mass moment of inertia measured about an axis through the blade's C.G. directed from the trailing to leading edge	10.437 Kg-m^2 (27.692 slug-ft^2)
Mass moment of inertia measured about an axis through the blade's C.G. directed from the low to high pressure side	9.989 Kg-m^2 (27.362 slug-ft^2)

Table B-5. SH3052 Airfoil Data



COORDINATES FOR SH3052 AIRFOIL WITH 8.4 INCH CHORD

X	Y	X	Y	X	Y	X	Y	X	Y
8.4000	0.0420	4.5028	0.9519	0.5810	0.5406	0.5393	-0.1795	4.7198	0.2509
8.3486	0.0713	4.3527	0.9682	0.4768	0.4826	0.6694	-0.1877	4.8708	0.2715
8.2643	0.1142	4.2028	0.9829	0.3826	0.4240	0.8083	-0.1936	5.0213	0.2906
8.1640	0.1553	4.0530	0.9960	0.3007	0.3668	0.9535	-0.1974	5.1712	0.3081
8.0463	0.1977	3.9034	1.0072	0.2306	0.3115	1.1014	-0.1992	5.3206	0.3238
7.9171	0.2406	3.7540	1.0167	0.1735	0.2607	1.2497	-0.1990	5.4698	0.3378
7.7808	0.2831	3.6048	1.0243	0.1301	0.2173	1.3979	-0.1967	5.6189	0.3498
7.6399	0.3248	3.4560	1.0299	0.0972	0.1800	1.5461	-0.1925	5.7678	0.3598
7.4963	0.3653	3.3075	1.0335	0.0714	0.1463	1.6943	-0.1861	5.9159	0.3677
7.3511	0.4047	3.1594	1.0350	0.0507	0.1150	1.8418	-0.1775	6.0624	0.3733
7.2046	0.4430	3.0118	1.0343	0.0340	0.0867	1.9883	-0.1668	6.2067	0.3761
7.0570	0.4802	2.8647	1.0314	0.0210	0.0621	2.1337	-0.1537	6.3488	0.3757
6.9087	0.5164	2.7182	1.0261	0.0111	0.0409	2.2790	-0.1380	6.4887	0.3719
6.7599	0.5515	2.5724	1.0183	0.0045	0.0222	2.4256	-0.1198	6.6272	0.3645
6.6106	0.5857	2.4274	1.0081	0.0010	0.0048	2.5742	-0.0993	6.7648	0.3534
6.4609	0.6188	2.2834	0.9952	0.0007	-0.0120	2.7247	-0.0770	6.9026	0.3385
6.3107	0.6510	2.1403	0.9796	0.0035	-0.0288	2.8769	-0.0532	7.0420	0.3195
6.1604	0.6822	1.9985	0.9611	0.0098	-0.0456	3.0302	-0.0283	7.1834	0.2968
6.0098	0.7124	1.8580	0.9397	0.0197	-0.0620	3.1841	-0.0027	7.3266	0.2710
5.8591	0.7415	1.7190	0.9152	0.0342	-0.0768	3.3384	0.0235	7.4695	0.2425
5.7082	0.7697	1.5818	0.8875	0.0540	-0.0897	3.4928	0.0501	7.6109	0.2117
5.5571	0.7968	1.4464	0.8565	0.0798	-0.1011	3.6474	0.0770	7.7502	0.1783
5.4060	0.8228	1.3133	0.8221	0.1119	-0.1121	3.8020	0.1039	7.8864	0.1425
5.2549	0.8477	1.1828	0.7843	0.1506	-0.1239	3.9563	0.1305	8.0163	0.1048
5.1041	0.8714	1.0552	0.7428	0.1974	-0.1361	4.1103	0.1564	8.1369	0.0655
4.9536	0.8937	0.9304	0.6975	0.2547	-0.1479	4.2636	0.1816	8.2476	0.0243
4.8033	0.9146	0.8089	0.6484	0.3275	-0.1589	4.4162	0.2058	8.3448	-0.0164
4.6530	0.9340	0.6921	0.5960	0.4222	-0.1695	4.5682	0.2289	8.3680	-0.0271



AREA = 2.955 IN^2
Ix = .323 IN^4
Iy = 12.552 IN^4
PMOI = 12.015 LB*IN^2
(for 1 foot section)

Appendix C – Instrumentation, Data Collection, and Data Processing

Data files from the ADAS system are collected and stored. Shown below is the channel list for the ADAS DAT files.

The Crunch software [9] was created at the NWTC to perform the following tasks:

1. Read in the data files, the DAT file channel list is shown in the previous table.
2. Convert strain-gage data to engineering units using the zeros and calibration matrices described earlier.
3. Perform calculated channel calculations.
4. Calculate all 10-minute blocks, the minimums, means, maximums, and standard deviations of all parameters output by Crunch. Analyze data in several other ways, including power spectral densities (PSDs), azimuth averaging, and time series data.

There are two different output header files for the CRUNCH output files, known as MOD files. The difference is that the Configuration A MOD files have an additional calculated channel to account for a transformation for the shaft torque signal from the shim angle. The MOD files for Configuration A and B/C are shown below. Note that channels 1-33 are the same as the DAT files and that the remaining channels, 33-86, are calculated channels (this is for Configuration A, subtract one for Configurations B and C). Channels 35-40 are meteorological parameters from the site M2 meteorological tower and are described in a later section of this appendix. Channels 73-86 are the calculated inflow parameters and are described in equations 4-17 of this report. Equations describing the N_{Ri} are contained in a later section of this Appendix. Channels 57-72 are calculated channels that may of interest to future data analysis but have not been used much in the data analysis to date.

Table C-1. SWRT Channel List for DAT Files

Channel #	Parameter	Units
1	Time	Seconds
2	B1Edge	V
3	B1Flap	V
4	B2Edge	V
5	B2 Flap	V
6	B3 Edge	V
7	B3 Flap	V
8	Rotor Position	deg
9	Rotor RPM	rpm
10	Shaft 0	mV
11	Shaft 90	mV
12	Thrust	mV
13	Torque	mV
14	Tail wind speed Ux	m/s
15	Tail wind speed Uy	m/s
16	Tail wind speed Uz	m/s
17	Furl angle	deg
18	Tower Top - 1	mV
19	Tower Top - 2	mV
20	Tower Top - 3	mV
21	Barametric Pressure	kPa
22	Yaw Position 5	deg
23	Yaw velocity 6	rpm
24	Wind Direction	deg
25	spare 8	Counts
26	Wind speed hub Ux	m/s
27	Wind speed hub Uy	m/s
28	Wind speed hub Uz	m/s
29	Wind speed hub	m/s
30	Wind speed mid tower	m/s
31	Wind speed 3 meters	m/s
32	Atmos temp	Deg C
33	AC Power	Kw
34	rotor position calculated	Counts
35	wrap yaw position	Counts

Table C-2. Mod Files for Configuration A

Channel #	Parameter	Units	Comments if applicable
1	Time	Sec	
2	Hub Az	deg	Defined as 0 with blade 1 up; rotates CC
3	WS-HH	M/s	Mechanical annomometer at hub heigth
4	WS-Ux	M/s	Hub heigth sonic annomometer
5	WS-Uy	m/s	Hub heigth sonic annomometer
6	WS-Uz	M/s	Hub heigth sonic annomometer
7	B1 Flap	n-m	With crosstalk correction
8	B1 Edge	n-m	With crosstalk correction
9	B2 Flap	n-m	With crosstalk correction
10	B2 Edge	n-m	With crosstalk correction
11	B3 Flap	n-m	With crosstalk correction
12	B3 Edge	n-m	With crosstalk correction
13	ShftThrust	volts	volts, no crosstalk correction
14	ShftTiltMx	volts	volts, no crosstalk correction
15	ShaftTor	volts	volts, no crosstalk correction
16	ShaftYawMz	volts	volts, no crosstalk correction
17	ShftThrus2	volts	Thrust with temperature correlation
18	RotorSpd	RPM	
19	TT 1	volts	Tower top 1 load cell output
20	TT 2	volts	Tower top 2 load cell output
21	TT 3	volts	Tower top 3 load cell output
22	Furl	deg	
23	Yaw vel	RPM	Note that this is not in radians per second!
24	AirTemp	DegC	
25	AirPress	kPa	
26	Epower	kW	
27	YawPos	deg	
28	wind dir	deg	From mechanical wind vane
29	Tail w-sUx	m-s	Tail sonic annomometer
30	Tail w-sUy	m-s	Tail sonic annomometer
31	Tail w-sUz	m-s	Tail sonic annomometer
32	WSMid-anno	m/s	Mechanical annomometer
33	WS 3m-anno	m/s	Mechanical annomometer
34	YawNoMod	deg	Yaw signal without 360 mod command (I.e., no wrap at 360)
35	M2AvgWdSp	m/s	*Wind speed from site M2
36	M2WdSpdev	m/s	*Standard deviation of M2 wind speed
37	RichNumb		*Richardson number
38	u*	m/s	*Local friction velocity
39	u* Qual		*Local friction velocity quality
40	MeanPowLaw		*Mean power law
41	Shftthrust	N	With crosstalk correction

Channel #	Parameter	Units	Comments if applicable
42	ShftTiltMx	N-m	With crosstalk correction - in shaft sensor coordinate frame
43	Shft Tor	N-m	With crosstalk correction
44	ShftYawMz	N-m	Final calculated channel - with crosstalk correction
45	ShftThrus2	N	Final calculated channel -with crosstalk correction
46	ShfTiltIECMx	N-m	Final calculated channel - with crosstalk correction in IEC
			coordinate frame
47	TorqueFin	N-m	Final calculated channel - with crosstalk correction and shim
			angle transformation
48	SonicWSMet	m-s	Meteorilogical tower wind speed (Vector sum of Ux and Uy
			for met tower)
49	SonicWDir	deg	Wind direction from sonic
50	ConvecCor	Sec	Time delay met tower wind speed to rotor (See CRUNCH file
			calculated channels)
51	ConvecTime	Sec	Calculated time at rotor with wind speed delay (Channel 50 time
			delay + channel 1 time)
52	WakSpdNor	m-s	Vector sum of Ux and Uy for tail wind speed
53	WindDirMod	deg	Wind direction signal from wind vane with 360 mod command
			(I.e., wrap at 360)
54	yaw error	deg	Wind direction - yaw position
55	CenThrtAng	deg	** Center of thrust angle (MOD(ATAN2D((C46/C45),(C44/C45))+360,360))
56	CenThrtLen	m	** Center of thrust length (SQRT((C44/C45)^2+(C46/C45)^2))
57	Ct		Coefficient of thrust (C45/((3.4837*C25/(C24+273))*26.414*C48^2))
58	SideThrst	N	Side thrust (C45*TAND(C54))
59	Sonic^3	(m/s)^3	Cube of the meteorological (channel 48) sonic wind speed
			(used for Cp analysis)
60	SinWind	deg	sind(C49)
61	SinYaw	deg	sind(C27)
62	CosWind	deg	cosd(C49)
63	CosYaw	deg	cosd(C27)
64	SinWdMech	deg	sind(C53)
65	CosWdMech	deg	cosd(C53)
66	Wake Ux	m-s	Wake Ux in the nacelle frame (C29*cosd(8.0)-C31*sind(8.0))
67	Wake Uy	m-s	C30
68	Wake Uz	m-s	Wake Uz in the nacelle frame (C29*sind(8.0)+C31*cosd(8.0)")
69	WakeDir	deg	MOD(ATAN2D(C30,C29)+360, 360)
70	WakeSpd	m-s	Wake wind speed in the nacelle frame (SQRT(C66^2 + C67^2))
71	WdVSlowIn%	dec%	(C48-C70)/C48
72	WdVSloOut%	dec%	(C48-C52)/C48
73	angle B	deg	see inflow equations in later section of this Appendix
74	angle f	deg	see inflow equations in later section of this Appendix

Channel #	Parameter	Units	Comments if applicable
75	FlowAVG	m/s	see inflow equations in later section of this Appendix
76	FlowX	m/s	see inflow equations in later section of this Appendix
77	FlowY	m/s	see inflow equations in later section of this Appendix
78	FlowZ	m/s	see inflow equations in later section of this Appendix
79	TurbIV	m/s	see inflow equations in later section of this Appendix
80	TurbIW	m/s	see inflow equations in later section of this Appendix
81	TurbIU	m/s	see inflow equations in later section of this Appendix
82	RstresUW		see inflow equations in later section of this Appendix
83	RstresUV		see inflow equations in later section of this Appendix
84	RstresVW		see inflow equations in later section of this Appendix
85	TKE		see inflow equations in later section of this Appendix
86	CoTKE		see inflow equations in later section of this Appendix

Table C-3. Mod Files for Configuration B/C

Channel #	Parameter	Units	Comments if applicable
1	Time	Sec	
2	Hub Az	deg	Defined as 0 with blade 1 up; rotates CC
3	WS-HH	M/s	Mechanical anemometer at hub height
4	WS-Ux	M/s	Hub-height sonic anemometer
5	WS-Uy	m/s	Hub-height sonic anemometer
6	WS-Uz	M/s	Hub-height sonic anemometer
7	B1 Flap	n-m	With crosstalk correction
8	B1 Edge	n-m	With crosstalk correction
9	B2 Flap	n-m	With crosstalk correction
10	B2 Edge	n-m	With crosstalk correction
11	B3 Flap	n-m	With crosstalk correction
12	B3 Edge	n-m	With crosstalk correction
13	ShftThrust	volts	volts, no crosstalk correction
14	ShftTiltMx	volts	volts, no crosstalk correction
15	ShaftTor	volts	volts, no crosstalk correction
16	ShaftYawMz	volts	volts, no crosstalk correction
17	ShftThrus2	volts	Thrust with temperature correlation
18	RotorSpd	RPM	
19	TT 1	volts	Tower top 1 load cell output
20	TT 2	volts	Tower top 2 load cell output
21	TT 3	volts	Tower top 3 load cell output
22	Furl	deg	
23	Yaw vel	RPM	Note that this is not in radians per second!
24	AirTemp	DegC	
25	AirPress	kPa	
26	Epower	kW	
27	YawPos	deg	
28	wind dir	deg	From mechanical wind vane
29	Tail w-sUx	m-s	Tail sonic anemometer
30	Tail w-sUy	m-s	Tail sonic anemometer
31	Tail w-sUz	m-s	Tail sonic anemometer
32	WSMid-anno	m/s	Mechanical anemometer
33	WS 3m-anno	m/s	Mechanical anemometer
34	YawNoMod	deg	Yaw signal without 360 mod command (I.e., no wrap at 360)
35	M2AvgWdSp	m/s	*Wind speed from site M2
36	M2WdSpdev	m/s	*Standard deviation of M2 wind speed
37	RichNumb		*Richardson number
38	u*	m/s	*Local friction velocity
39	u* Qual		*Local friction velocity quality
40	MeanPowLaw		*Mean power law
41	Shftthrust	N	With crosstalk correction

Channel #	Parameter	Units	Comments if applicable
42	ShftTiltMx	N-m	With crosstalk correction - in shaft sensor coordinate frame
43	Shft Tor	N-m	With crosstalk correction
44	ShftYawMz	N-m	Final calculated channel - with crosstalk correction
45	ShftThrus2	N	Final calculated channel -with crosstalk correction
46	ShfTiltIECMx	N-m	Final calculated channel - with crosstalk correction in IEC coordinate frame
47	SonicWSMet	m-s	Meteorological tower wind speed (Vector sum of Ux and Uy for met tower)
48	SonicWDir	deg	Wind direction from sonic
49	ConvecCor	Sec	Time delay met tower wind speed to rotor (See CRUNCH file calculated channels)
50	ConvecTime	Sec	Calculated time at rotor with wind speed delay (Channel 50 time delay + channel 1 time)
51	WakSpdNor	m-s	Vector sum of Ux and Uy for tail wind speed
52	WindDirMod	deg	Wind direction signal from wind vane with 360 mod command (I.e., wrap at 360)
53	yaw error	deg	Wind direction - yaw position
54	CenThrtAng	deg	** Center of thrust angle (MOD(ATAN2D((C46/C45),(C44/C45))+360,360))
55	CenThrtLen	m	** Center of thrust length (SQRT((C44/C45)^2+(C46/C45)^2))
56	Ct		Coefficient of thrust (C45/((3.4837*C25/(C24+273))*26.414*C48^2))
57	SideThrst	N	Side thrust (C45*TAND(C54))
58	Sonic^3	(m/s)^3	Cube of the meteorological (channel 48) sonic wind speed (used for Cp analysis)
59	SinWind	deg	sind(C49)
60	SinYaw	deg	sind(C27)
61	CosWind	deg	cosd(C49)
62	CosYaw	deg	cosd(C27)
63	SinWdMech	deg	sind(C53)
64	CosWdMech	deg	cosd(C53)
65	Wake Ux	m-s	Wake Ux in the nacelle frame (C29*cosd(8.0)-C31*sind(8.0))
66	Wake Uy	m-s	C30
67	Wake Uz	m-s	Wake Uz in the nacelle frame (C29*sind(8.0)+C31*cosd(8.0)")
68	WakeDir	deg	MOD(ATAN2D(C30,C29)+360, 360)
69	WakeSpd	m-s	Wake wind speed in the nacelle frame (SQRT(C66^2 + C67^2))
70	WdVSlowIn%	dec%	(C48-C70)/C48
71	WdVSloOut%	dec%	(C48-C52)/C48
72	angle B	deg	see inflow equations in later section of this Appendix
73	angle f	deg	see inflow equations in later section of this Appendix
74	FlowAVG	m/s	see inflow equations in later section of this Appendix
75	FlowX	m/s	see inflow equations in later section of this Appendix
76	FlowY	m/s	see inflow equations in later section of this Appendix
77	FlowZ	m/s	see inflow equations in later section of this Appendix
78	TurbIV	m/s	see inflow equations in later section of this Appendix

Channel #	Parameter	Units	Comments if applicable
79	**TurbIW**	**m/s**	**see inflow equations in later section of this Appendix**
80	**TurbIU**	**m/s**	**see inflow equations in later section of this Appendix**
81	**RstresUW**		**see inflow equations in later section of this Appendix**
82	**RstresUV**		**see inflow equations in later section of this Appendix**
83	**RstresVW**		**see inflow equations in later section of this Appendix**
84	**TKE**		**see inflow equations in later section of this Appendix**
85	**CoTKE**		**see inflow equations in later section of this Appendix**

Six atmospheric measurements were taken from the Measurement and Instrumentation Data Center's M2 tower located at the NWTC:

1. M2 average wind speed
2. M2 wind speed standard deviation
3. N_{Ri}
4. Local friction velocity (u*)
5. Local friction velocity quality (u* qual)
6. Mean power law

- The Data Center archives its data in 1 min averages. Every Data Center measurement is taken every two seconds and averaged over one minute.
- The available archived data was averaged to create 10-minute averages, because 10 minute atmospheric data is the most widely accepted as valid.
- These 10-minute averages were then appended to the SWRT data file with a corresponding timestamp. Note: there was only 1 value per measurement per SWRT data file. In other words, every row in the atmospheric measurement column was the same for the above files in a given 10-minute SWRT file. This was done in order to get a "time series representation" of the atmospheric measured variables.

Shown below, for reference, is a sample CRUNCH file that contains the equations for the calculated channels.

Input file for testing Crunch v2.81 with SWRT data

0 is the row with the channel titles on it (zero if no titles are available or if titles are specified below).
0 is the row with the channel units on it (zero if no units are available or if units are specified below).
1 is the first row of data.
0 data records will be read from each file (0 to automatically determine which rows to read).
0.0, 0.0 are the start and end times (enter zeros if you want to use all the data records in the file).

True Output statistics?
True Output modified data?
True Tab-delimited output? (best for spreadsheets)
"ES12.5e2" Numerical-output format specifier. See manual for limitations.
False Output aggregate analysis files? False for separate analysis files for each input file.
"Aggregate" is the root name of the aggregate files, if aggregates were specified above.

```
41 columns in each input file.
40 columns will be used.
Format for column info is: Col_Title(10 char max), Orig_Col_#, Scale, Offset
"Time"          "Sec"           1       1.0     0.0
"Hub Az"        "deg"           34      1.0     0.0
"WS-HH"         "M/s"           29      1.0     0.0
"WS-Ux"         "M/s"           26      1.0     0.0
"WS-Uy"         "m/s"           27      1.0     0.0
"WS-Uz"         "M/s"           28      1.0     0.0
"B1 Flap"       "n-m"           3       1.0     -5.925
"B1 Edge"       "n-m"           2       1.0     -6.932
"B2 Flap"       "n-m"           5       1.0     -5.887
"B2 Edge"       "n-m"           4       1.0     -6.065
"B3 Flap"       "n-m"           7       1.0     -6.034
"B3 Edge"       "n-m"           6       1.0     -5.455
"ShftThrust""volts"     12      1.0     2.31E-02
"ShftTiltMx" "volts"    11      1.0     -4.46E-03
"ShaftTor"  "volts"     13      1.0     2.86E-03
"ShftYawMz"   "volts"   10      1.0     8.16E-05
"ShftThrus2""volts"     12      1.0     0.0
"RotorSpd"      "RPM"           9       1.0     0.0
"TT 1"  "volts" 18      1.0     0.000420949
"TT 2"  "volts" 19      1.0     0.002436564
"TT 3"  "volts" 20      1.0     0.008488855
"Furl"  "deg"   17      1.0     0.0
"Yaw vel"       "RPM"           23      1.0     0.0
"AirTemp"       "DegC"          32      1.0     0.0
"AirPress"      "kPa"           21      1.0     0.0
"Epower"        "kW"            33      1.0     0.0
"YawPos"        "deg"           35      1.0     0.0
"wind dir"      "deg"           24      1.0     0.0
"Tail w-sUx""m-s"               14      1.0     0.0
"Tail w-sUy""m-s"               15      1.0     0.0
"Tail w-sUz""m-s"               16      1.0     0.0
"WSMid-anno""m/s"               30      1.0     0.0
"WS 3m-anno" "m/s"      31      1.0     0.0
"YawNoMod"   "deg"              22      1.0     0.0
"M2AvgWdSp" "m/s"               36      1.0     0.0
"M2WdSpdev"  "m/s"              37      1.0     0.0
"RichNumb"      ""              38      1.0     0.0
"u*"            "m/s"   39      1.0     0.0
"u* Qual"               ""      40      1.0     0.0
"MeanPowLaw"            ""      41      1.0     0.0

0 of the output columns are to be modified by the IIR filter.  Next four lines ignored if zero.
27
1 is the type of filter (1-lowpPass, 2-high-pass, 3-Band-pass)
0.0 is the low cutoff frequency (ignored for low-pass filters)
2.0 is the high cutoff frequency (ignored for high-pass filters)
```

```
32 new calculated channels will be generated.
1234567890 is the integer seed for the random number generator (-2,147,483,648 to
2,147,483,647)
Format for column info is: Col_Title(10 char max), Units(10 char max), Equation.  Put each field
in double quotes.
"Shftthrust""N" "((C13*5845.00)+(c14*755.8)-(c15*6616.0)+(c16*2861.0))*(4.4482)*
(cosd(4))"
"ShftTiltMx""N-m"       "(-(C13*2513.00)+(c14*2065000.0)+(c15*890.0)-
(c16*28030.0))*(0.11306)"
"Shft Tor"        "N-m"   "(-
(C13*24.23)+(c14*1700.0)+(c15*210400.0)+(c16*1926.0))*(0.11306)"
"ShftYawMz"    "N-m"   "((C13*584.60)+(c14*31270.0)-
(c15*3563.0)+(c16*2047000.0))*(0.11306)"
"ShftThrus2" "N"          "((((C17)-((C24*0.0016)-0.0154))*5845.00)+(c14*755.8)-
(c15*6616.0)+(c16*2861.0))*(4.4482)*(cosd(4.0))"
"ShfTiltIEC""N-m"       "-((c42*(cosd(4.0))) - (c43 *(sind (4.0))))"
"TorqueFin"     "N-m" "(c43*(cosd(4.0)) + (c42*(sind(4.0))))"
"SonicWSMet""m-s" "SQRT((c4^2)+(c5^2))"
"SonicWDir"     "deg"    "MOD(ATAN2D(C4,C5)+360+17, 360)"
"ConvecCor"     "Sec"    "19.812/C48"
"ConvecTime""Sec"       "C1+C50"
"WakSpdNor"  "m-s"  "SQRT((c29^2)+(c30^2))"
"WindDirMod""deg"      "MOD(C28+360, 360)"
"yaw error"      "deg"    "C49-C27"
"CenThrtAng""deg"       "MOD(ATAN2D((C46/C45),(C44/C45))+360,360)"
"CenThrtLen""m" "SQRT((C44/C45)^2+(C46/C45)^2)"
"Ct"                 "" "C45/((3.4837*C25/(C24+273))*26.414*C48^2)"
"SideThrst"      "N"      "C45*TAND(C54)"
"Sonic^3"          "(m/s)^3" "C48^3"
"SinWind"        "deg" "sind(C49)"
"SinYaw"          "deg"    "sind(C27)"
"CosWind"        "deg"    "cosd(C49)"
"CosYaw"          "deg"    "cosd(C27)"
"SinWdMech" "deg" "sind(C53)"
"CosWdMech"  "deg"    "cosd(C53)"
"Wake Ux"        "m-s"    "C29*cosd(8.0)-C31*sind(8.0)"
"Wake Uy"        "m-s"    "C30"
"Wake Uz"        "m-s"    "C29*sind(8.0)+C31*cosd(8.0)"
"WakeDir"        "deg"    "MOD(ATAN2D(C30,C29)+360, 360)"
"WakeSpd"       "m-s"    "SQRT(C66^2 + C67^2)"
"WdVSlowIn%""dec%""(C48-C70)/C48"
"WdVSloOut%""dec%""(C48-C52)/C48"

0 channels will have moving averages generated for them.
Format for moving-average info is: "Title" (10 char max), channel #, averaging period

1 is the Time column.
48 is the primary wind-speed column (used for mean wind speed and turbulence intensity, 0 for
none)

0 pair(s) of channels will have load roses generated for them.
```

```
Format for column info is: Rose_Title(8 char max), 0-degree load, 90-degree load, # sectors

0 columns are to be azimuth averaged.  Next four lines ignored if 0.
0
0 is the number of azimuth bins.
0 is the azimuth column.
True      Output azimuth averages to a file?

3 pairs of columns will have their crosstalk removed.
Format for crosstalk info is: OutCol #1, OutCol #2, XT(1,1), XT(1,2), XT(2,1), XT(2,2).
7 8  -465          -48       -63       -894
9 10 -429          -43       -65       -910
11 12 -440         -56       -35       -923

0 of the output columns are to be modified by the peak finder.  Next line ignored if zero.
0

0 channels will have their peaks and/or valleys listed to a file.  Next three lines ignored if zero.
2                   Method of identifying peaks (1: slope change, 2: thresholds)
False     Include the time in the peak-list file(s)?
Format for peak-list info is: Channel, WriteTroughs?, Trough Thresh., WritePeaks?, Peak Thresh.

0 of the output columns will have PDFs generated for them.  Next two lines ignored if zero.
0 is the number of bins.
Format for column info is: Column #, Minimum, Maximum.  If Min=Max=0, autocalculate them.

0 of the output columns will have rainflow cycle counts generated for them.  Next six lines
ignored if zero.
0 seconds is the rainflow counting period.
False               Normalize rainflow cycle counts by bin width?
True                For bins with zero counts, output a space if we are using tab-delimited output?
0 is the number of rainflow range bins.  Use "0" to output the actual cycles instead of binned
cycles.
0 is the number of rainflow means bins.  Use "1" to output ranges only.
Format for column info is: Column #, Max Range, Min Mean, Max Mean.

0 groups of parameters will have their extreme events recorded.  Next line ignored if zero.
Format for column info is: Group_Title(100 char max), #ExtCols, ColList(#ExtCols long),
#InfCols(may be 0), ColList(#InfCols long)

0 of the output columns will have statistics put in separate summary files.  Next line ignored if
zero.
0

0 of the output columns will have their statistics extrapolated.
Format for statistics info is: Col_#,  Hours_to_extrapolate_to, Quantile desired
```

A second CRUNCH file was used to calculate the final inflow parameters. The calculated equations from the CRUNCH file are shown below for reference.

14 new calculated channels will be generated.
1234567890 is the integer seed for the random number generator (-2,147,483,648 to 2,147,483,647)
Format for column info is: Col_Title(10 char max), Units(10 char max), Equation. Put each field in double quotes.

```
73"angle B"   "deg"  "-174.905610598252"
74"angle f"   "deg"  "179.944837900584"
75"FlowAVG"   "m/s"  "abs(C4*cosd(C73)+C5*sind(C73))"
76"FlowX"     "m/s"  "C75*cosd(C74)+C6*sind(C74)"
77"FlowY"     "m/s"  "-C4*sind(C73)+C5*cosd(C73)"
78"FlowZ"     "m/s"  "-C48*sind(C74)+C6*cosd(C74)"
79"TurblV"    "m/s"  "C77"
80"TurblW"    "m/s"  "C78"
81"TurblU"    "m/s"  "C76- 1.34875E+01"
82"RstresUW"  ""     "C81*C80"
83"RstresUV"  ""     "C79*C81"
84"RstresVW"  ""     "C79*C80"
85"TKE"       ""     "0.5*(C79^2+C80^2+C81^2)"
86"CoTKE"     ""     "0.5*SQRT(C82^2+C83^2+C84^2)"
```

INFLOW DATA PROCESSING EQUATIONS

Measurements/Heights:

z_1 = lower measurement elevation

z_2 = upper measurement elevation (tower top or top of rotor disk), (m)

z_s = sonic anemometer elevation, (m)

z_{hub} = hub elevation, (m)

P_1 = barometric (station) pressure at z_1, (hPa or mb)

T_1 = air temperature at z_1, (°C)

ΔT = temperature difference between z_2 and z_1 elevations (T_2 - T_1), (°C)

$U_{1,2}$ = cup anemometer wind speeds at $z_{1,2}$,(m/s)

Sonic Inputs:

u_{p_1} = u-component, probe coordinates, (m/s)

u_{p_2} = v-component, probe coordinates, (m/s)

u_{p_3} = w-component, probe coordinates, (m/s)

T_s = temperature (virtual), (°C)

Outputs (aligned with local flow vector):

u' = turbulent or fluctuating longitudinal velocity component, (m/s)

v' = turbulent or fluctuating lateral (transverse) velocity component, (m/s)

w' = turbulent fluctuating vertical velocity component, (m/s)

$u'w'$, $u'v'$, $v'w'$ = Reynolds stress components, (m^2/s^2)

u_{o*} = local (hub-height) friction velocity, (m/s)

u_{p_H} = sonic horizontal wind speed, (m/s)

Definitions and Transformations:

$\bar{x} \equiv$ *temporal* mean quantity of *x(t)* for a continuous record of length $T = \frac{1}{T}\int_0^T x(t)dt$.

For a *discrete* time record consisting of N samples of $x(t_i)$ of length $N\Delta t$,

$$\bar{x} = \frac{1}{N}\sum_{i=0}^{N} x(t_i),$$

where T = 10 minutes and Δt is the sampling interval.

<u>Sonic Anemometer Data Reduction</u>

u_{p_1} = horizontal velocity component measured along *probe* x(1)-axis

u_{p_2} = horizontal velocity component measured along *probe* y(2)-axis

u_{p_3} = vertical velocity component measured along *probe* z(3)-axis

T_s = temperature

Instantaneous *sonic* horizontal wind speed

$$u_{p_H}(t_i) \equiv \sqrt{u_{p_1}(t_i)^2 + u_{p_2}(t_i)^2}$$

Mean component velocities…

$$\overline{u_{p_H}} = \frac{1}{N}\sum_{i=0}^{N} u_{p_H}(t_i)\,;\ \ \overline{u_{p_j}} = \frac{1}{N}\sum_{i=0}^{N} u_{p_j}(t_i)\,;\ \text{j=1,3}$$

<u>Calculation of Turbulent Flow Properties:</u> u_{o*} and Reynolds stresses

(1) Determine local flow angles w.r.t. fixed (probe) coordinate system: horizontal (x-y) and vertical (x/y-z) planes

$$\beta = \arctan\,(\overline{u_{p_2}} \,/\, \overline{u_{p_1}})$$

$$\phi = \arctan\,(\overline{u_{p_3}} \,/\, \overline{u_{p_H}})$$

(2) Rotate the wind vector measured in the probe coordinate system ($p_{1,2,3}$) to one aligned with the flow ($f_{1,2,3}$) and in the direction of the mean shearing stress . . .

$$u_{f_H}(t_i) = |\,u_{p_1}(t_i)\cos\beta + u_{p_2}(t_i)\sin\beta\,|$$

$$u_{f_1}(t_i) = u_{f_H}(t_i)\cos\phi + u_{p_3}(t_i)\sin\phi$$

$$u_{f_2}(t_i) = -\,u_{p_1}(t_i)\sin\beta + u_{p_2}(t_i)\cos\beta$$

$$u_{f_3}(t_i) = -u_{p_H}(t_i)\sin\phi + u_{p_3}(t_i)\cos\phi$$

(3) Only the longitudinal component aligned with the flow vector (u_{f_1}) now has a non-zero mean. The *turbulent or fluctuating* (zero-mean) component velocities; i.e*., longitudinal, transverse or lateral, and vertical*, respectively are defined as

$$u'(t_i) = u_{f_1}(t_i) - \overline{u_{f_1}} = u_{f_1}(t_i) - \frac{1}{N}\sum_{i=1}^{N} u_{f_1}(t_i)$$

$$v'(t_i) = u_{f_2}(t_i)$$

$$w'(t_i) = u_{f_3}(t_i)$$

(4) The instantaneous Reynolds stresses then are defined as

$$u'w'(t_i) = u'(t_i) \cdot w'(t_i)$$

$$u'v'(t_i) = u'(t_i) \cdot v'(t_i)$$

$$v'w'(t_i) = v'(t_i) \cdot w'(t_i)$$

(5) The local friction velocity, uo* at height zs is defined as

$$\mathbf{u_{o*}} = \sqrt{|u'w'|} = -\left| \sqrt{\frac{1}{N}\sum_{i=1}^{N} u'w'(t_i)} \right|$$

Thermodynamic/Stability parameters:

$$T_{1,s} = [T_1(t_i) + T_s(t_i)]/2$$

$$P_s(t_i) = P_1(t_i) - [0.0341416(P_1(t_i)/[T_{1,s}(t_i) + 273.16])](z_s - z_1)$$

$$\theta_s(t_i) = (T_s(t_i) + 273.16)\left(1000 / P_s(t_i)\right)^{0.286}$$

$$\theta_s'(t_i) = \theta_s(t_i) - \overline{\theta_s(t)} = \theta_s(t_i) - \frac{1}{N}\sum_{i=1}^{N}\theta_s(t_i)$$

$$w'\theta_s'(t_i) = w'(t_i) \cdot \theta_s'(t_i)$$

$$\overline{\theta_s} = \frac{1}{N}\sum_{i=1}^{N}\theta_s(t_i); \quad \overline{w'\theta_s'} = \frac{1}{N}\sum_{i=1}^{N} w'\theta'_s(t_i)$$

$$\overline{\aleph} = \frac{1}{N}\sum_{i=1}^{N}\aleph(t_i), \quad \text{where } \aleph = T_1, \Delta T, P_1, \theta_1, \theta_2$$

Gradient Richardson number, *N_{Ri}*:

$$\overline{T_{1,2}} = \overline{T} + \overline{\Delta T}/2$$

$$\overline{P_2} = \overline{P_1} - [0.0341416(\overline{P_1}/[\overline{T_{1,2}} + 273.16)](z_2 - z_1)$$

$$\overline{\theta_1} = (\overline{T_1} + 273.16) \cdot (1000/\overline{P_1})^{0.286}$$

$$\boxed{\overline{\theta_2} = (\overline{T_1} + \overline{\Delta T} + 273.16) \cdot \left[1000 / \overline{P_2}\right]^{0.286}}$$

$$\theta_m = (\overline{\theta_2} + \overline{\theta_1}) / 2$$

$$d\theta = (\overline{\theta_2} - \overline{\theta_1}) / (z_2 - z_1)$$

$$dU = (\overline{U_2} - \overline{U_1}) / (z_2 - z_1)$$

if $dU^2 = 0$, then $dU^2 = 10^{-3}$

$$Ri = (g / \theta_m) \cdot \left(\frac{d\theta}{dU^2} \right)$$

Instrumentation

Figures C1 – C3 show the wiring and instrumentation for the up-tower nacelle junction box and the tower top junction box.

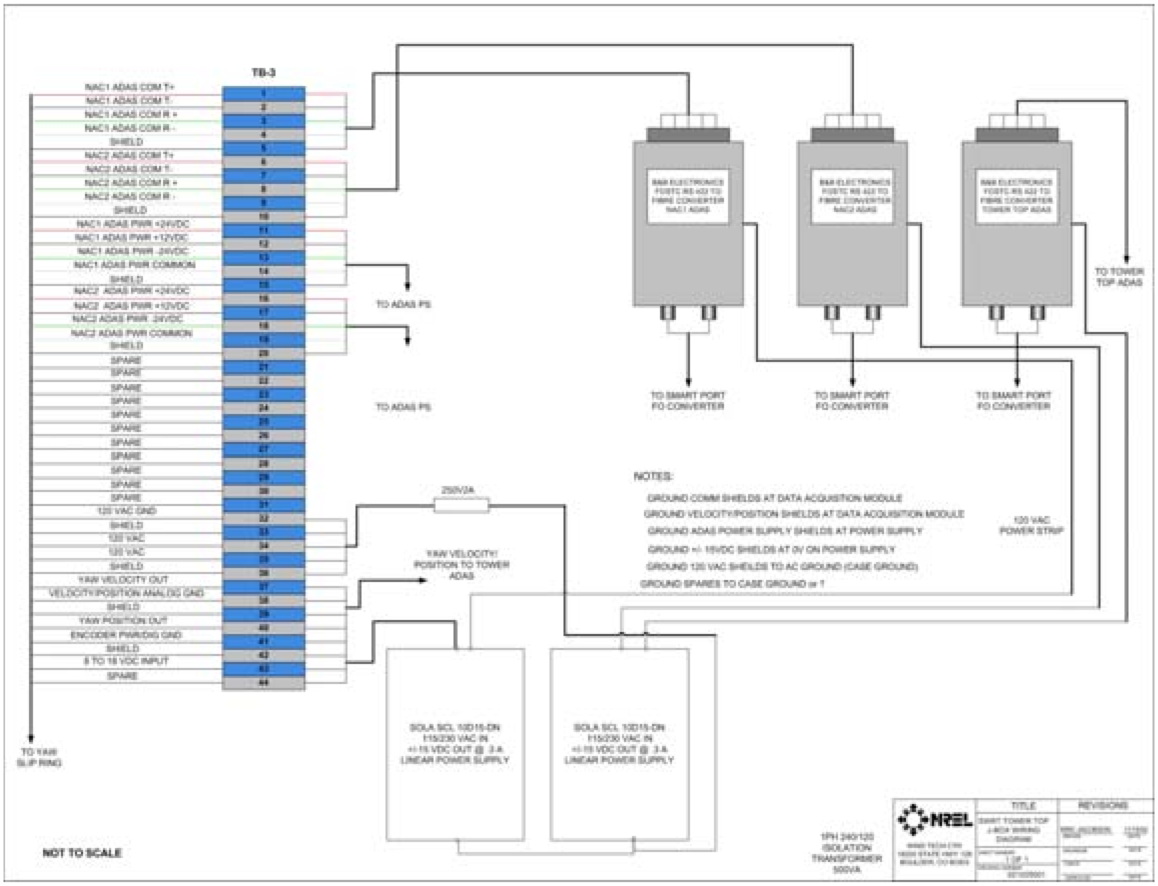


Figure C-1. SWRT tower top junction box wiring diagram

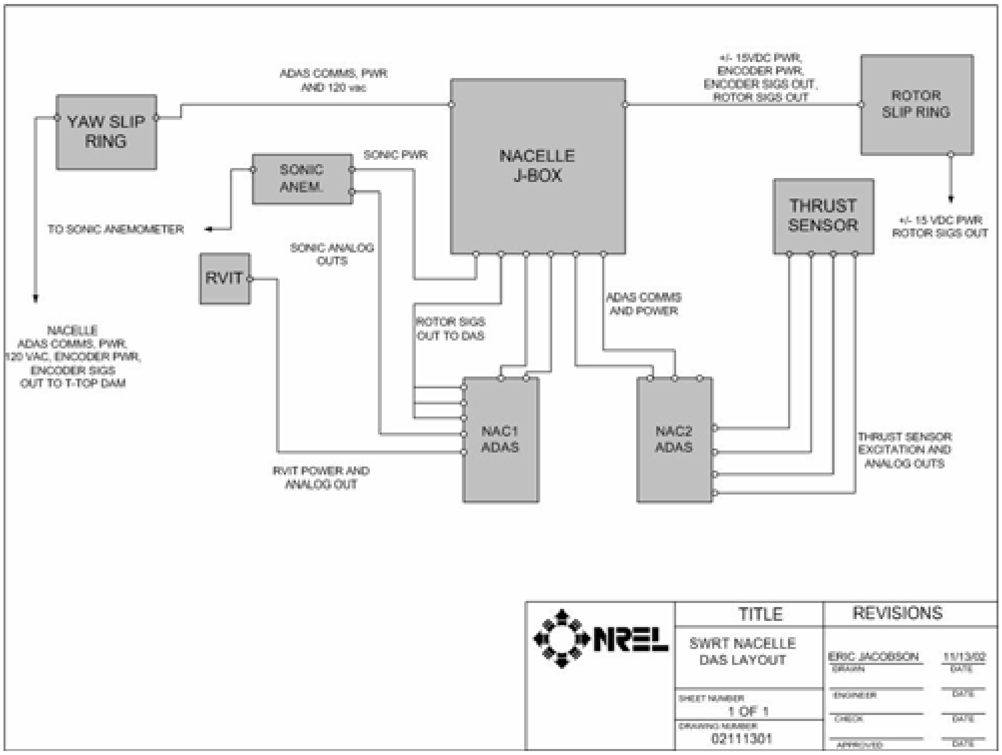


Figure C-2. SWRT nacelle data acquisition system layout

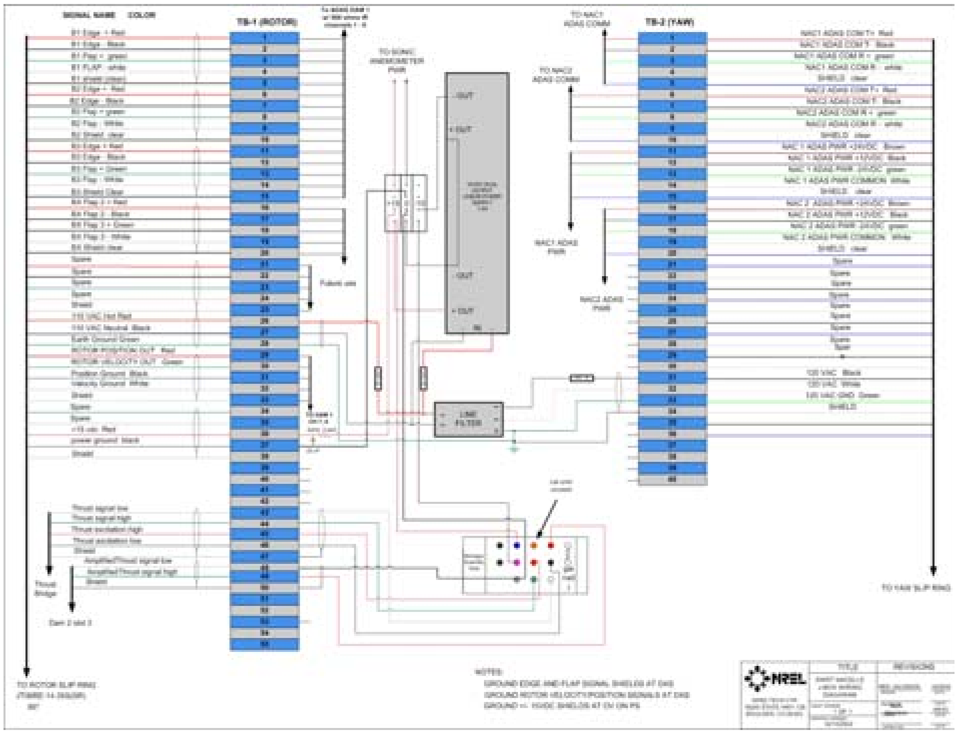


Figure C-3. SWRT nacelle junction box diagram

Description of Rotor Hub Strain Gage Amplification System

System Overview

The model AMPEH-6 is a weather-proof strain gage amplifier assembly. It was manufactured for wind turbine testing. It houses a total of six (6) strain gauge amplifiers each with an excitation voltage of 10VDC. Each amplifier can have different shunt calibration and gain settings. These are determined by resistors or wire soldered to the shunt calibration and gain set terminals *(see the AMP-SG manual for more information).*

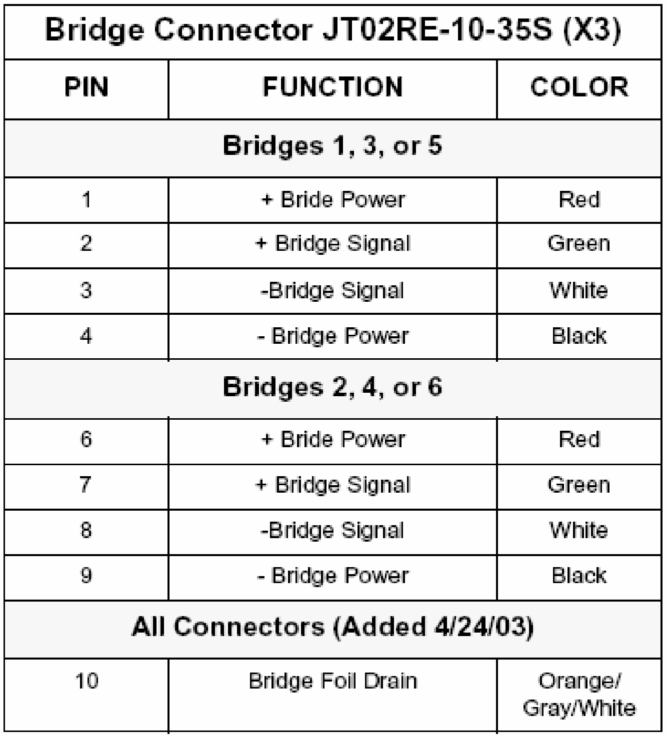
The bridges are connected to the amplifiers via the three Bendix JT02RE-10-35S connectors. Two full strain gauge bridges occupy each connector. A shield and bridge foil drain connection are also provided.

The bridge lead shield can be connected a total of three different methods. In the first method, the shield is connected to the data acquisition (DAQ) common. This connection is accomplished by connecting the internal Omnetics connectors without any labels. Normally, this is the preferred method for minimization of ground loops and/or noise. The second method breaks the connection to DAQ common. This is accomplished by disconnecting the Omnetics connectors. The third method connects the bridge lead shields to amplifier power ground at the amplifier's terminals. This is accomplished by connecting the Omnetics connector to the lead labeled Power GND. Typically, this type of connection produces a ground loop and a lot of noise. After making any change in shield connections , it is advisable to monitor the amplifier signal outputs with an oscilloscope and a digital voltmeter.

The bridge foil drain is a connection between aluminum foil placed over the strain gauge bridges and earth ground. This connection may dissipate electrical noise caused by static electricity, electric motors, etc. This is a separate circuit from power ground or shield and should be connected to earth ground.

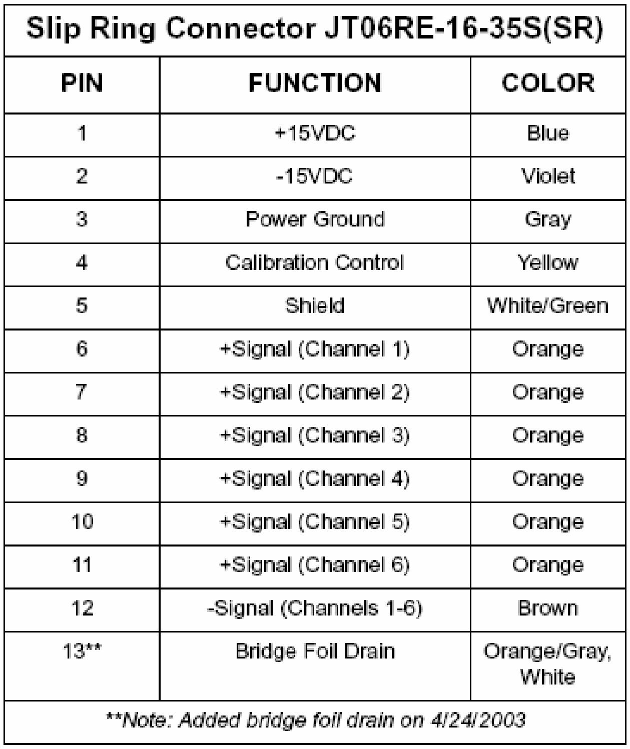
The amplified signals exit the housing via a Bendix JT02RE-14-35S(SR) connector that plugs into the rotor of the 36-channel slip ring. The slip ring has an encoder with integrated tachometer circuit.

The following pages contain detailed connection and wiring information.



Bridge Connector JT02RE-10-35S (X3)

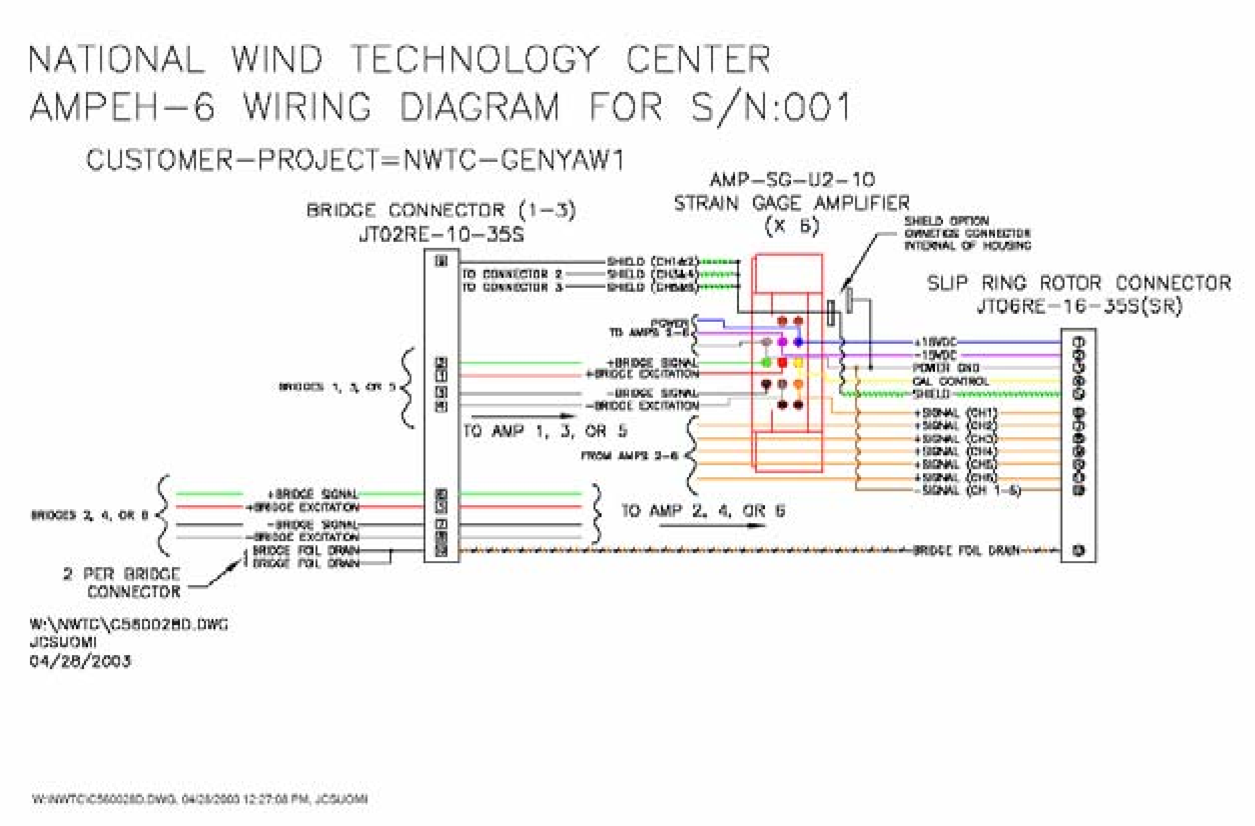
PIN	FUNCTION	COLOR
Bridges 1, 3, or 5		
1	+ Bride Power	Red
2	+ Bridge Signal	Green
3	-Bridge Signal	White
4	- Bridge Power	Black
Bridges 2, 4, or 6		
6	+ Bride Power	Red
7	+ Bridge Signal	Green
8	-Bridge Signal	White
9	- Bridge Power	Black
All Connectors (Added 4/24/03)		
10	Bridge Foil Drain	Orange/ Gray/White

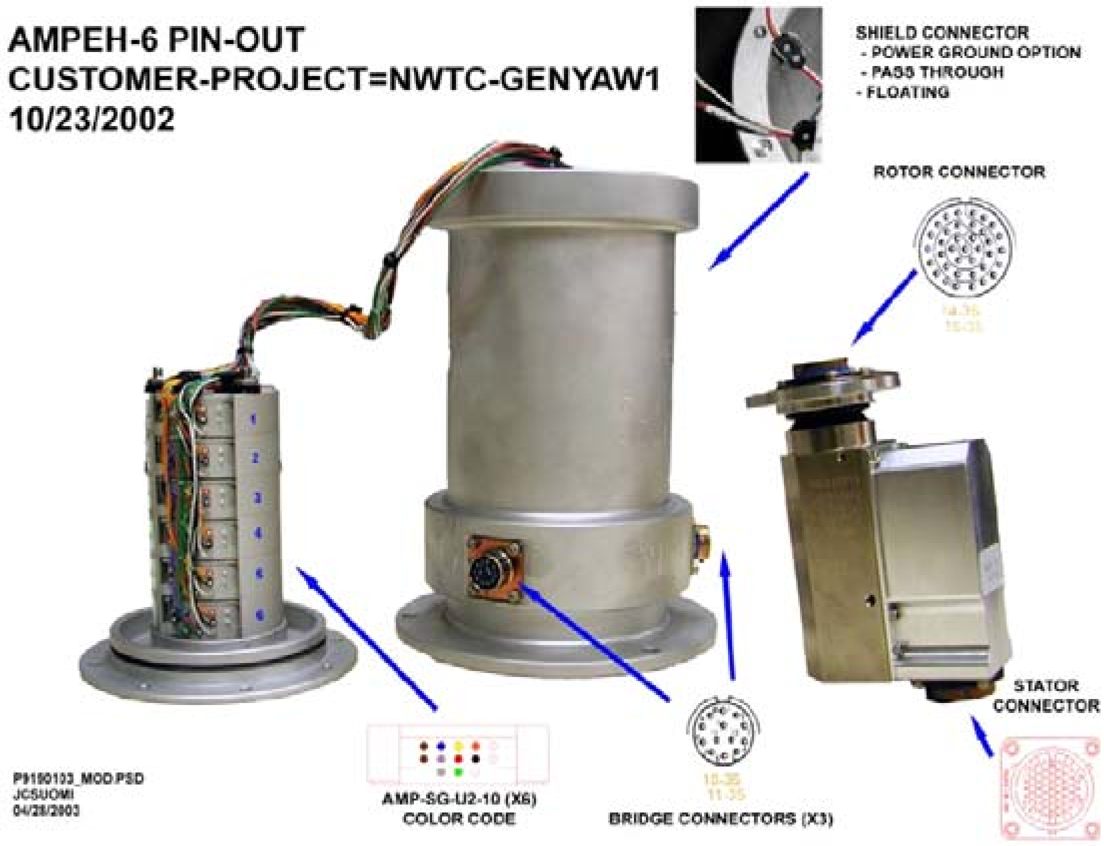


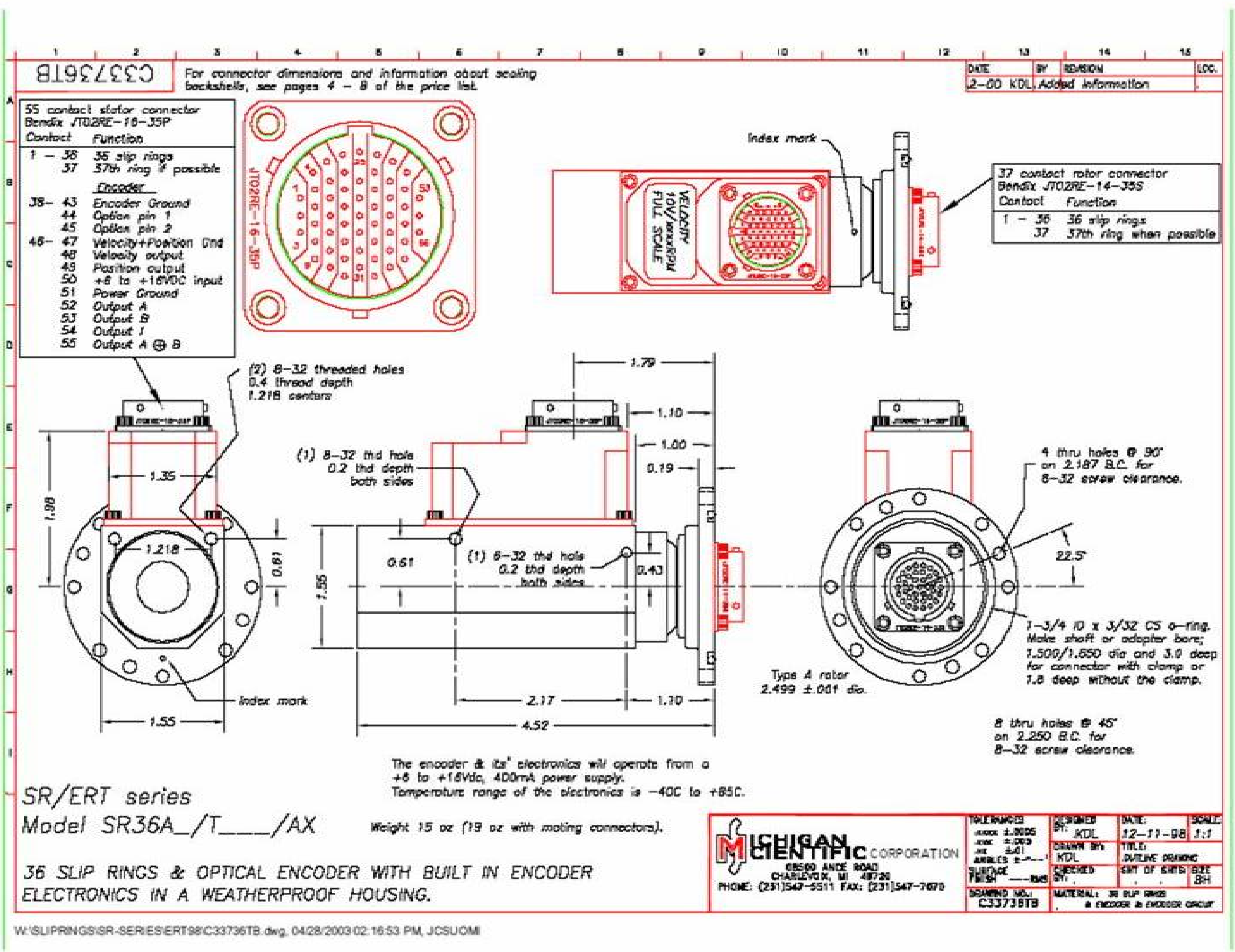
Slip Ring Connector JT06RE-16-35S(SR)

PIN	FUNCTION	COLOR
1	+15VDC	Blue
2	-15VDC	Violet
3	Power Ground	Gray
4	Calibration Control	Yellow
5	Shield	White/Green
6	+Signal (Channel 1)	Orange
7	+Signal (Channel 2)	Orange
8	+Signal (Channel 3)	Orange
9	+Signal (Channel 4)	Orange
10	+Signal (Channel 5)	Orange
11	+Signal (Channel 6)	Orange
12	-Signal (Channels 1-6)	Brown
13**	Bridge Foil Drain	Orange/Gray, White

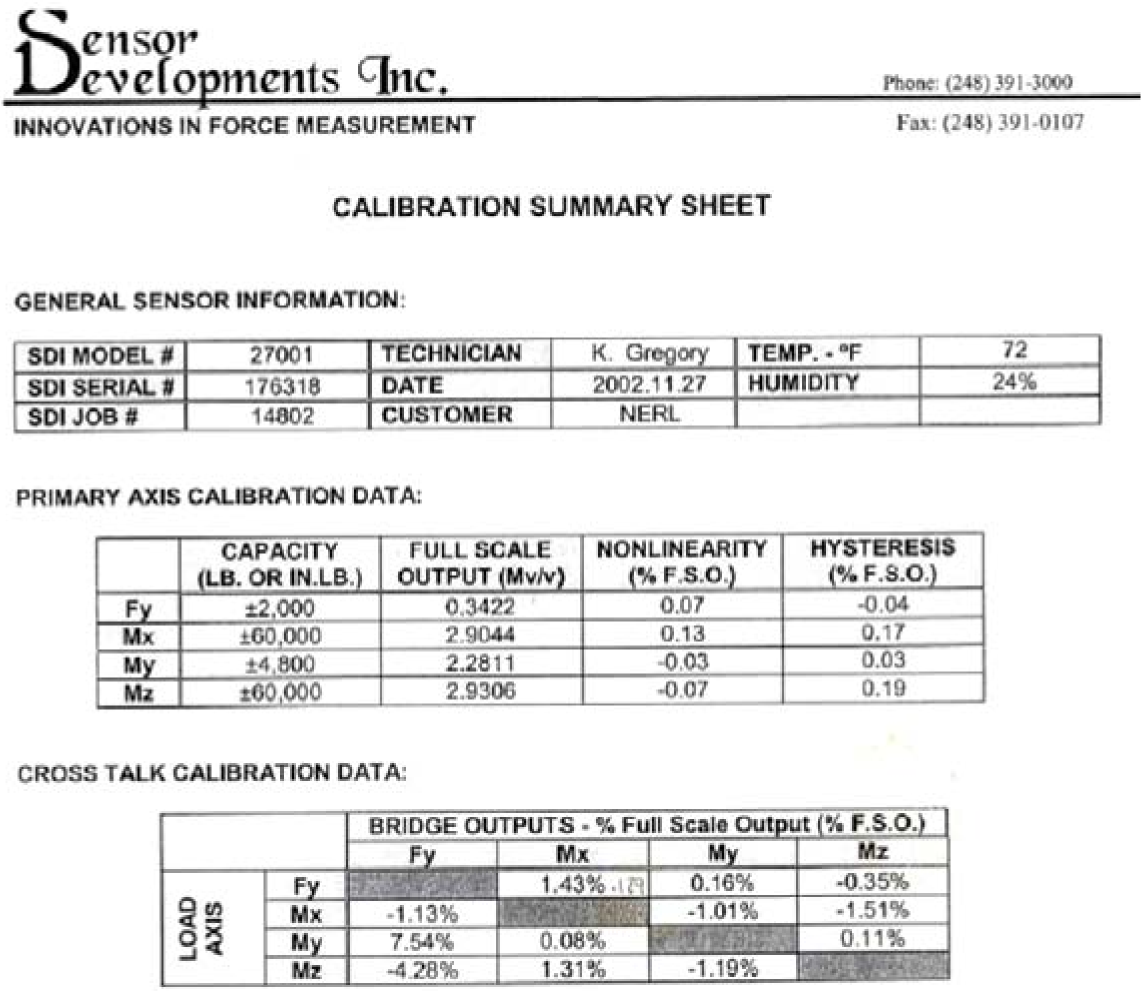
***Note: Added bridge foil drain on 4/24/2003*


NATIONAL WIND TECHNOLOGY CENTER
AMPEH–6 WIRING DIAGRAM FOR S/N:001
CUSTOMER–PROJECT=NWTC–GENYAW1
BRIDGE CONNECTOR (1–3)
JT02RE–10–35S
AMP–SG–U2–10
STRAIN GAGE AMPLIFIER
(X 6)
SHIELD OPTION
OHMETICS CONNECTOR
INTERNAL OF HOUSING
SLIP RING ROTOR CONNECTOR
JT06RE–16–35S(SR)
TO CONNECTOR 2
TO CONNECTOR 3
SHIELD (CH1&2)
SHIELD (CH3&4)
SHIELD (CH5&6)
POWER
TO AMPS 2–6
BRIDGES 1, 3, OR 5
+BRIDGE SIGNAL
+BRIDGE EXCITATION
–BRIDGE SIGNAL
–BRIDGE EXCITATION
TO AMP 1, 3, OR 5
FROM AMPS 2–6
+15VDC
–15VDC
POWER GND
CAL CONTROL
SHIELD
+SIGNAL (CH1)
+SIGNAL (CH2)
+SIGNAL (CH3)
+SIGNAL (CH4)
+SIGNAL (CH5)
+SIGNAL (CH6)
–SIGNAL (CH 1–6)
BRIDGES 2, 4, OR 6
+BRIDGE SIGNAL
+BRIDGE EXCITATION
–BRIDGE SIGNAL
–BRIDGE EXCITATION
BRIDGE FOIL DRAIN
BRIDGE FOIL DRAIN
TO AMP 2, 4, OR 6
BRIDGE FOIL DRAIN
2 PER BRIDGE
CONNECTOR
W:\NWTC\C5600280.DWG
JCSUOMI
04/28/2003
W:\NWTC\C5600280.DWG, 04/28/2003 12:27:08 PM, JCSUOMI


AMPEH-6 PIN-OUT
CUSTOMER-PROJECT=NWTC-GENYAW1
10/23/2002
SHIELD CONNECTOR
- POWER GROUND OPTION
- PASS THROUGH
- FLOATING
ROTOR CONNECTOR
14-35
15-35
1
2
3
4
5
6
STATOR
CONNECTOR
P9190103_MOD.PSD
JCSUOMI
04/28/2003
AMP-SG-U2-10 (X6)
COLOR CODE
10-35
11-35
BRIDGE CONNECTORS (X3)


C33736TB
For connector dimensions and information about sealing backshells, see pages 4 – 8 of the price list.
DATE BY REVISION LOC.
2-00 KDL Added information
55 contact stator connector
Bendix JT02RE-16-35P
Contact Function
1 – 36 36 slip rings
37 37th ring if possible
Encoder
38– 43 Encoder Ground
44 Option pin 1
45 Option pin 2
46– 47 Velocity+Position Gnd
48 Velocity output
49 Position output
50 +6 to +16VDC input
51 Power Ground
52 Output A
53 Output B
54 Output I
55 Output A ⊕ B
JT02RE-16-35P
Index mark
VELOCITY
10V/xxxxRPM
FULL SCALE
37 contact rotor connector
Bendix JT02RE-14-35S
Contact Function
1 – 36 36 slip rings
37 37th ring when possible
(2) 8-32 threaded holes
0.4 thread depth
1.218 centers
1.79
1.10
1.00
0.19
(1) 8-32 thd hole
0.2 thd depth
both sides
1.35
1.98
1.218
0.81
0.61
1.55
0.43
4 thru holes @ 90°
on 2.187 B.C. for
8-32 screw clearance.
22.5°
1-3/4 ID x 3/32 CS o-ring.
Make shaft or adapter bore;
1.500/1.650 dia and 3.0 deep
for connector with clamp or
1.8 deep without the clamp.
Type 4 rotor
2.499 ±.001 dia.
Index mark
1.55
2.17
1.10
4.52
8 thru holes @ 45°
on 2.250 B.C. for
8-32 screw clearance.
The encoder & its' electronics will operate from a
+6 to +16Vdc, 400mA power supply.
Temperature range of the electronics is -40C to +85C.
SR/ERT series
Model SR36A_/T___/AX
Weight 15 oz (19 oz with mating connectors).
36 SLIP RINGS & OPTICAL ENCODER WITH BUILT IN ENCODER
ELECTRONICS IN A WEATHERPROOF HOUSING.
MICHIGAN SCIENTIFIC CORPORATION
8500 ANCE ROAD
CHARLEVOIX, MI 49720
PHONE: (231)547-5511 FAX: (231)547-7070
TOLERANCES
.xxxx ±.0005
.xxx ±.003
.xx ±.01
ANGLES ±
SURFACE FINISH
DESIGNED BY: KDL
DATE: 12-11-98
SCALE 1:1
DRAWN BY: KDL
TITLE: OUTLINE DRAWING
CHECKED BY:
SHT OF SHTS
SIZE BH
DRAWING NO.: C33736TB
MATERIAL: 36 SLIP RINGS & ENCODER & ENCODER CIRCUIT
W:\SLIPRINGS\SR-SERIES\ERT98\C33736TB.dwg, 04/28/2003 02:16:53 PM, JCSUOMI

Shaft Sensor Calibration Data and Crosstalk Matrix
(Note – Only pre-test calibration data is shown but all post calibration data was within calibration tolerances.)



Sensor Developments Inc.
Phone: (248) 391-3000
INNOVATIONS IN FORCE MEASUREMENT
Fax: (248) 391-0107

CALIBRATION SUMMARY SHEET

GENERAL SENSOR INFORMATION:

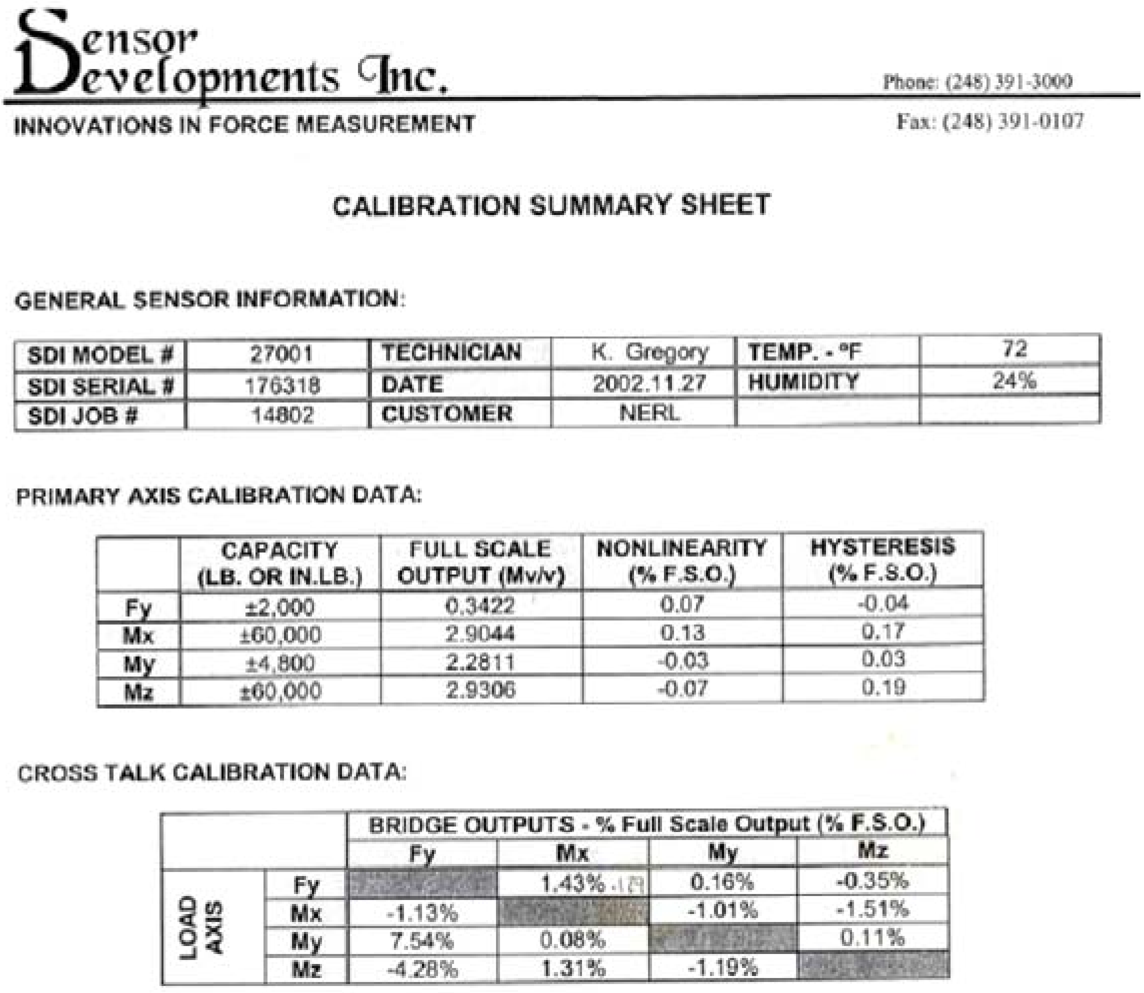
SDI MODEL #	27001	TECHNICIAN	K. Gregory	TEMP. - °F	72
SDI SERIAL #	176318	DATE	2002.11.27	HUMIDITY	24%
SDI JOB #	14802	CUSTOMER	NERL		

PRIMARY AXIS CALIBRATION DATA:

	CAPACITY (LB. OR IN.LB.)	FULL SCALE OUTPUT (Mv/v)	NONLINEARITY (% F.S.O.)	HYSTERESIS (% F.S.O.)
Fy	±2,000	0.3422	0.07	-0.04
Mx	±60,000	2.9044	0.13	0.17
My	±4,800	2.2811	-0.03	0.03
Mz	±60,000	2.9306	-0.07	0.19

CROSS TALK CALIBRATION DATA:

		BRIDGE OUTPUTS - % Full Scale Output (% F.S.O.)			
		Fy	Mx	My	Mz
LOAD AXIS	Fy	▨	1.43% .19	0.16%	-0.35%
	Mx	-1.13%	▨	-1.01%	-1.51%
	My	7.54%	0.08%	▨	0.11%
	Mz	-4.28%	1.31%	-1.19%	▨



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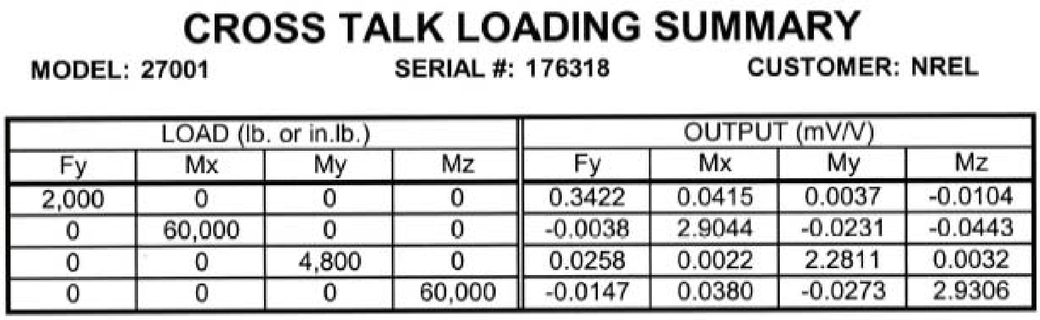
Mx	±60,000	2.9044	0.13	0.17
My	±4,800	2.2811	-0.03	0.03
Mz	±60,000	2.9306	-0.07	0.19

CROSS TALK CALIBRATION DATA:

		BRIDGE OUTPUTS - % Full Scale Output (% F.S.O.)			
		Fy	**Mx**	**My**	**Mz**
LOAD AXIS	**Fy**		1.43%	0.16%	-0.35%
	Mx	-1.13%		-1.01%	-1.51%
	My	7.54%	0.08%		0.11%
	Mz	-4.28%	1.31%	-1.19%	



CROSS TALK LOADING SUMMARY

MODEL: 27001 **SERIAL #: 176318** **CUSTOMER: NREL**

LOAD (lb. or in.lb.)				OUTPUT (mV/V)			
Fy	Mx	My	Mz	Fy	Mx	My	Mz
2,000	0	0	0	0.3422	0.0415	0.0037	-0.0104
0	60,000	0	0	-0.0038	2.9044	-0.0231	-0.0443
0	0	4,800	0	0.0258	0.0022	2.2811	0.0032
0	0	0	60,000	-0.0147	0.0380	-0.0273	2.9306

Sensor Developments Inc.

Crosstalk Calibration by the Matrix Inversion Method

SECTION A - How to use the crosstalk compensation matrix

The crosstalk compensation matrix for **S/N 176318** is shown directly below:

$$M^{-1} = \begin{bmatrix} 5.845\cdot10^{3} & 7.558 & -6.616\cdot10^{1} & 2.861\cdot10^{1} \\ -2.513\cdot10^{3} & 2.065\cdot10^{4} & 8.900 & -2.803\cdot10^{2} \\ -2.423\cdot10^{1} & 1.700\cdot10^{1} & 2.104\cdot10^{3} & 1.926\cdot10^{1} \\ 5.846\cdot10^{2} & 3.127\cdot10^{2} & -3.563\cdot10^{1} & 2.047\cdot10^{4} \end{bmatrix}$$

Any output set measured from the four sensor bridges can be multiplied by this inverse matrix to reveal the loading condition that must have produced the output. For example, if a loading condition resulted in this output:

Fy	**+0.3141 mV/V**
Mx	**+1.0329 mV/V**
My	**-0.0223 mV/V**
Mz	**+1.9291 mV/V**

then we create a column matrix from the measured output:

$$O := \begin{bmatrix} 0.3141 \\ 1.0329 \\ -.0223 \\ 1.9291 \end{bmatrix}$$

and multiply the crosstalk matrix by the column matrix, resulting in a load matrix:

$$M^{-1}\cdot O = \begin{bmatrix} 1900 \\ 20000 \\ 0 \\ 40000 \end{bmatrix}$$

Thus, the loading condition which caused the above output was:

Fy = 1,900 lbs.
Mx = 20,000 in-lbs.
My = 0
Mz = 40,000 in-lbs.

Note that the order of the column matrices is important. Both the measured voltage output and the resultant load matrices must read, from top to bottom, Fy, Mx, My, Mz.

SECTION B - Creating the crosstalk matrix

If a load cell exhibited no crosstalk sensitivity - that is, if none of the bridges responded to any loads other than those which they are designed to measure, compensation would be unnecessary. In reality, however, each bridge does respond, however slightly, to other loading conditions. This undesired response is termed **crosstalk**, and in order to improve load-cell accuracy, it needs to be removed.

One method of compensating for crosstalk response is done arithmetically, by the **matrix-inversion method**.

The underlying mathematic processes used in determining the inverse matrix are discussed below.

Consider a system of equations:

$$
\begin{aligned}
1x_1 - 2x_2 + 3x_3 + 1x_4 &= 1 \\
2x_1 - 3x_2 + 4x_3 - 1x_4 &= -12 \\
2x_1 + 2x_2 - 3x_3 + 5x_4 &= 50 \\
5x_1 - 1x_2 + 4x_3 - 3x_4 &= 7
\end{aligned}
$$

We can represent the system using matrices:

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$$

where

$$
\mathbf{A} = \begin{bmatrix} 1 & -2 & 3 & 1 \\ 2 & -3 & 4 & -1 \\ 2 & 2 & -3 & 5 \\ 5 & -1 & 4 & -3 \end{bmatrix}
\qquad
\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}
\qquad
\mathbf{b} = \begin{bmatrix} 1 \\ -12 \\ 50 \\ 7 \end{bmatrix}
$$

We can relate this to load-cell performance: In our application, $\mathbf{x}$ is the loading condition, $\mathbf{b}$ is the load cell output, and matrix $\mathbf{A}$ shows how each bridge responds to each load. It shows response to on-axis loading, as well as crosstalk response.

To construct the response matrix, we apply a series of known loads to the load cell, and record its response (output) to each load. The applied loads must be isolated loads, not combination loads. The matrix is then constructed as shown here:

$$
\mathbf{A} = \begin{bmatrix}
\dfrac{\text{Output from } F_y \text{ bridge}}{F_y \text{ load}} & \dfrac{\text{Output from } F_y \text{ bridge}}{M_x \text{ load}} & \dfrac{\text{Output from } F_y \text{ bridge}}{M_y \text{ load}} & \dfrac{\text{Output from } F_y \text{ bridge}}{M_z \text{ load}} \\
\dfrac{\text{Output from } M_x \text{ bridge}}{F_y \text{ load}} & \dfrac{\text{Output from } M_x \text{ bridge}}{M_x \text{ load}} & \dfrac{\text{Output from } M_x \text{ bridge}}{M_y \text{ load}} & \dfrac{\text{Output from } M_x \text{ bridge}}{M_z \text{ load}} \\
\dfrac{\text{Output from } M_y \text{ bridge}}{F_y \text{ load}} & \dfrac{\text{Output from } M_y \text{ bridge}}{M_x \text{ load}} & \dfrac{\text{Output from } M_y \text{ bridge}}{M_y \text{ load}} & \dfrac{\text{Output from } M_y \text{ bridge}}{M_z \text{ load}} \\
\dfrac{\text{Output from } M_z \text{ bridge}}{F_y \text{ load}} & \dfrac{\text{Output from } M_z \text{ bridge}}{M_x \text{ load}} & \dfrac{\text{Output from } M_z \text{ bridge}}{M_y \text{ load}} & \dfrac{\text{Output from } M_z \text{ bridge}}{M_z \text{ load}}
\end{bmatrix}
$$

Although, in the calibration lab, we apply known loads to the load cell, and note its response, the end user desires to measure the response of the load cell, and from it, determine the loading condition which must have caused that response. Applying this to our simple example above, **b** is the known variable, and **x** is the unknown.

Therefore to solve for **x** given a known **b**, we must find the inverse of the the crosstalk matrix **A**, designated $\mathbf{A}^{-1}$ Note that this is **not** 1/**A**.

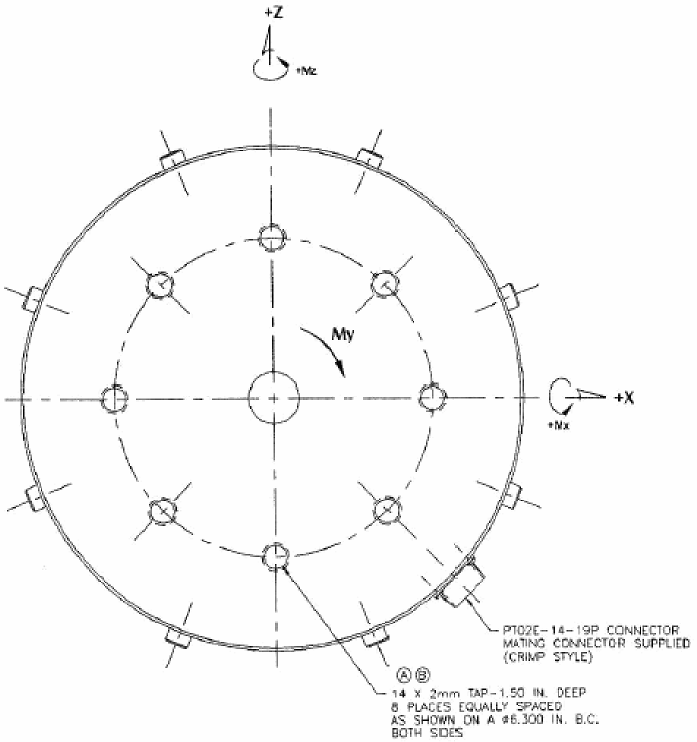
The inverse may be calculated by any one of number of different methods, such as row-reduction or LU decomposition. Computer programs such as Mathcad or Excel, as well as some hand-held calculators, contain algorithms to simplify this tedious process.

Having found the inverse matrix, it is a simple matter to solve for the loading condition, given the output of the load cell:

$$\mathbf{x} = \mathbf{A}^{-1} \cdot \mathbf{b}$$

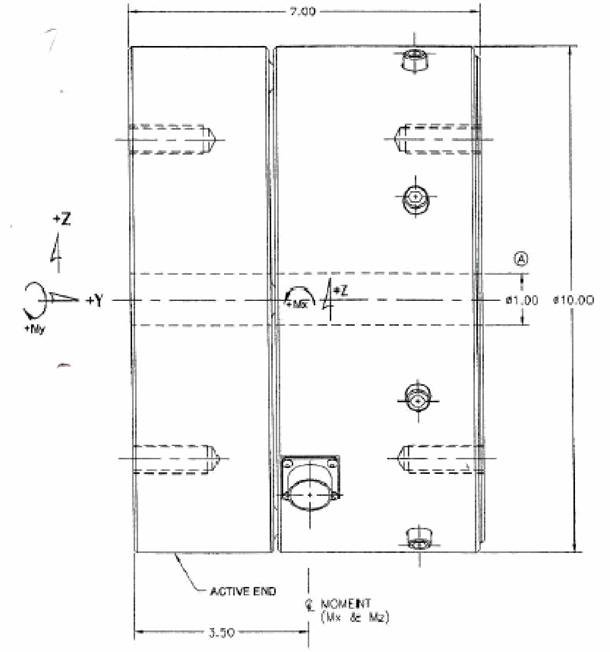
The practical application of this is shown in Section A, above.

REV	DESCRIPTION	BY	DATE	CHK	ENG	REL DATE
–	REL. FOR PRODUCTION	–	–	–	–	6-28-02
A	BOLT PATTERN ROTATED; ø1.00 WAS ø.75; 9/16-18 TAP-1.25 DEEP WAS 1/2-13 TAP-1.25 DEEP; ø.625 ±.888 C'BORE REMOVED	GMC	8-7-02	DS	DS	8-13-02
B	14 X 2mm TAP WAS 9/16-18	GMC	8-14-02	DS	DS	8-14-02
C	Mz PINS CORRECTED	GMC	11-25-02			– –



PT02E-14-19P CONNECTOR
MATING CONNECTOR SUPPLIED
(CRIMP STYLE)

Ⓐ Ⓑ
14 X 2mm TAP-1.50 IN. DEEP
8 PLACES EQUALLY SPACED
AS SHOWN ON A ø6.300 IN. B.C.
BOTH SIDES



ACTIVE END

℄ MOMENT
(Mx & Mz)

SPECIFICATIONS MODEL: 27001-00A-E0000

CAPACITY-LBS.	Fy	±2,000
CAPACITY-IN. LBS.	Mx	±60,000
	My	±4,800
	Mz	±60,000
OUTPUT NOM. (mV/V)	Fy	.32
	Mx, Mz	2.7
	My	2.0
OVERLOAD CAPACITY (%F.S.)		150
NON-LINEARITY (%F.S.)		.25
HYSTERESIS (%F.S.)		.25
TEMP RANGE (°F)		-65 TO +250

NOTE: CROSS-TALK CORRECTION
MATRIX PROVIDED W/CALIBRATION
DATA PACKAGE

POLARITY: AS SHOWN
ASSEMBLY DWG REF: 192270O-*
*-INDICATES CURRENT REV

WIRING CODE

Fy		Mx		My		Mz	
PIN	FUNCTION	PIN	FUNCTION	PIN	FUNCTION	PIN	FUNCTION
A	+ EXC.	E	+ EXC.	J	+ EXC.	N	+ EXC.
B	+ SIG.	F	+ SIG.	K	+ SIG.	P	+ SIG.
C	– SIG.	G	– SIG.	L	– SIG.	R	– SIG.
D	– EXC.	H	– EXC.	M	– EXC.	S	– EXC.

INSTALLATION MODEL: 27001-00A-E0000	CHECKED BY D.S.
	PROJ. ENG. D.S.
FINISH / SCALE FULL	DRAWN BY GMC
MATL.	DATE 6-26-02
UNLESS OTHERWISE SPECIFIED DIM'S ARE IN INCHES X.X ±.03 X.XX ±.01 X.XXX ±.005 ANG. ±.5°	D.E. REVIEW BY / DATE
Sensor Developments Inc. 1050 W SILVER BELL RD ORION, MI 48359	DRAWING NUMBER 1922800-C

KAIJO SONIC

Digitized Ultrasonic Anemometer-Thermometer

DA,DAT SERIES

Introducing KAIJO DENKI's new DA and DAT Series Ultrasonic Anemometer-Thermometers. These are radical improvements of the world-first PA and PAT Series, developed in 1963 under the direction of Professor Y. Mitsuta at Kyoto University, which have enjoyed wide acceptance for more than decade by weather personnel not only in Japan but all parts of the world.

With emphasis on user-oriented precision and dependability, these new series incorporate the latest advances in KAIJO technology acquired from years of experience as a leader in the industry and past successful achievements. New technological developments include a new measurement method, free from measurement errors associated with sound velocity changes; a new concept omnidirectional probe designed to exert no interference on winds from any wind direction; and a digital operation system.

In addition to the available AD Series Data Analysers, these new series represent KAIJO's continuous efforts to produce products which are effective in general meteorological research endeavors and in air pollution monitoring.

FEATURES

1. Zero m/sec Wind Velocity Measurement

The system is capable of measuring zero m/sec wind velocity because the anemometer sensor contains no wind-velocity-actuated mechanism and requires no "starting wind velocity."

2. Response Time of Only 0.05 Second

The ultrasonic anemometer, as well as the thermometer, has a zero inertia time with a response time of 0.05 sec and will efficiently sense even the slightest air movement. The thermometer sensor is common to the anemometer. The unique thermometer design frees the system from radiant heat effects and gives it the advantage of having no thermal capacity.

3. No Sound Velocity Error

Sound velocity in air largely depends on temperature changes, atmospheric pressure, humidity, etc. The DA Series Ultrasonic Anemometer is designed to eliminate measurement errors caused by sound velocity changes due to these meteorological factors and to obviate correction or calibration work for rectifying such measurement errors.

4. Freely Interchangeable Probe Head

A pair of probe heads on each axis ("single-pair" probe head) based on a time-sharing multiplex transmission/reception system eliminates the "zero point" drift caused by maladjustment of the span which assures complete probe interchangeability and allows selective use of a number of probes for greater cost performance.

5. "Omnidirectional Probe" (TR-61B probe) Exerts No Interference on Winds

Repeated wind tunnel experiments and detailed research, aimed at developing a probe exerting no interference on natural winds, have resulted in an omnidirectional probe which can accurately sense winds blowing from any direction. It will withstand winds of 90 m/sec.

6. Selection of Options Available

A complete range of peripheral devices are optionally available to meet particular requirements of the user: wind direction and wind velocity sensing vector composition cards, inclinometers for integration into the probe, coordination axis conversion cards, digital output cards, sigma meters, flux meters, and other analogue data processors.

SPECIFICATIONS

Description	Ultrasonic Anemometer	Ultrasonic Thermometer
Measuring mode	Time-sharing multiplex transmission/reception ultrasonic pulse emission	Time-sharing multiplex transmission/reception ultrasonic pulse emission
Range	Standard type: 0 ~ ±30 m/S Strong wind type: 0 ~ ±60m/S	Temperature: -10°C ~ ±40°C Fluctuating temp.: 0 ~ ±5°C
Accuracy	±1% of value measured	±1% of value measured
Resolution	0.5 cm/s	0.025°C
Measurement cycle	20 times/sec	20 times/sec
Analogue signal output	OUT – 1: 0~±1V/10m/s 8V max OUT – 2: 0~±1V/full scale Full scale A ±1, ±2, ±5, ±10 m/s B ±5, ±10, ±25, ±50 m/s Vector synthesizer type U: ±15, ±30 m/S (standard type) ±15, ±30, ±60 m/S (strong wind type) θ: 0 ~ 540°	OUT – 1: 0~±1V/±50°C OUT – 2: 0~±1V/Tset ±5°C
Digital signal output (optional)	15-bit binary digital code	12-bit binary digital code
Temperature	Main Unit: –10°C ~ +40°C, probe & junction box: -20°C ~ +50°C	
Power supply	AC100/115/220 ± 10% 50/60 Hz	

LIST OF MODELS

Classification			Model	Description	Composition		
					Main unit	Junction box	Probe
Wind components measuring type	Standard type	1 direction	DA – 100	Used to measure X,Y,W wind components up to max. 30 m/s.	DA – 100	OA–40	TR-41
		2 directions	DA – 200		DA – 200	OA–50	TR-51
		3 directions	DA – 300		DA – 300	OA–60	TR-61C or TR-61A
		1 direction	DAT–100	Provided with ultrasonic thermometer	DAT–100	OA–40	TR-41
		2 directions	DAT–200		DAT–200	OA–50	TR-51
		3 directions	DAT–300		DAT–300	OA–60	TR-61C or TR-61A
	Strong wind type	3 directions	DA – 300	Measuring range: 0~60 m/s	DA – 300	OA–60	TR-61B
		3 directions	DAT–300		DAT–300	OA–60	TR-61B
Vector synthesizer type	Standard type	2 directions	DA – 210	Vector synthesizer & mean cards incorporated for measuring instantaneous & mean values of wind velocity. Directional component values are output simultaneously.	DA – 210	OA–50	TR-51
		3 directions	DA – 310		DA – 310	OA–60	TR-61C or TR-61A
		2 directions	DAT–210		DAT–210	OA–50	TR-51
		3 directions	DAT–310		DAT–310	OA–60	TR-61C or TR-61A
	Strong wind type	3 directions	DA – 310		DA – 310	OA–60	TR-61B
		3 directions	DAT–310		DAT–310	OA 60	TR-61B

* Custom orders subject to negotiations

RECORDERS, OPTIONALS

	Model 15R-6S	Model 15R-2P-2T	Model 25-6S
Model	6-point potentiometric recording	Dual-pen continuous recording (ink used)	6-point potentiometric recording
Effective chart width	150 mm	150 mm	250 mm
Pen speed	1 sec. F.S.	1 sec. F.S.	1 sec. F.S.
Chart speed	30,60,300,1200 mm/h	30,60,300,1200 mm/h	30,60,300,1200 mm/h
Print time interval	5 sec.	–	5 sec.
Application	recording for $\overline{U}$, $\overline{\theta}$	recording for U, θ or $\overline{U}$, $\overline{\theta}$	recording for $\overline{U}$, $\overline{\theta}$, $\overline{W}$, available of recording for $\overline{U}$, $\overline{\theta}$ $\overline{W}$, σU, $\sigma\theta$, σW with AD-700 analog analyzer joint operation

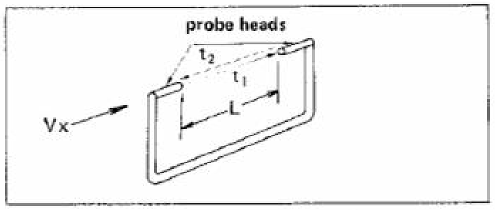
PRINCIPLE OF OPERATION

[Principle of Wind Velocity Measurement]

- The term "ultrasonic wave" refers to sound having a frequency beyond the audibility of the human ear. Ultrasonic waves, like ordinary sound waves, propagate linearly in air at an essentially constant speed of approximately 340 m/sec.

Ultrasonic propagating speed in moving air, however, is slightly variable, that is, the sound travels faster in a tail wind and slower in a head wind.

- The DA Ultrasonic Anemometer, operating on this principle, comprises two probe heads facing each other at a fixed interval as shown in the illustration below, and pulses are alternately emitted from the heads in specified time cycle.



More precisely, two ultrasonic pulse signals are alternately emitted in opposite directions. The relationship of the propagation times (t_1 and t_2) with the wind velocity is represented by the following equation:

$$t_1 = \frac{L}{C + Vx} \text{ ......(1)} \qquad t_2 = \frac{L}{C - Vx} \text{ ....(2)}$$

$$\therefore \frac{L}{t_1} - Vx = \frac{L}{t_2} + Vx$$

$$\therefore 2Vx = \frac{t_2 L - t_1 L}{t_1 t_2}$$

$$\therefore Vx = \frac{L}{2} \left(\frac{t_2 - t_1}{t_1 t_2} \right) \text{ .... (3)}$$

Where: Vx = Wind velocity component along the path
C = Sound velocity in still air
L = Interval (span) between two prove heads

As seen from Equation (3), wind velocity Vx can be readily derived from the calculations of t_1 and t_2. The linear output signal and proportional constant "L" make the system immune to the effects of fluctuating temperature, humidity, and other meteorological factors, thus assuring accurate wind velocity measurements at all times.

[Principle of Temperature Measurement]

- Propagation times t_1 and t_2 of the ultrasonic pulses are represented by Equations (1) and (2), respectively. The relationship of t_1 and t_2 with sound velocity C may be expressed as:

$$t_1 = \frac{L}{C + Vx} \text{ ...... (1)} \qquad t_2 = \frac{L}{C - Vx} \text{ .... (2)}$$

$$\therefore \frac{L}{t_1} - C = -\frac{L}{t\,t_2} + C$$

$$\therefore 2C = \frac{t_1 L + t_2 L}{t_1 t_2}$$

$$\therefore C = \frac{L}{2} \left(\frac{t_1 + t_2}{t_1 t_2} \right) \text{ .... (4)}$$

Sound velocity in air, fluctuated by the effects of temperature, humidity, and atomospheric pressure, is given in the following equation:

$$C = 20.067 \sqrt{T \left(1 - 0.3192 \frac{e}{P}\right)} \text{ .... (5)}$$

Where: T = Temperature in air
(°K absolute temperature)
e = Vapor pressure
P = Atmospheric pressure

Given that the fluctuating cycle of atomospheric presure and humidity is much longer than that of temperature, it follows that sound velocity in air is proportional to the square root of absolute temperature, thereby reproducing Equation (4) to Equation (6) as follows:

$$T = \left(K \cdot \frac{L}{2} \left(\frac{t_1 + t_2}{t_1 t_2} \right) \right)^2 \text{ .... (6)}$$

where: K = Proportional constant

As is evident from Equation (6), given a proportional constant, temperature in air can be obtained from the calculations of t_1 and t_2. The DAT Series Ultrasonic Anemometer-Thermometer repeats the measurement 20 times per second, making it possible to measure temperature fluctuations with a response time of 10 Hz.

[Single-pair probe head system]

- The system has probe heads arranged on two or three axes, each emitting ultrasonic pulses at a rate of approximately 20 pulses per second while measuring the wind velocity components for each axial direction based on the above principle.
- A pair of probe heads provided on each axis (single-pair probe head) are designed to automatically switch between receiving and transmitting circuits and are much simpler than the double probe heads in configuration, eliminating the concern over possible drift of the zero point resulting from maladjustment of the two spans.

[Processing Mode and Output]

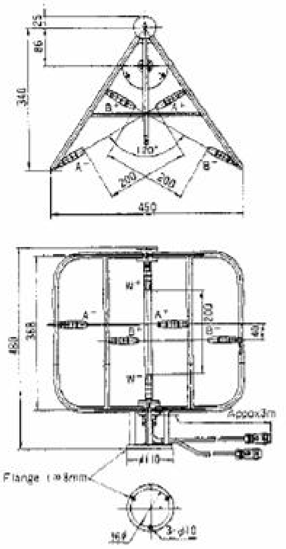
- Measurements and processing of the propagation time of ultrasonic pulses are digitally read out by application of high-performance ICs and a crystal oscillation circuit, giving high accuracy and dependability.

Measurement data are output as 12-bit binary code digital signals and may be converted into 0 to ±1V analogue signals, thus permitting connection of the main unit to a AD Series Data Analyser as well as a Digitalized Data Recorder or computer and telemeter.

DIMENSIONS

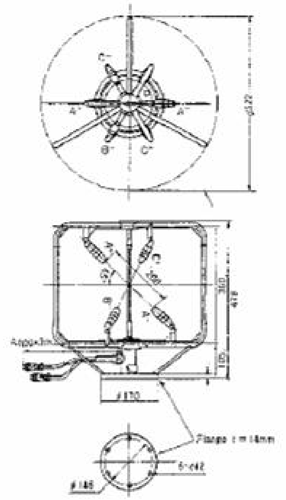
TR-61A Probe

(for researches)
A,B axes crossing at 120°
for measurement of main wind direction
Measuring range: 0~30m/s



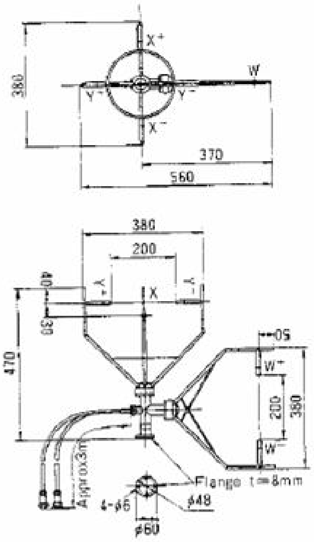
TR-61B Probe

(for strong wind observation)
A,B,C axes crossing at 120°
for measurement of omnidirectional wind
Measuring range: 0~60m/s

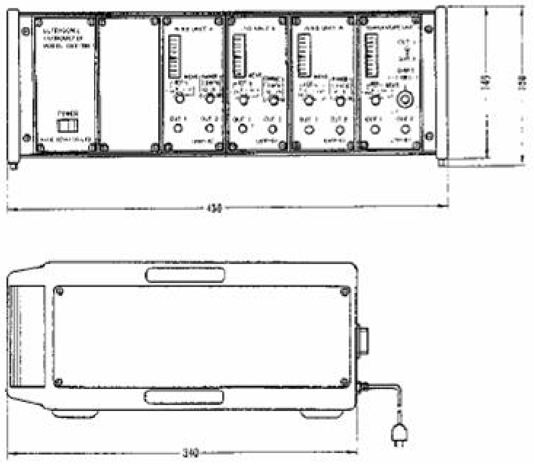


TR-61C Probe

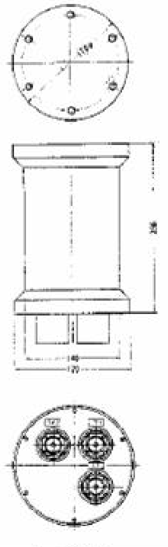
(for general observation)
X,Y,W axes crossing at 90°
for measurement of omnidirectional wind
Measuring range 0~30m/s



MAIN UNIT



Junction Box

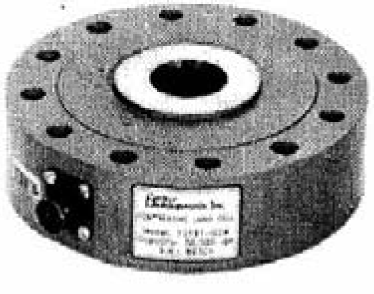


KAIJO DENKI CO. LTD

No.19,1-Chome,Kanda-Nishikicho,Chiyoda-ku,Tokyo,101,Japan
TEL.: (03)295-5609
TLX.: 02226245 KAIDEN J
CABLE: KAIJOSONIC, TOKYO

10191

Pancake Fatigue Force Sensor



Overview

Model 10191 is a pancake shaped force sensor for tension, compression, or universal force measurement applications. The sensor is suited for rugged applications including material and component testing machines, weighing, and other laboratory uses. The unit is extremely resistant to extraneous bending and side loading forces. Available options include a load button for compression only measurements and a base for high precision applications.

Features

- Fatigue rated
- NIST traceable calibration
- Auto-ID available, eliminating instrument scaling
- Compact, low profile
- Mating connector supplied

MODEL	CAPACITY
	LB
10191-014	10,000
10191-024	20,000
10191-034	50,000
10191-044	100,000
LOAD BUTTON	OPTIONAL
TENSION BASE	OPTIONAL

Specifications

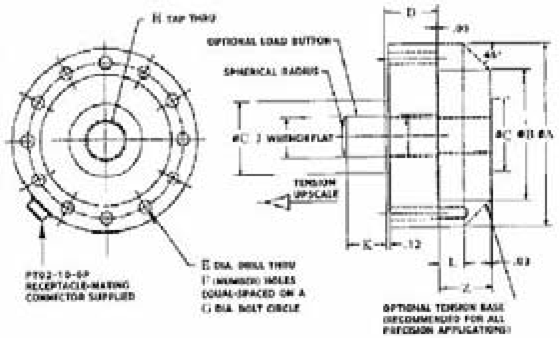
Capacity	10K to 100K lbs. (See Chart)
Overload capacity	150% of Full Scale
Output at Full Scale	2.0 mV/V nominal
Non-Linearity	0.25% of Full Scale
Hysteresis	0.25% of Full Scale
Zero balance	1.00% of Full Scale
Compensated temp.	70 to 170° F
Useable temp	-65 to +250° F
Temp. effect on Zero	0.002% of Full Scale/°F
Temp. effect on Span	0.002% of Rdg./°F
Bridge resistance	350 Ω
Excitation voltage, max	20 V dc
Material	Alloy Steel

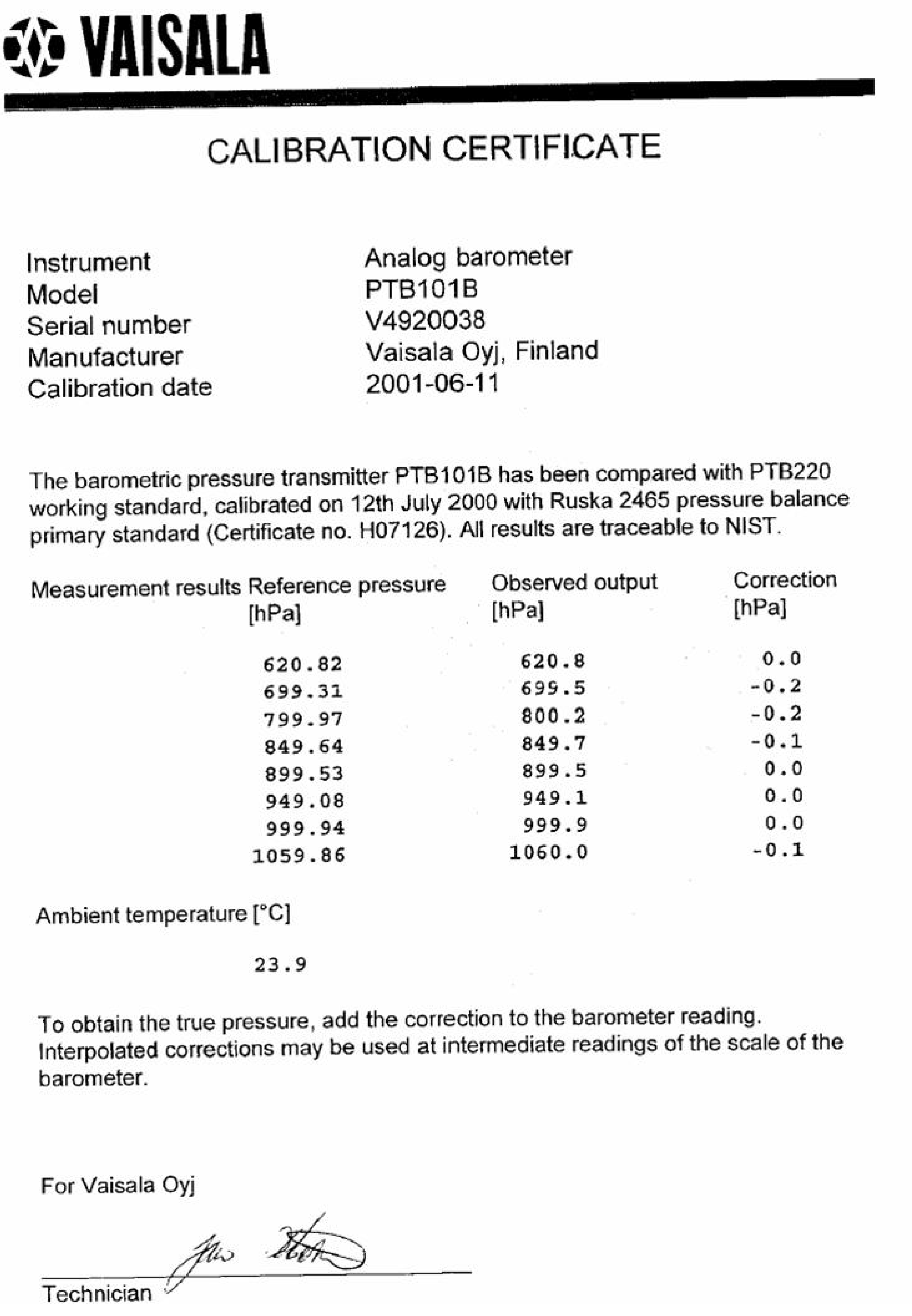
For suggested instrumentation see the PMAC 2000, (page 48)

Dimensions (inches)

CAPACITY	A	B	C	D	E	F	G	H	J	K	L	Z
10K	6.00	4.506	2.47	1.75	13.00	12	5.13	1.25-12	1 5/16	1.31	0.81	1.75
20K	6.00	4.506	2.47	1.75	13.00	12	5.125	1.25-12	1 5/16	1.31	0.81	1.75
50K	8.00	5.187"	3.84	2.50	17.00	16	6.000	1.75-12	2 1/4	2.00	1.97	2
100K	11.5	7.000	4.82	3.50	21.00	16	9.000	2.75-8	3 3/4	2.90	3.47	3.60

Note: Add "A" to the part number for Auto-ID i.e., 10191-014A





VAISALA

CALIBRATION CERTIFICATE

Instrument	Analog barometer
Model	PTB101B
Serial number	V4920038
Manufacturer	Vaisala Oyj, Finland
Calibration date	2001-06-11

The barometric pressure transmitter PTB101B has been compared with PTB220 working standard, calibrated on 12th July 2000 with Ruska 2465 pressure balance primary standard (Certificate no. H07126). All results are traceable to NIST.

Measurement results

Reference pressure [hPa]	Observed output [hPa]	Correction [hPa]
620.82	620.8	0.0
699.31	699.5	-0.2
799.97	800.2	-0.2
849.64	849.7	-0.1
899.53	899.5	0.0
949.08	949.1	0.0
999.94	999.9	0.0
1059.86	1060.0	-0.1

Ambient temperature [°C]

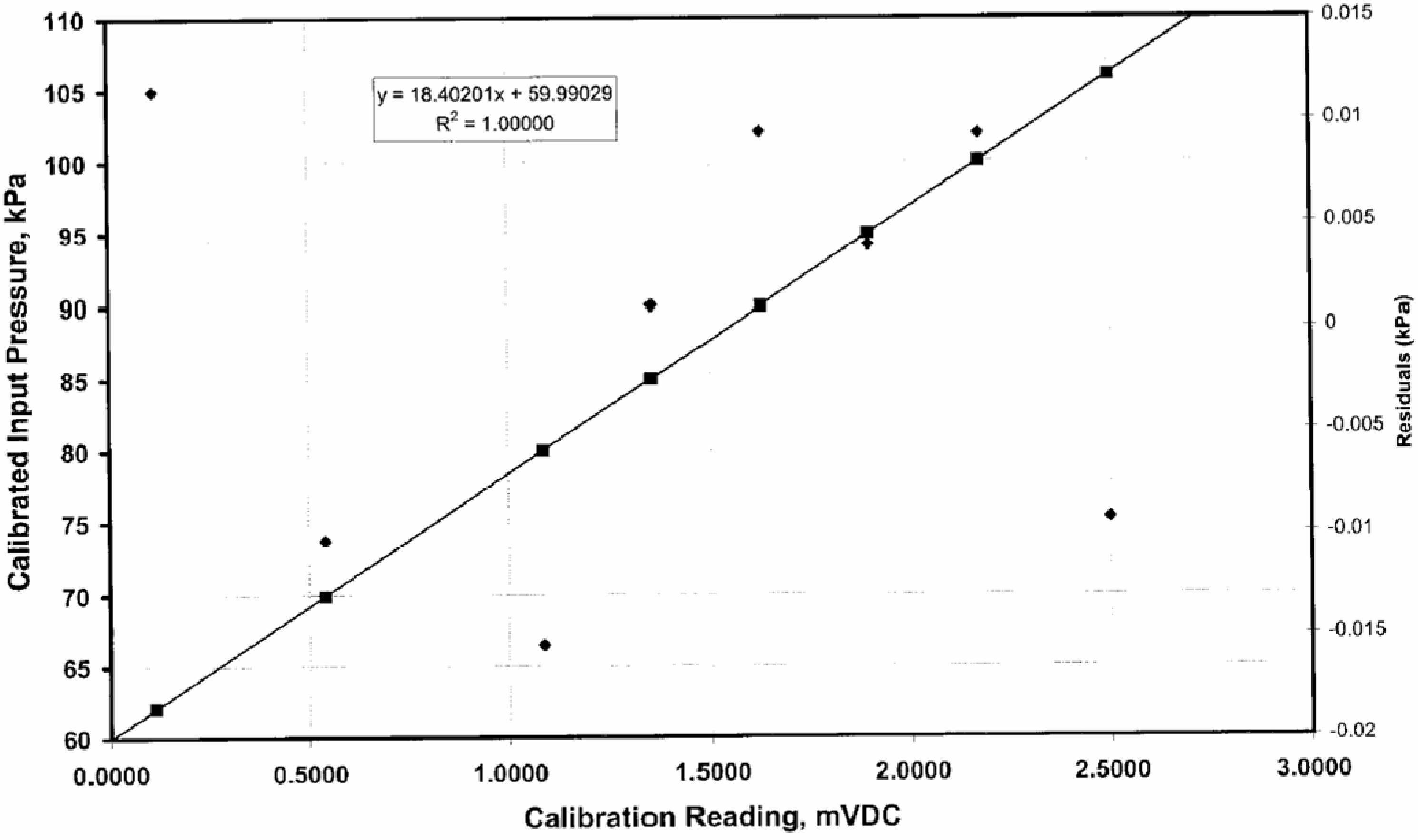
23.9

To obtain the true pressure, add the correction to the barometer reading. Interpolated corrections may be used at intermediate readings of the scale of the barometer.

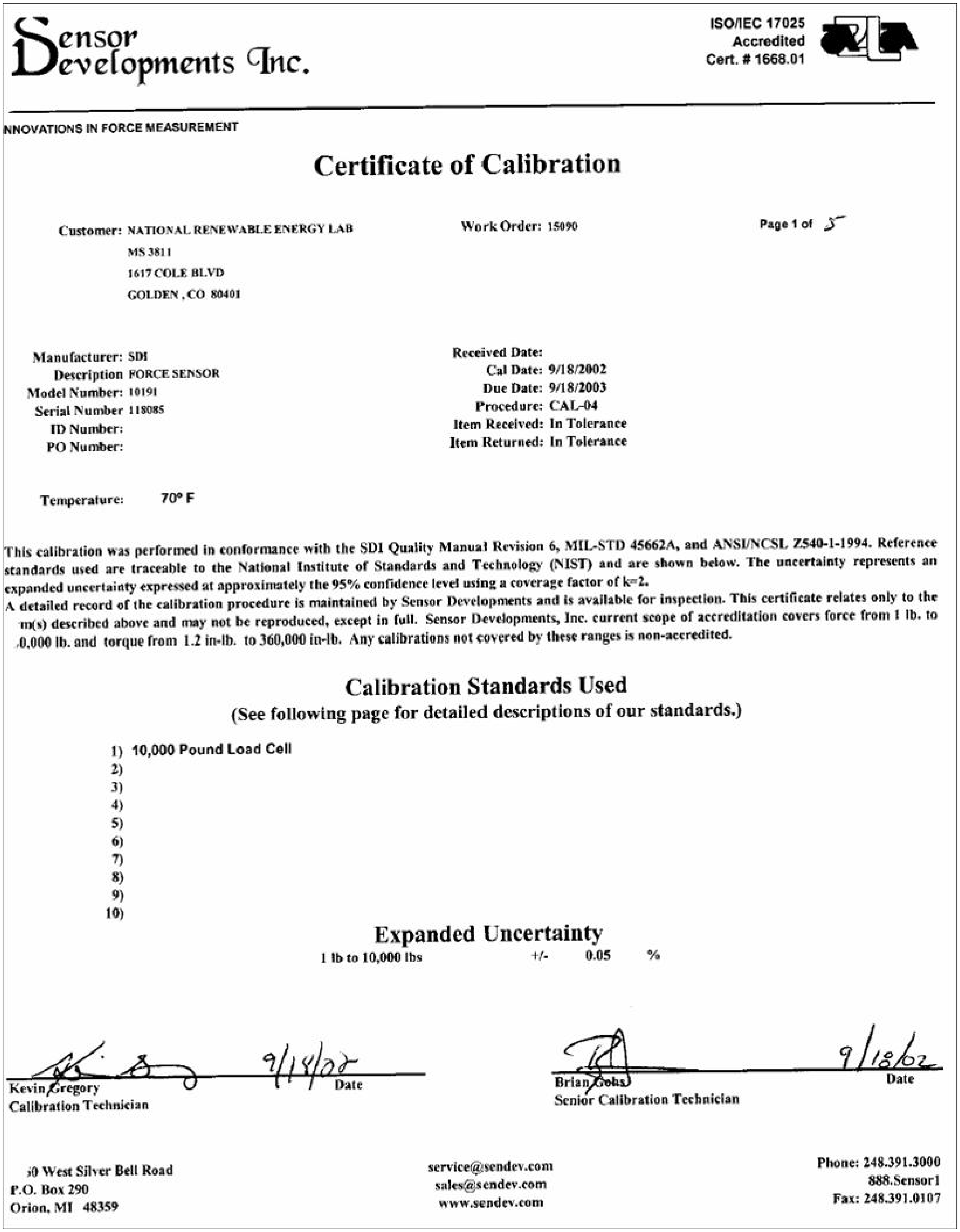
For Vaisala Oyj

Technician

NWTC Instrument Calibrations
Viasala Pressure Sensor
PTB101B SN:V4920038 - Feburary 12, 2003



Mark Meadors F:\Certification Equipment\Calibrations\Air Pressure Vaisala cals [SN V4920038 Cal (C)] 2/12/2003 4:52 PM



Sensor Developments Inc.

ISO/IEC 17025
Accredited
Cert. # 1668.01

NNOVATIONS IN FORCE MEASUREMENT

Certificate of Calibration

Customer: NATIONAL RENEWABLE ENERGY LAB
MS 3811
1617 COLE BLVD
GOLDEN , CO 80401

Work Order: 15090

Page 1 of 5

Manufacturer: SDI
Description FORCE SENSOR
Model Number: 10191
Serial Number 118085
ID Number:
PO Number:

Received Date:
Cal Date: 9/18/2002
Due Date: 9/18/2003
Procedure: CAL-04
Item Received: In Tolerance
Item Returned: In Tolerance

Temperature: 70° F

This calibration was performed in conformance with the SDI Quality Manual Revision 6, MIL-STD 45662A, and ANSI/NCSL Z540-1-1994. Reference standards used are traceable to the National Institute of Standards and Technology (NIST) and are shown below. The uncertainty represents an expanded uncertainty expressed at approximately the 95% confidence level using a coverage factor of k=2.
A detailed record of the calibration procedure is maintained by Sensor Developments and is available for inspection. This certificate relates only to the m(s) described above and may not be reproduced, except in full. Sensor Developments, Inc. current scope of accreditation covers force from 1 lb. to ,0,000 lb. and torque from 1.2 in-lb. to 360,000 in-lb. Any calibrations not covered by these ranges is non-accredited.

Calibration Standards Used

(See following page for detailed descriptions of our standards.)

1) 10,000 Pound Load Cell
2)
3)
4)
5)
6)
7)
8)
9)
10)

Expanded Uncertainty

1 lb to 10,000 lbs +/- 0.05 %

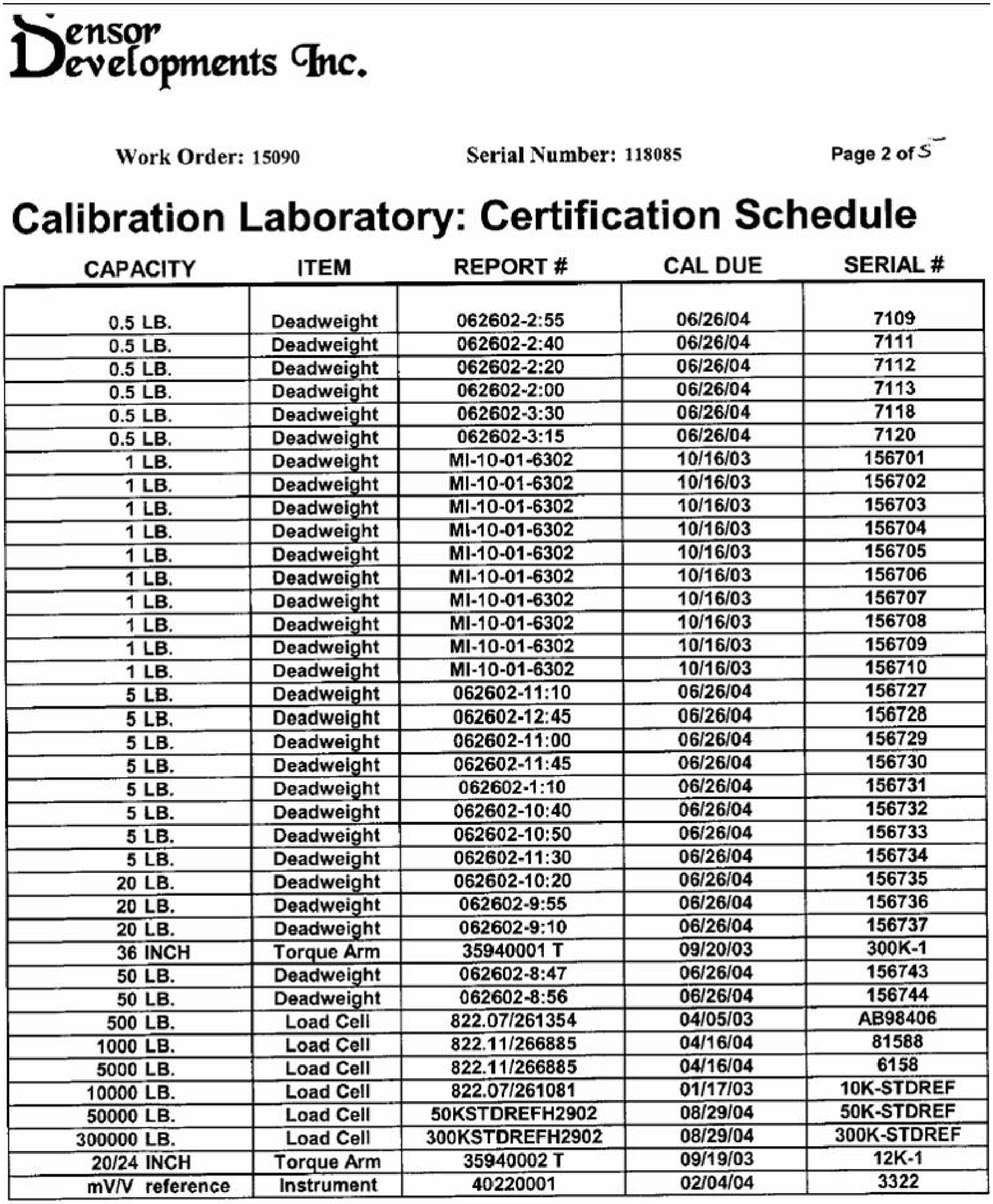
9/18/02
Kevin Gregory
Calibration Technician
Date

9/18/02
Brian Gohs
Senior Calibration Technician
Date

i0 West Silver Bell Road
P.O. Box 290
Orion, MI 48359

service@sendev.com
sales@sendev.com
www.sendev.com

Phone: 248.391.3000
888.Sensor1
Fax: 248.391.0107



Sensor Developments Inc.

Work Order: 15090 **Serial Number:** 118085 **Page 2 of** 5

Calibration Laboratory: Certification Schedule

CAPACITY	ITEM	REPORT #	CAL DUE	SERIAL #
0.5 LB.	Deadweight	062602-2:55	06/26/04	7109
0.5 LB.	Deadweight	062602-2:40	06/26/04	7111
0.5 LB.	Deadweight	062602-2:20	06/26/04	7112
0.5 LB.	Deadweight	062602-2:00	06/26/04	7113
0.5 LB.	Deadweight	062602-3:30	06/26/04	7118
0.5 LB.	Deadweight	062602-3:15	06/26/04	7120
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156701
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156702
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156703
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156704
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156705
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156706
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156707
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156708
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156709
1 LB.	Deadweight	MI-10-01-6302	10/16/03	156710
5 LB.	Deadweight	062602-11:10	06/26/04	156727
5 LB.	Deadweight	062602-12:45	06/26/04	156728
5 LB.	Deadweight	062602-11:00	06/26/04	156729
5 LB.	Deadweight	062602-11:45	06/26/04	156730
5 LB.	Deadweight	062602-1:10	06/26/04	156731
5 LB.	Deadweight	062602-10:40	06/26/04	156732
5 LB.	Deadweight	062602-10:50	06/26/04	156733
5 LB.	Deadweight	062602-11:30	06/26/04	156734
20 LB.	Deadweight	062602-10:20	06/26/04	156735
20 LB.	Deadweight	062602-9:55	06/26/04	156736
20 LB.	Deadweight	062602-9:10	06/26/04	156737
36 INCH	Torque Arm	35940001 T	09/20/03	300K-1
50 LB.	Deadweight	062602-8:47	06/26/04	156743
50 LB.	Deadweight	062602-8:56	06/26/04	156744
500 LB.	Load Cell	822.07/261354	04/05/03	AB98406
1000 LB.	Load Cell	822.11/266885	04/16/04	81588
5000 LB.	Load Cell	822.11/266885	04/16/04	6158
10000 LB.	Load Cell	822.07/261081	01/17/03	10K-STDREF
50000 LB.	Load Cell	50KSTDREFH2902	08/29/04	50K-STDREF
300000 LB.	Load Cell	300KSTDREFH2902	08/29/04	300K-STDREF
20/24 INCH	Torque Arm	35940002 T	09/19/03	12K-1
mV/V reference	Instrument	40220001	02/04/04	3322

SENSOR DEVELOPMENTS INC.
BOX 290
Lake Orion, MI 48361
(248) 391-3000

CALIBRATION DATA SHEET

Description of Calibration: TENSION

SDI Serial No.: 118085

Date: 09-18-2002

FS Capacity: 10000 Lbf

LOAD	OUTPUTS (mV/V)				DEVIATIONS		
	ASCENDING	DESCENDING	AVERAGE	BF/0	N/L	HYS	BF/0
0	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00
1000	0.1942	0.1939	0.1940	0.1931	0.07	-0.02	0.05
2000	0.3881	0.3875	0.3878	0.3863	0.13	-0.03	0.09
3000	0.5816	0.5809	0.5813	0.5794	0.17	-0.04	0.11
4000	0.7749	0.7741	0.7745	0.7726	0.19	-0.04	0.12
5000	0.9679	0.9670	0.9674	0.9657	0.20	-0.04	0.12
6000	1.1605	1.1597	1.1601	1.1589	0.19	-0.04	0.10
7000	1.3529	1.3521	1.3525	1.3520	0.17	-0.04	0.06
8000	1.5449	1.5444	1.5446	1.5451	0.13	-0.03	0.02
9000	1.7366	1.7363	1.7365	1.7383	0.07	-0.02	-0.05
10000	1.9281	1.9281	1.9281	1.9314	0.00	0.00	-0.12

Shunt Cal Data:

Value (OHMS)	Across	Produces mV/V	Simulated Signal of: Lbf(Term)	(BF/0)
60K	- EXCITE & - SIGNAL	2.8947	15013.2	14987.2
120K	- EXCITE & - SIGNAL	1.4514	7527.9	7514.8
60K	+ EXCITE & - SIGNAL	-2.9025	-15053.6	-15027.5
120K	+ EXCITE & - SIGNAL	-1.4558	-7550.4	-7537.3

Load may be computed using this equation: Load = (K1 + K2*Output)*Output
Where Load is in Lbf & Output is in mV/V

CURVE	K1	K2
Ascending	5145.4555	21.29740
Descending	5154.6203	16.54403
Average	5150.0379	18.92072
Terminal	5145.4555	0.00000
Best Fit/0	5177.5225	0.00000

Bridge Resistance (OHMS):

Excitation	700
Signal	699

SENSOR DEVELOPMENTS INC.
BOX 290
Lake Orion, MI 48361
(248) 391-3000

CALIBRATION DATA SHEET

Description of Calibration: COMPRESSION

SDI Serial No.: 118085

Date: 09-18-2002

FS Capacity:-10000 Lbf

LOAD	OUTPUTS (mV/V)				DEVIATIONS		
	ASCENDING	DESCENDING	AVERAGE	BF/0	N/L	HYS	BF/0
0	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00
-1000	-0.1937	-0.1928	-0.1933	-0.1943	-0.04	-0.05	-0.05
-2000	-0.3876	-0.3860	-0.3868	-0.3887	-0.07	-0.08	-0.09
-3000	-0.5816	-0.5796	-0.5806	-0.5830	-0.09	-0.11	-0.11
-4000	-0.7759	-0.7735	-0.7747	-0.7773	-0.11	-0.12	-0.12
-5000	-0.9703	-0.9678	-0.9690	-0.9717	-0.11	-0.13	-0.11
-6000	-1.1648	-1.1625	-1.1637	-1.1660	-0.11	-0.12	-0.09
-7000	-1.3596	-1.3575	-1.3585	-1.3603	-0.09	-0.11	-0.06
-8000	-1.5545	-1.5529	-1.5537	-1.5547	-0.07	-0.08	-0.02
-9000	-1.7496	-1.7487	-1.7491	-1.7490	-0.04	-0.05	0.04
10000	-1.9448	-1.9448	-1.9448	-1.9433	-0.00	0.00	0.12

Shunt Cal Data:

Value (OHMS)	Across	Produces Simulated Signal of: mV/V	Lbf (Term)	(BF/0)
60K	- EXCITE & - SIGNAL	2.8946	14883.7	14895.1
120K	- EXCITE & - SIGNAL	1.4567	7490.2	7495.9
60K	+ EXCITE & - SIGNAL	-2.8972	-14896.9	-14908.3
120K	+ EXCITE & - SIGNAL	-1.4505	-7458.4	-7464.1

Load may be computed using this equation: Load = (K1 + K2*Output)*Output
Where Load is in Lbf & Output is in mV/V

CURVE	K1	K2
Ascending	5164.4880	11.61871
Descending	5190.5709	25.03019
Average	5177.5295	18.32445
Terminal	5164.4880	0.00000
Best Fit/0	5145.8213	0.00000

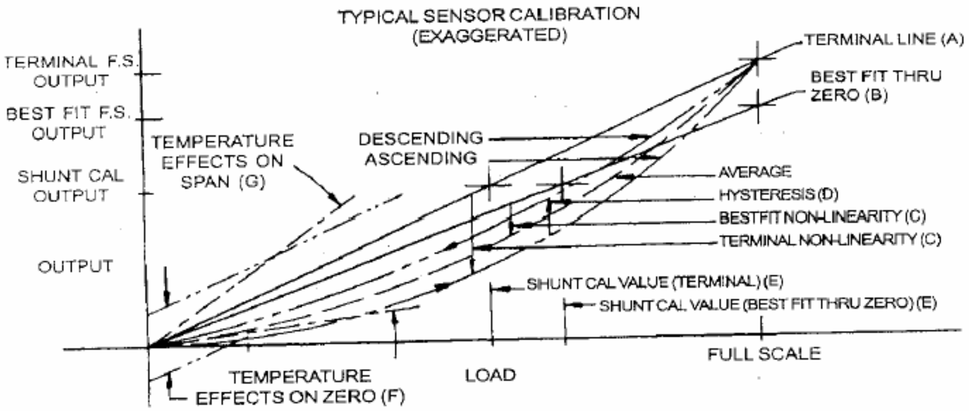
Bridge Resistance (OHMS):

Excitation	700
Signal	699

GENERAL CALIBRATION PROCEDURE:

Sensor is load cycled thru operating range to develop stable hysteresis loop. Known loads are then applied to sensor by means of dead weights or reference load cell in ascending and descending increments with RAW DATA recorded. RAW DATA is then best fit to second degree equations which describe the ascending, descending and average calibration curves. These equations are incrementally solved to generate theoretical sensor outputs at various loads as shown under REDUCED DATA. Terminal non-linearity is computed from deviations of ascending theoretical data from straight line connecting zero and full scale (FS) ascending readings. Terminal hysteresis is computed from differences between descending and ascending theoretical data. Best fit thru zero non-linearity is computed from deviations of average theoretical data from straight line thru zero (0) with a slope determined to produce minimum deviations with average theoretical data.

IN GENERAL - BEST FIT THRU ZERO OUTPUTS AND BEST FIT THRU ZERO SHUNT CAL values should be used when sensor is assumed to have linear characteristics. If instrumentation capable of correcting second order non-linearity is used, AVERAGE OUTPUTS and SHUNT CAL OUTPUT values should be used.



WARRANTY:

All Sensor Developments Inc. products are warranted to be free from defects in material and workmanship for one year from the date of shipment from our factory. Our obligation is limited to repairing, or at our option, replacing products and components which, on our verification, prove to be defective, at our factory in Orion, Michigan. Sensor Developments Inc. shall not be liable for installation charges, for damages from delay or loss of use, or other indirect or consequential damages of any kind. Sensor Developments Inc. extends this warranty only upon proper use of the products in the application for which intended and does not cover products which have been modified without Sensor Developments' approval or which have been subjected to unusual physical or electrical stress, or upon which the original identification marks have been removed or altered.

Whenever the design of the equipment to be furnished or the system in which it is to be incorporated originate with the buyer, manufacturer's warranty is limited specifically to matters relating to furnishing of equipment free of defects in material and workmanship and assumes no responsibility for implied warranties of fitness for purpose or use.

Transportation charges for material shipped to our factory for warranty repair are to be paid by the shipper. Sensor Developments Inc. will return items repaired or replaced under warranty prepaid. No item shall be returned for repair without prior authorization from Sensor Developments Inc.

RVIT-15-60/RVIT-15-120I RVITs

DC-Operated Rotary Variable Inductance Transducers

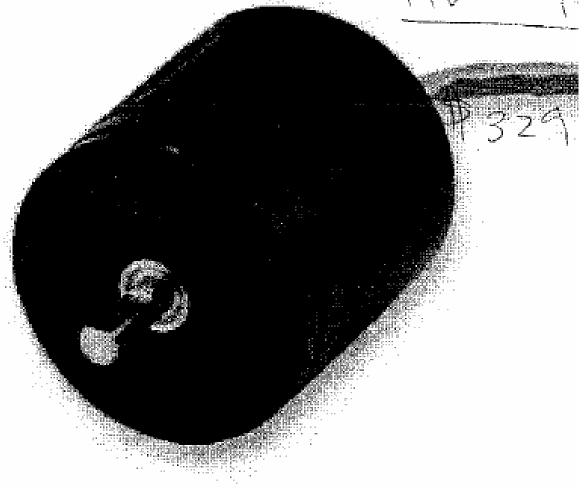
$319
+10 Ship

$329

RVITs are DC operated noncontact rotary transducers. The RVIT proprietary design incorporates a set of printed circuit coils and a conductive spoiler to achieve superior performance and low cost. During operation, the conductive spoiler rotates with the transducer shaft, altering the magnetic field generated by the printed circuit coils. The resulting unbalance is precisely measured using a patented autoplexing circuit. This signal is then converted to a linear DC output signal that is directly proportional to the angle of the rotor shaft.

The predominantly digital circuit is very resistant to environmental disturbances and is ideally compatible for use with most digital electronics. For original equipment manufacturers who desire a microprocessor interface, a pulse width modulated output can be supplied as a special order option. Other specialized options for volume applications include, regulated single or bipolar excitation, extended operating ranges, and custom calibration.

RVITs are available with a choice of standard face mounting or optional four hole flange mounting. A shaft seal is available with flange mounting for applications where contamination is critical. RVITs offer wide operating temperature range, infinite resolution, and a virtually infinite rotational life.

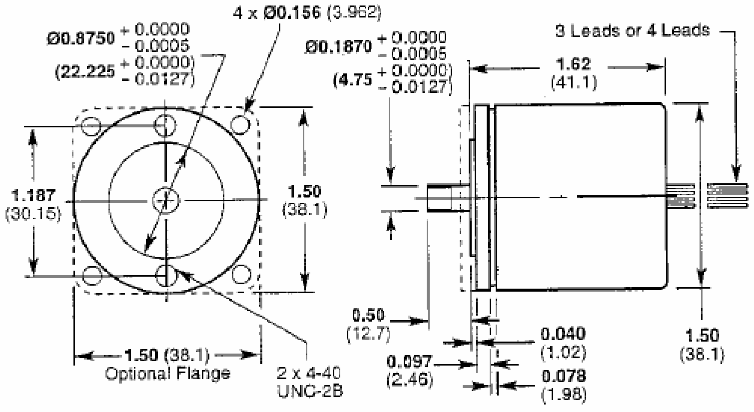


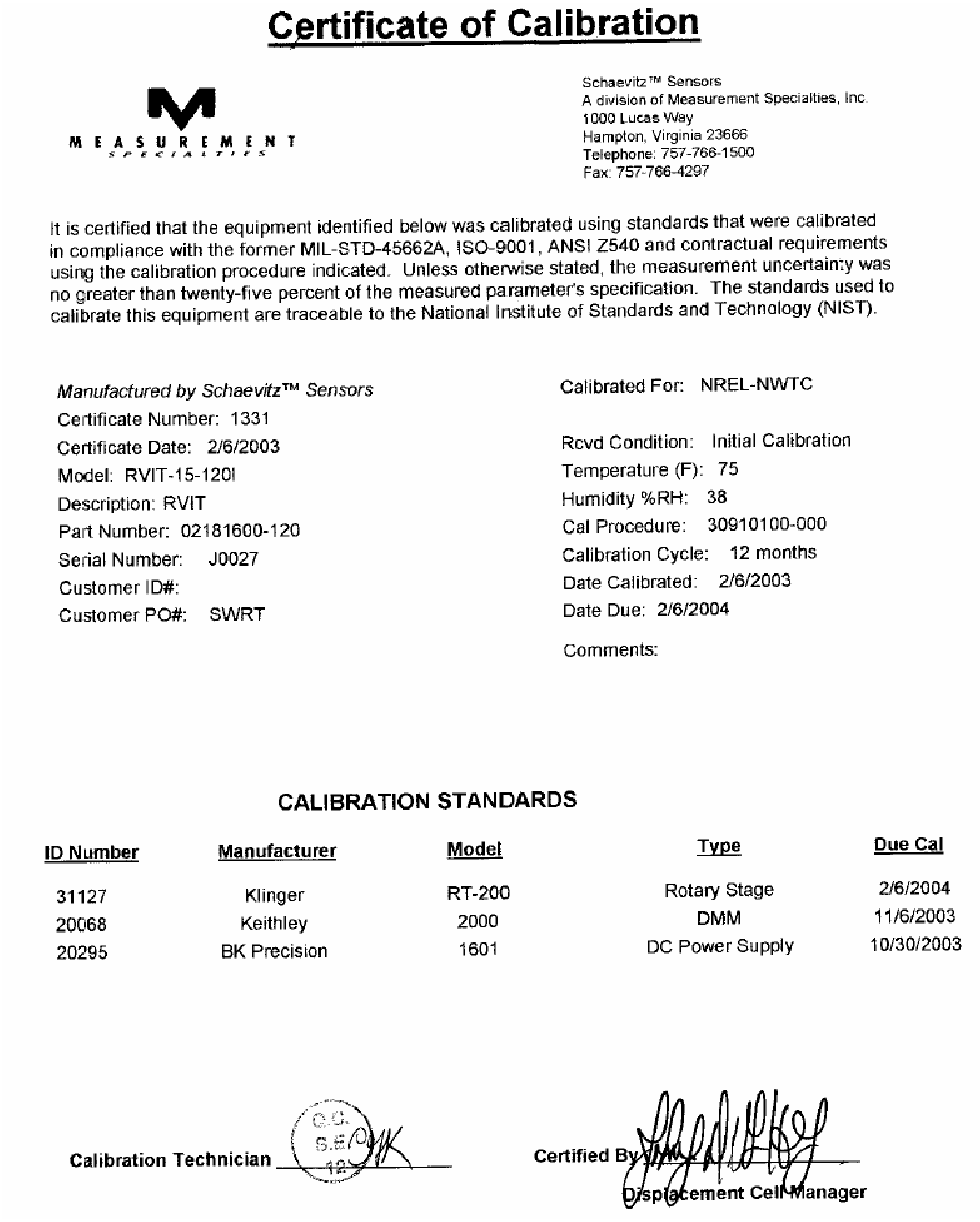
RVIT-15-60 and RVIT-15-120I

The RVIT-15-60 and RVIT-15-120I rotary transducers are available in a variety of versions which provide a range of supply and output configurations. Calibrated outputs of ±3 VDC and 4-20 mA offer ideal flexibility for specialized OEM designs where unique power supply and interfacing requirements exist. Other specialized ranges, internal regulation and custom calibrated outputs are available for special order.

The standard RVIT 15-60 transducer emulates a potentiometer in that any change in input voltage results in a proportional change in output voltage. Although this output is ratiometric, the RVIT-15-60 offers a considerably higher scale factor of 50 mV per degree over an extended range of ±60 degrees. In addition, the noncontact design of the RVIT provides virtually infinite rotational life and extremely high accuracy of ±0.25% FS.

Dimensions in (mm)





Certificate of Calibration

MEASUREMENT SPECIALTIES

Schaevitz™ Sensors
A division of Measurement Specialties, Inc.
1000 Lucas Way
Hampton, Virginia 23666
Telephone: 757-766-1500
Fax: 757-766-4297

It is certified that the equipment identified below was calibrated using standards that were calibrated in compliance with the former MIL-STD-45662A, ISO-9001, ANSI Z540 and contractual requirements using the calibration procedure indicated. Unless otherwise stated, the measurement uncertainty was no greater than twenty-five percent of the measured parameter's specification. The standards used to calibrate this equipment are traceable to the National Institute of Standards and Technology (NIST).

Manufactured by Schaevitz™ Sensors
Certificate Number: 1331
Certificate Date: 2/6/2003
Model: RVIT-15-120I
Description: RVIT
Part Number: 02181600-120
Serial Number: J0027
Customer ID#:
Customer PO#: SWRT

Calibrated For: NREL-NWTC

Rcvd Condition: Initial Calibration
Temperature (F): 75
Humidity %RH: 38
Cal Procedure: 30910100-000
Calibration Cycle: 12 months
Date Calibrated: 2/6/2003
Date Due: 2/6/2004

Comments:

CALIBRATION STANDARDS

ID Number	Manufacturer	Model	Type	Due Cal
31127	Klinger	RT-200	Rotary Stage	2/6/2004
20068	Keithley	2000	DMM	11/6/2003
20295	BK Precision	1601	DC Power Supply	10/30/2003

Calibration Technician Q.C. S.E. 12

Certified By
Displacement Cell Manager

NREL METROLOGY LABORATORY

Traceability Statement

Test Instrument: Transducer

Model # : P-143E S/N : 9100896

Calibration Date: 11/15/2001 Due Date: 11/15/2003

Environmental Conditions:

1. Temperature: 23 °C, ± 1 °C
2. Relative Humidity: 40%, ± 10%

Traceability:

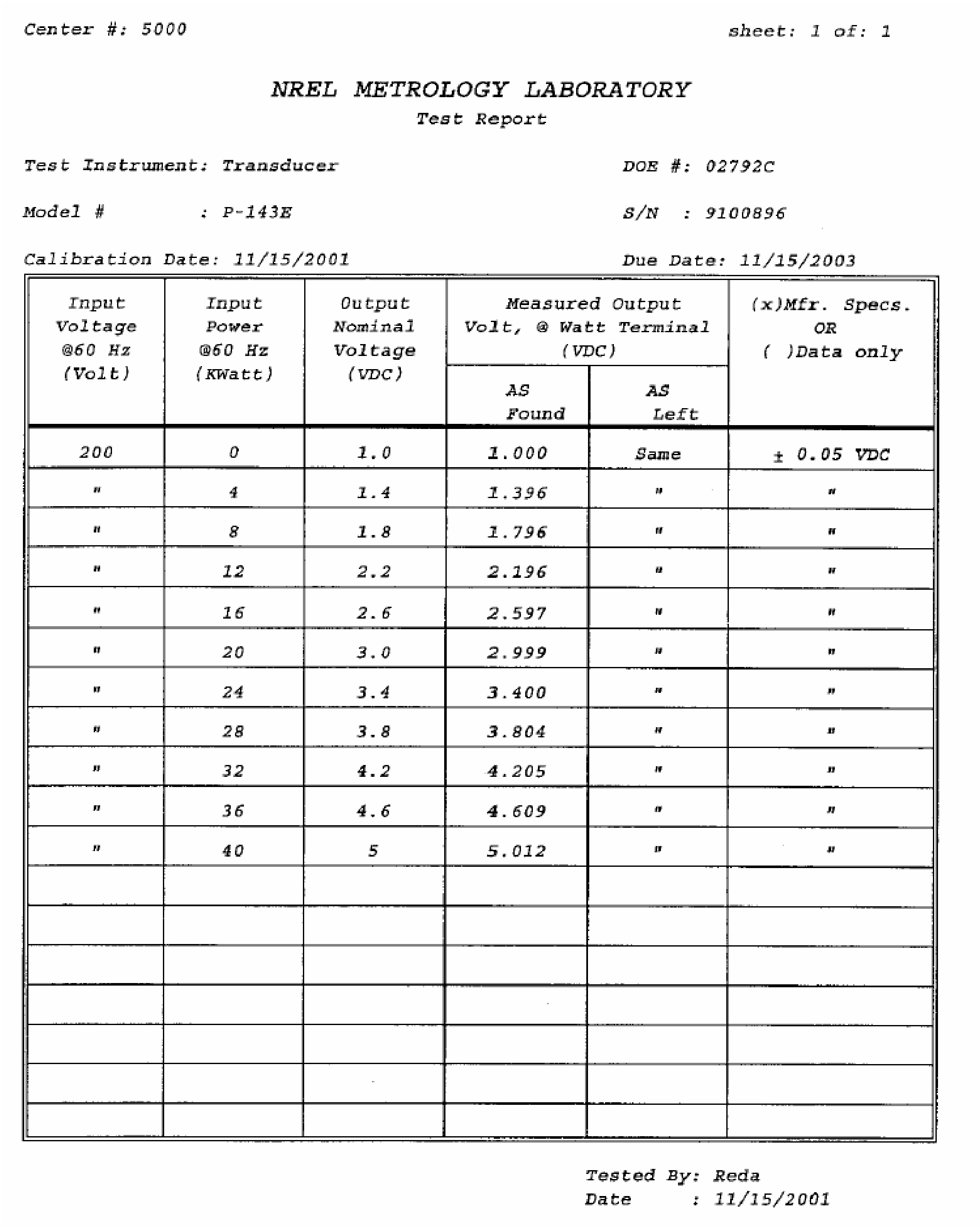
Calibration was performed using the following standards:

1. HP34401A, DOE# 02301C
2. Rotek 8000A, DOE# 126314
3. Rotek8000A, DOE#126314-01

The standards are calibrated and traceable to the National Institute of Standards and Technology (NIST). Test Uncertainty Ratio (TUR) > 4

Ibrahim Reda
I. Reda
Senior Metrology Engineer

Date: 11/15/2001



Center #: 5000 sheet: 1 of: 1

NREL METROLOGY LABORATORY

Test Report

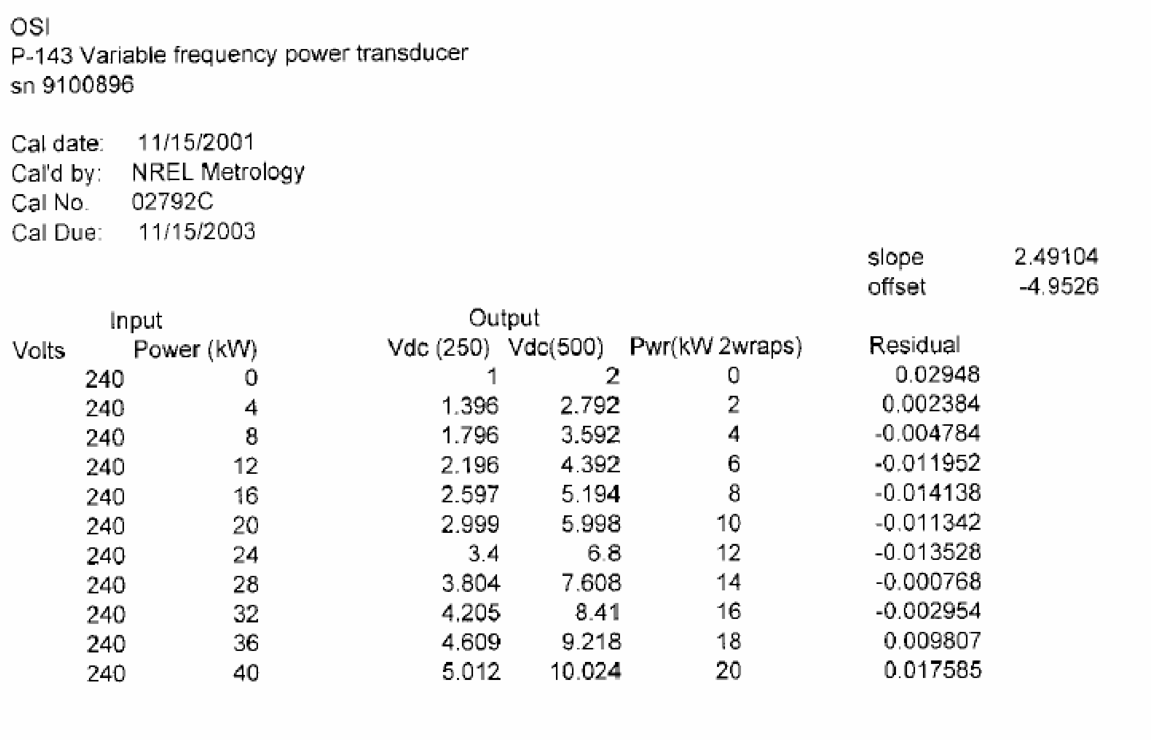
Test Instrument: Transducer DOE #: 02792C

Model # : P-143E S/N : 9100896

Calibration Date: 11/15/2001 Due Date: 11/15/2003

Input Voltage @60 Hz (Volt)	Input Power @60 Hz (KWatt)	Output Nominal Voltage (VDC)	Measured Output Volt, @ Watt Terminal (VDC)		(x)Mfr. Specs. OR ( )Data only
			AS Found	AS Left	
200	0	1.0	1.000	Same	± 0.05 VDC
"	4	1.4	1.396	"	"
"	8	1.8	1.796	"	"
"	12	2.2	2.196	"	"
"	16	2.6	2.597	"	"
"	20	3.0	2.999	"	"
"	24	3.4	3.400	"	"
"	28	3.8	3.804	"	"
"	32	4.2	4.205	"	"
"	36	4.6	4.609	"	"
"	40	5	5.012	"	"

Tested By: Reda
Date : 11/15/2001



OSI
P-143 Variable frequency power transducer
sn 9100896

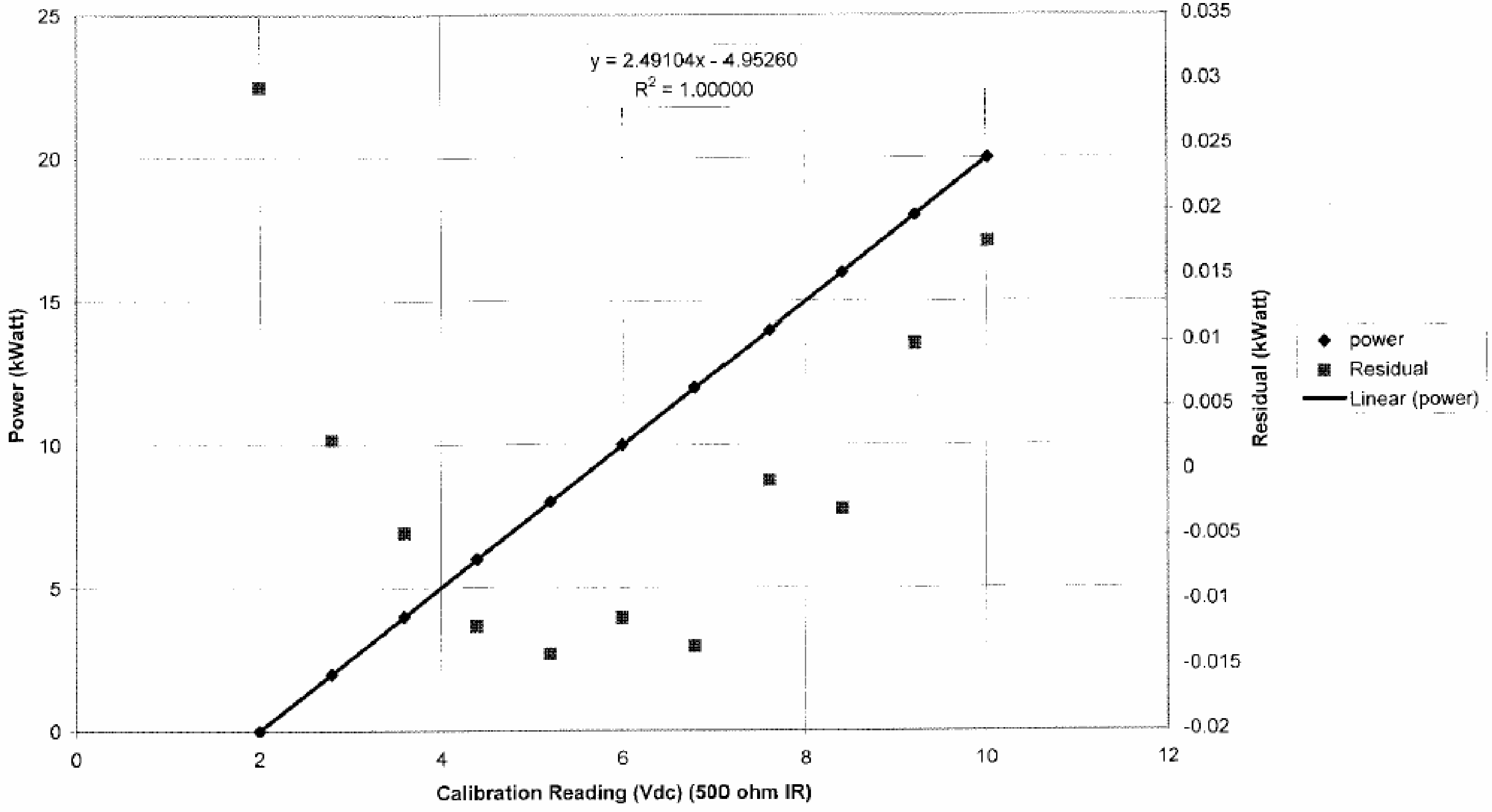
Cal date: 11/15/2001
Cal'd by: NREL Metrology
Cal No. 02792C
Cal Due: 11/15/2003

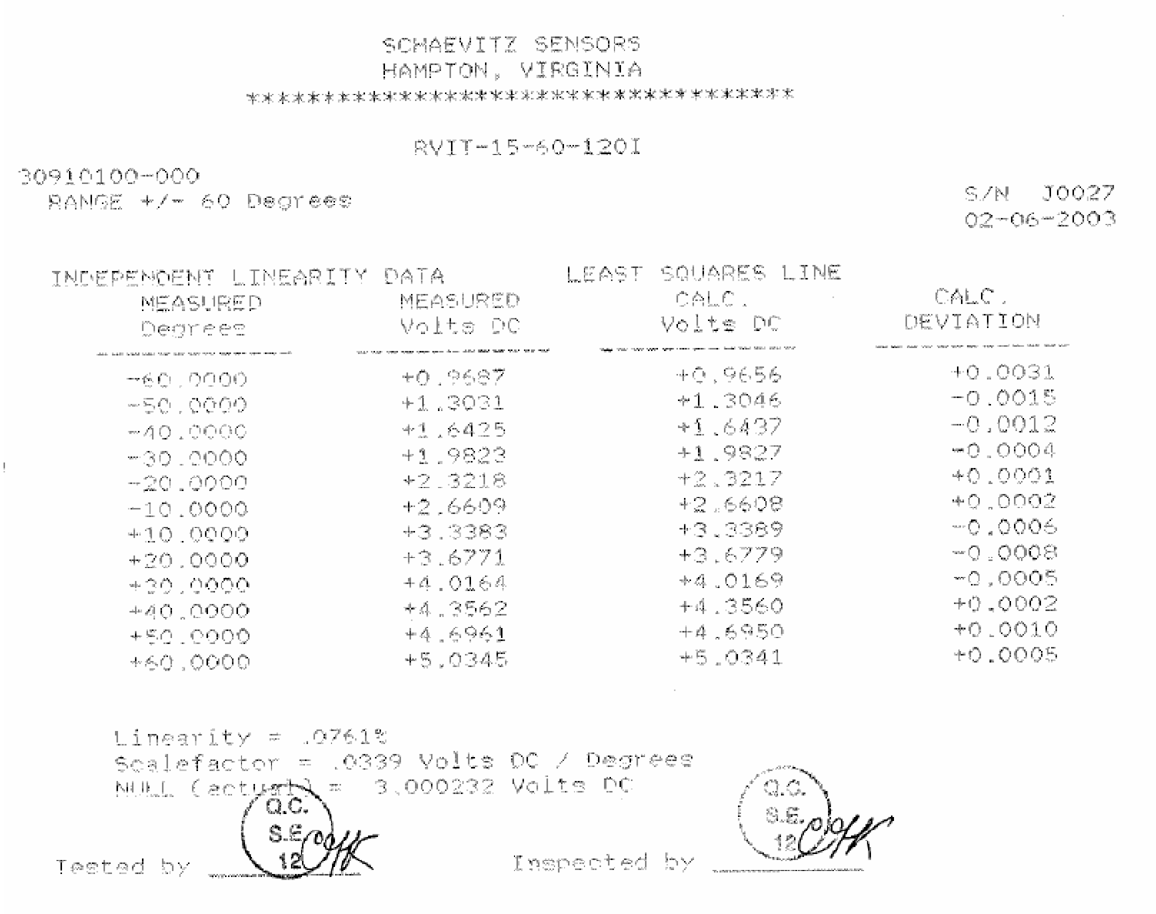
slope 2.49104
offset -4.9526

Input		Output			
Volts	Power (kW)	Vdc (250)	Vdc(500)	Pwr(kW 2wraps)	Residual
240	0	1	2	0	0.02948
240	4	1.396	2.792	2	0.002384
240	8	1.796	3.592	4	-0.004784
240	12	2.196	4.392	6	-0.011952
240	16	2.597	5.194	8	-0.014138
240	20	2.999	5.998	10	-0.011342
240	24	3.4	6.8	12	-0.013528
240	28	3.804	7.608	14	-0.000768
240	32	4.205	8.41	16	-0.002954
240	36	4.609	9.218	18	0.009807
240	40	5.012	10.024	20	0.017585

CTs with two wraps

NWTC Instrument Calibrations
OSI Power Transducer
P-143E s/n 9100896 - November 15, 2001





SCHAEVITZ SENSORS
HAMPTON, VIRGINIA
****

RVIT-15-60-120I

30910100-000
RANGE +/- 60 Degrees

S/N J0027
02-06-2003

INDEPENDENT LINEARITY DATA		LEAST SQUARES LINE	
MEASURED Degrees	MEASURED Volts DC	CALC. Volts DC	CALC. DEVIATION
-60.0000	+0.9687	+0.9656	+0.0031
-50.0000	+1.3031	+1.3046	-0.0015
-40.0000	+1.6425	+1.6437	-0.0012
-30.0000	+1.9823	+1.9827	-0.0004
-20.0000	+2.3218	+2.3217	+0.0001
-10.0000	+2.6609	+2.6608	+0.0002
+10.0000	+3.3383	+3.3389	-0.0006
+20.0000	+3.6771	+3.6779	-0.0008
+30.0000	+4.0164	+4.0169	-0.0005
+40.0000	+4.3562	+4.3560	+0.0002
+50.0000	+4.6961	+4.6950	+0.0010
+60.0000	+5.0345	+5.0341	+0.0005

Linearity = .0761%
Scalefactor = .0339 Volts DC / Degrees
NULL (actual) = 3.000232 Volts DC

Tested by Q.C. S.E. 12

Inspected by Q.C. S.E. 12

Determination of Zeroes

Special slow roll tests were conducted to provide data to determine zeros, or offsets, for the blade bending moment gages. Slow rolls were conducted by letting the turbine coast at speeds from 2 to 10 RPM. Signals were plotted against the hub azimuth position and the average signal was taken as the zero for all signals. Zeroes for the shaft sensor, which is located on the non-rotating shaft, were obtained by taking "zero" files in low wind conditions with the turbine not rotating. Zeros for the blade and shaft gages were calculated from data taken as close as possible in time to the testing.

Special 360° tests were conducted in a similar manner to the slow rolls to provide data to determine zeros for the tower top load cells. In this case the turbine brake was applied and the turbine was yawed a full 360° for several revolutions. The signals were then averaged over the yaw position and the average signal was used as the zero.

Validation of blade signals was conducted by taking the slopes and offsets from the calibrations and running the CRUNCH program to calculate final engineering units for a slow roll. This data was then compared to data developed from the turbine geometry, such as the mass and center of gravity, taking into account the 8° tilt of the turbine.

Table C-4. Calculated Offsets for Flap and Edge Bending

SH3052 Blade Properties and Calculated Edge and Flap Bending								
Gravity		9.8	m/sec^2			Offset Flap Blade	43.63	N-m
Xcg		2.0328	m			Offset Edge Blade	9.4331	N-m
Blade Mass		16.1	kg			Offset In plane	3E-14	N-m
Tilt Angle		8	degrees	0.13962634	rad	Offset Out of plane	44.638	N-m
Pitch Angle		12.2	degrees	0.212930169	rad			
Coning Angle		0	degrees	0	rad			

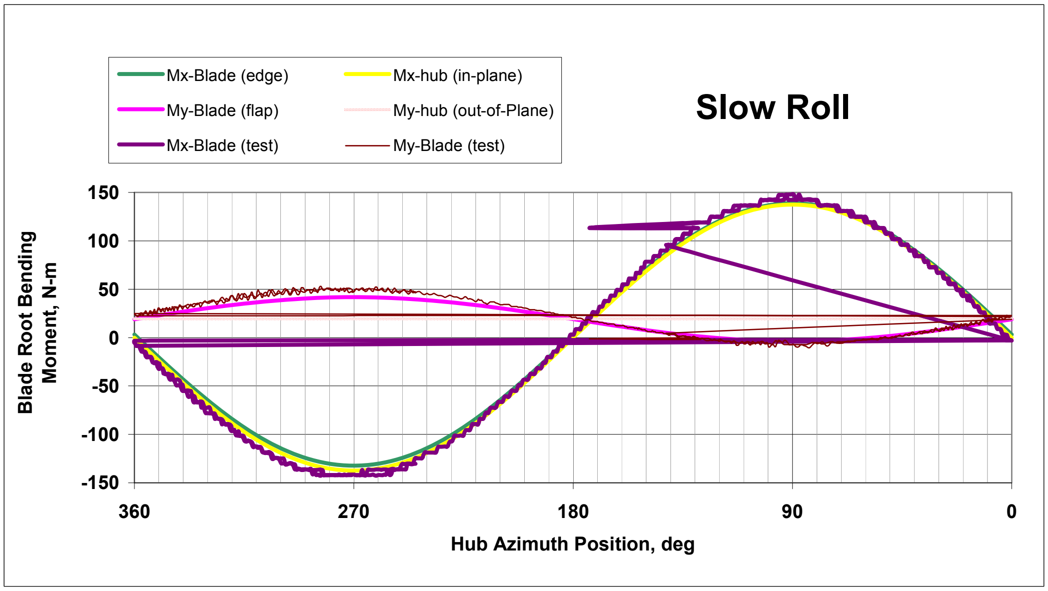


Figure C-4. Comparison of calculated and measured flap and edge bending moments for a slow roll

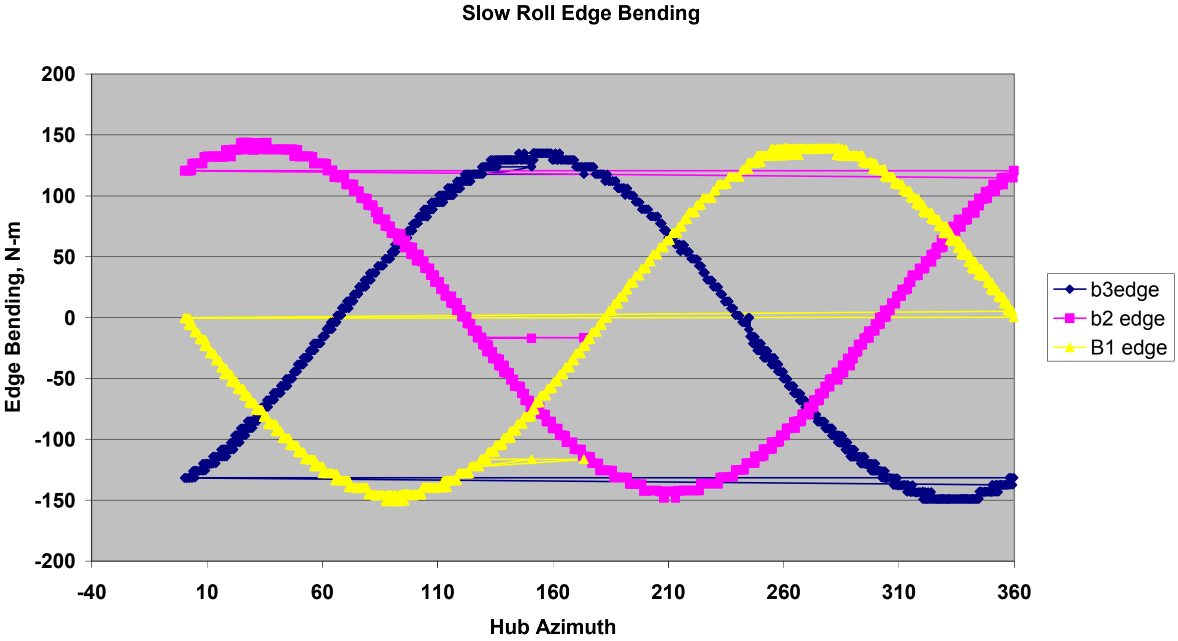


Figure C-5. Edge bending moments versus hub azimuth

As mentioned previously, CRUNCH was used for all 10-minute DAT files to calculate the minimums, means, maximums, and standard deviations of all parameters. The data was also analyzed in several other ways including power spectral densities (PSDs), azimuth averaging, and time series data. Shown below is an example of the azimuth averaged data.

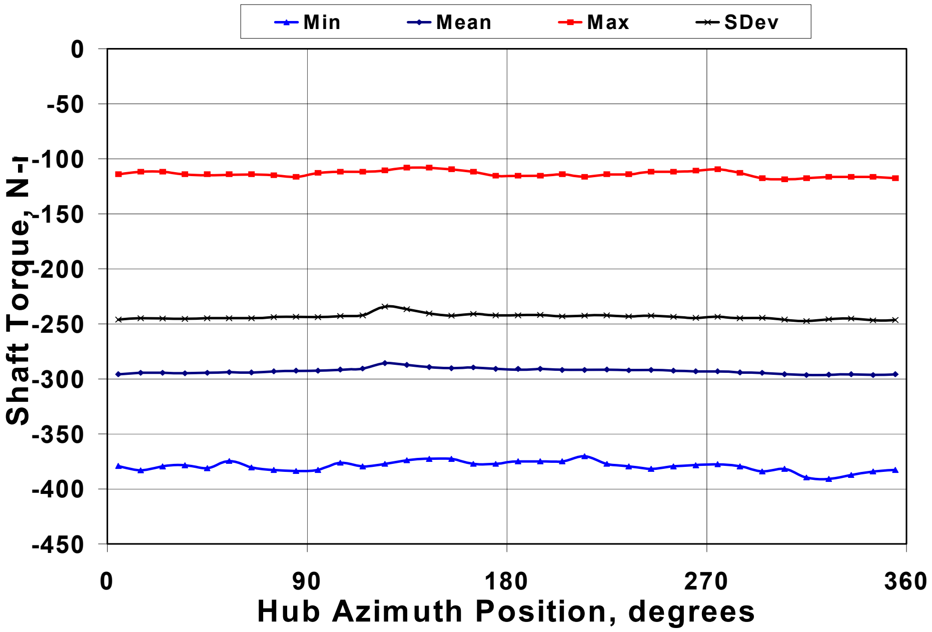


Figure C-6. Azimuth averaged torque signal

Turbine Control

Hysteresis in the inverter controller software for torque control resulted in some scatter in the torque-RPM curves. Fig. C-7 shows a plot of torque versus RPM for Configuration C in bins of 5 RPM for 10-minute data sets. The coordinate system conforms to the IEC standard, so torque is shown as negative because the turbine rotates counterclockwise. For model validation data sets, scatter in the torque-RPM curve is undesirable, so for each configuration a limited number of data sets were taken with a fixed resistance load that reduced the torque-RPM scatter. Fig. C-8 shows a plot of torque versus RPM from one 10-minute data set for Configuration C and a fixed resistance load.

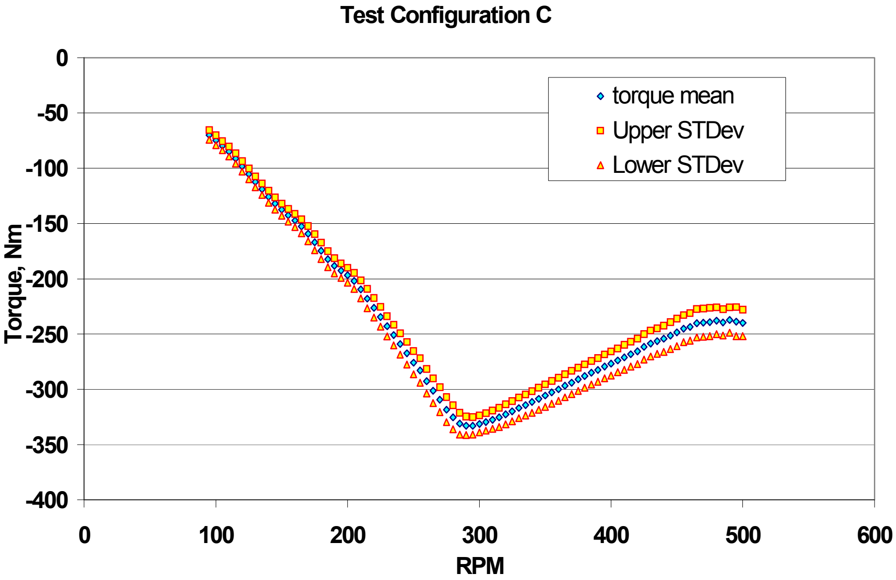


Figure C-7. Torque RPM curve for Configuration C

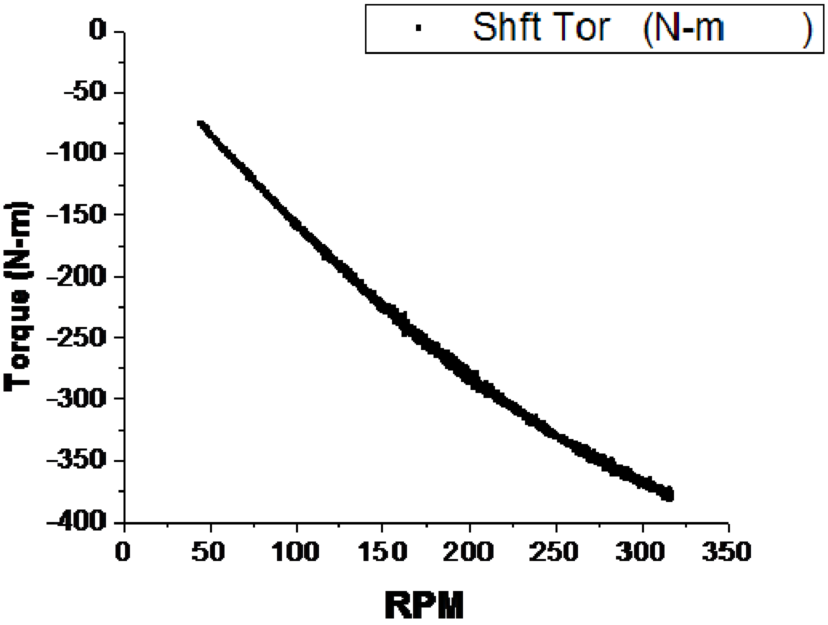


Figure C-8. Torque versus RPM

Appendix D – Data Set Summary

Table D-1 shows a data set summary for Configuration A, along with the 10-minute means for each data set for rotor speed (RotorSpd), furl, electric power (Epower), wind speed (SonicWSMet), and yaw error. There were problems with the yaw sensor after power outages during high winds at the NWTC, because it could not be reset until the winds became calm. Hence, there are several data sets without yaw position and yaw error for these data sets is blank in the Table D-1. Similarly, some blade signals are missing from the data sets due to strain gauge failure. Parameters that are not available are summarized at the end of each data set summary. There are additional data sets available in the data archive that are not included in the summary table below. These data sets have periods of at least two minutes when the inverter is off-line, mostly due to a low wind inverter cut-out. Most of these data sets have low wind speeds.

Table D-1. Configuration A Data Set Summary with Selected 10- Minute Means

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-01-19-06-03-36S	211.2	0.4	4.1	10.5	19.8
SWRT2004-01-19-06-42-36S	264.8	0.8	6.7	12.4	20.5
SWRT2004-01-19-07-11-34S	217.3	0.3	4.2	10.5	19.6
SWRT2004-01-19-07-40-28S	200.5	0.3	3.6	9.8	19.0
SWRT2004-01-19-09-00-17S	195.4	0.3	3.3	9.6	19.1
SWRT2004-01-19-09-29-08S	231.0	0.6	4.9	11.1	20.9
SWRT2004-01-22-00-50-16S	148.5	0.3	1.6	7.8	
SWRT2004-01-22-03-51-54S	150.1	0.3	1.6	7.6	
SWRT2004-01-22-04-31-04S	158.8	0.3	1.8	8.3	
SWRT2004-01-22-04-59-58S	163.1	0.3	1.9	8.0	
SWRT2004-01-22-05-28-58S	166.6	0.3	2.0	8.2	
SWRT2004-01-22-06-38-33S	130.7	0.3	1.1	6.7	
SWRT2004-01-22-17-51-36S	177.0	0.4	2.6	8.9	18.7
SWRT2004-01-22-21-23-44S	155.2	0.3	1.7	8.0	18.6
SWRT2004-01-23-00-55-44S	220.1	0.4	4.4	10.9	19.5
SWRT2004-01-23-01-24-26S	256.6	0.9	6.0	12.2	19.5
SWRT2004-01-23-01-53-09S	325.3	2.9	8.5	15.0	20.2
SWRT2004-01-23-04-54-37S	181.5	0.3	2.6	9.0	19.4
SWRT2004-01-23-05-23-21S	233.4	0.6	5.0	11.7	19.3
SWRT2004-01-23-06-02-17S	253.6	0.9	5.8	12.1	19.5
SWRT2004-01-23-06-30-59S	272.6	2.0	6.5	13.4	18.4
SWRT2004-01-23-06-59-42S	269.6	1.8	6.5	12.6	20.2
SWRT2004-01-23-07-28-23S	246.9	1.7	5.4	11.7	18.8
SWRT2004-01-23-07-57-08S	252.2	1.4	5.4	11.9	18.8
SWRT2004-01-23-09-05-04S	337.1	12.4	8.5	16.3	24.5
SWRT2004-01-23-09-33-57S	347.7	6.5	8.8	16.4	21.7
SWRT2004-01-23-10-02-41S	274.0	2.2	6.5	12.9	20.1

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-01-23-10-41-38S	204.5	0.4	3.7	10.1	17.8
SWRT2004-01-23-11-10-18S	270.2	1.6	6.3	12.7	19.7
SWRT2004-01-23-11-40-15S	263.9	0.8	6.2	12.6	19.8
SWRT2004-01-23-12-08-57S	230.8	0.4	4.7	11.6	20.2
SWRT2004-01-23-12-37-40S	204.6	0.4	3.6	10.4	17.6
SWRT2004-01-23-13-06-23S	268.8	1.5	6.5	13.2	18.9
SWRT2004-01-23-13-35-10S	264.1	0.8	6.3	13.1	18.2
SWRT2004-01-23-14-03-52S	238.5	1.4	5.1	12.2	18.4
SWRT2004-01-23-14-32-33S	285.5	2.2	7.3	14.0	19.2
SWRT2004-01-25-02-33-53S	223.6	0.6	4.6	11.1	18.8
SWRT2004-01-25-03-02-35S	270.0	1.7	6.6	12.6	19.8
SWRT2004-01-25-03-51-41S	357.2	10.0	9.3	16.4	22.8
SWRT2004-01-25-04-20-24S	236.9	0.6	5.1	11.9	17.2
SWRT2004-01-25-04-49-06S	257.3	1.0	6.2	12.7	19.3
SWRT2004-01-25-05-17-47S	284.0	1.0	7.3	14.1	19.5
SWRT2004-01-25-05-46-31S	224.6	0.5	4.6	11.5	17.4
SWRT2004-01-25-06-55-59S	180.5	0.4	2.7	9.6	19.1
SWRT2004-01-25-10-48-43S	173.0	0.3	2.3	8.9	17.4
SWRT2004-01-25-11-17-29S	189.3	0.4	3.0	9.6	18.6
SWRT2004-01-25-11-46-15S	237.9	0.4	5.3	11.7	19.3
SWRT2004-01-26-17-09-58S	228.9	0.5	5.0	11.1	
SWRT2004-01-26-17-59-09S	250.3	2.1	5.8	11.9	
SWRT2004-01-26-18-27-44S	282.1	6.7	6.9	13.3	
SWRT2004-01-26-18-56-31S	234.5	2.4	5.2	11.3	
SWRT2004-01-26-19-55-49S	252.7	1.5	5.9	12.2	
SWRT2004-01-26-20-24-33S	227.0	0.5	4.8	11.0	
SWRT2004-01-26-20-53-18S	234.2	0.5	5.2	11.3	
SWRT2004-01-26-21-21-59S	274.8	1.8	7.2	12.9	
SWRT2004-01-27-01-43-10S	186.2	0.4	3.1	9.2	
SWRT2004-01-27-02-22-12S	237.5	0.9	5.3	11.6	
SWRT2004-01-27-02-50-58S	247.9	1.5	5.9	12.4	
SWRT2004-01-27-03-19-47S	322.2	11.7	8.6	15.2	
SWRT2004-01-27-03-48-33S	264.6	1.7	6.7	12.6	
SWRT2004-01-27-04-17-20S	233.7	1.2	5.1	11.2	
SWRT2004-01-27-04-46-03S	292.8	5.4	7.5	13.7	
SWRT2004-01-27-05-24-59S	223.6	1.3	4.5	10.8	
SWRT2004-01-27-05-53-46S	243.3	7.3	5.5	12.1	
SWRT2004-01-27-06-22-34S	203.3	0.8	3.7	9.9	23.3

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-01-27-09-44-46S	223.6	1.0	4.5	11.0	19.1
SWRT2004-01-27-10-13-29S	317.6	12.1	8.2	15.4	
SWRT2004-01-27-10-42-15S	314.0	10.5	8.2	15.1	
SWRT2004-01-27-11-32-32S	324.4	25.7	8.3	16.5	
SWRT2004-01-27-12-11-25S	230.2	0.4	4.9	11.1	
SWRT2004-01-27-12-40-06S	273.0	2.5	6.7	12.9	
SWRT2004-01-27-13-49-27S	176.6	0.3	2.5	8.9	
SWRT2004-01-27-14-28-22S	162.9	0.2	1.9	8.6	
SWRT2004-01-27-14-57-02S	183.8	0.3	2.7	9.5	
SWRT2004-01-27-17-07-12S	200.6	0.3	3.6	10.2	
SWRT2004-01-27-17-35-56S	226.5	0.4	4.6	11.5	
SWRT2004-01-27-18-04-41S	236.0	2.8	5.0	11.6	
SWRT2004-01-27-18-33-30S	269.0	1.2	6.7	13.3	
SWRT2004-01-27-19-02-13S	268.9	0.7	6.5	13.2	
SWRT2004-01-27-19-30-59S	204.6	0.3	3.6	10.3	
SWRT2004-01-27-20-28-28S	249.7	0.4	5.9	12.6	
SWRT2004-01-27-21-07-27S	210.7	0.3	4.0	10.7	
SWRT2004-01-28-14-42-22S	239.9	0.6	5.2	11.4	
SWRT2004-01-29-00-28-18S	225.3	0.4	4.6	11.2	
SWRT2004-01-29-00-57-06S	215.6	0.4	4.1	10.6	
SWRT2004-01-29-01-25-51S	258.0	0.6	6.3	12.3	
SWRT2004-01-29-01-54-39S	251.6	0.5	6.0	12.1	
SWRT2004-01-29-02-23-26S	275.5	2.1	6.8	13.0	
SWRT2004-01-29-02-52-16S	234.9	0.4	5.2	11.6	
SWRT2004-01-29-03-21-04S	257.2	0.5	6.1	12.6	
SWRT2004-01-29-05-41-56S	154.2	0.3	1.8	8.0	
SWRT2004-01-29-11-39-02S	212.6	0.1	4.0	10.5	
SWRT2004-01-29-12-07-36S	194.0	0.0	3.2	10.0	
SWRT2004-01-29-14-08-10S	163.0	0.0	2.0	8.6	
SWRT2004-01-29-15-07-30S	205.1	0.0	3.7	10.4	
SWRT2004-01-29-17-47-01S	229.6	0.2	4.8	11.2	
SWRT2004-01-29-18-15-45S	240.9	0.3	5.3	11.6	
SWRT2004-01-29-18-44-30S	261.4	0.8	6.3	12.3	
SWRT2004-01-29-19-13-18S	274.8	1.1	7.0	12.8	
SWRT2004-01-29-19-52-14S	251.3	0.9	5.7	12.1	
SWRT2004-01-29-20-21-02S	291.0	4.5	7.3	13.4	
SWRT2004-01-29-20-49-46S	273.8	2.1	6.8	12.8	
SWRT2004-01-29-22-19-34S	267.7	3.6	6.5	12.9	
SWRT2004-01-29-22-58-34S	300.4	7.8	7.8	14.5	

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-01-29-23-27-22S	256.3	3.7	5.8	12.1	
SWRT2004-01-29-23-56-07S	284.2	2.6	6.9	13.2	
SWRT2004-01-30-00-24-53S	342.3	12.8	8.8	16.1	
SWRT2004-01-30-00-53-39S	312.1	2.9	8.3	14.3	
SWRT2004-01-30-01-22-25S	334.9	6.5	8.6	15.3	
SWRT2004-01-30-01-51-13S	285.2	4.7	7.0	13.3	
SWRT2004-01-30-02-19-59S	284.1	0.7	7.0	13.2	
SWRT2004-01-30-02-48-47S	261.6	1.1	5.9	12.3	
SWRT2004-01-30-06-41-23S	218.0	0.2	4.4	10.5	
SWRT2004-01-30-07-10-09S	164.2	0.1	2.2	8.6	
SWRT2004-01-30-10-33-47S	203.9	0.1	3.7	10.1	
SWRT2004-01-30-11-14-13S	171.6	0.0	2.2	8.8	
SWRT2004-01-30-12-28-42S	178.8	0.0	2.5	9.1	
SWRT2004-01-30-12-57-32S	172.6	0.0	2.3	8.8	
SWRT2004-01-30-14-07-05S	212.6	0.1	4.1	10.4	
SWRT2004-01-31-09-19-56S	154.0	0.1	1.7	8.4	
SWRT2004-02-15-02-51-56S	196.7	0.1	3.5	9.8	18.3
SWRT2004-02-15-03-20-46S	187.7	0.0	2.9	9.5	18.6
SWRT2004-02-15-03-49-38S	177.3	0.0	2.6	8.8	18.3
SWRT2004-02-15-04-59-04S	252.2	1.5	5.8	12.0	20.3
SWRT2004-02-15-05-38-03S	243.2	0.2	5.6	11.9	19.4
SWRT2004-02-15-20-33-56S	160.3	0.0	2.0	8.2	18.6
SWRT2004-02-15-22-34-24S	164.9	0.1	2.1	8.6	18.9
SWRT2004-02-16-01-35-58S	192.1	0.1	3.3	9.9	18.5
SWRT2004-02-16-02-55-42S	301.1	3.6	7.9	14.0	20.2
SWRT2004-02-16-04-05-09S	323.0	6.7	8.6	15.1	22.2
SWRT2004-02-16-04-33-56S	318.3	5.8	8.5	15.1	21.4
SWRT2004-02-16-05-02-40S	323.2	5.6	8.5	15.2	22.1
SWRT2004-02-16-05-31-23S	231.9	0.3	5.0	11.2	19.7
SWRT2004-02-16-07-01-20S	214.8	0.2	4.1	10.5	19.7
SWRT2004-02-16-07-40-16S	255.5	0.5	6.0	12.4	19.1
SWRT2004-02-16-08-09-01S	272.3	2.1	6.6	12.6	20.5
SWRT2004-02-16-08-37-48S	210.1	0.1	3.8	10.3	19.0
SWRT2004-02-16-09-06-34S	215.1	0.2	4.2	10.3	18.6
SWRT2004-02-16-09-45-30S	252.5	0.5	5.9	11.9	19.5
SWRT2004-02-16-10-14-15S	241.4	0.4	5.4	11.7	19.6
SWRT2004-02-16-11-13-33S	197.1	0.1	3.4	9.9	19.0
SWRT2004-02-16-12-02-43S	179.4	0.0	2.6	9.3	18.6
SWRT2004-02-16-12-31-30S	206.6	0.2	3.9	10.1	18.1

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-02-16-13-20-36S	198.3	0.0	3.4	9.8	18.7
SWRT2004-02-17-11-34-39S	272.9	0.8	6.7	12.7	19.8
SWRT2004-02-17-12-03-28S	289.7	0.9	7.5	14.0	20.1
SWRT2004-02-17-12-32-11S	172.9	-0.1	2.4	8.7	19.7
SWRT2004-02-18-04-39-18S	211.8	0.3	4.0	10.6	17.5
SWRT2004-02-29-17-33-43S	204.3	0.0	3.8	10.0	19.1
SWRT2004-02-29-21-16-04S	251.1	0.8	5.9	12.0	20.0
SWRT2004-02-29-21-44-55S	304.5	3.6	7.7	14.1	20.3
SWRT2004-02-29-22-13-44S	311.1	3.9	8.3	14.1	21.0
SWRT2004-02-29-22-42-30S	253.1	2.5	5.6	12.0	19.0
SWRT2004-02-29-23-11-18S	175.6	0.4	2.6	9.0	17.0
SWRT2004-02-29-23-50-23S	208.4	0.3	3.8	10.3	18.0
SWRT2004-03-01-00-19-12S	284.5	5.2	7.0	13.2	21.1
SWRT2004-03-01-00-47-58S	265.9	2.3	6.3	12.7	19.1
SWRT2004-03-01-01-16-44S	305.2	23.1	8.0	15.5	
SWRT2004-03-01-01-45-33S	309.8	10.9	7.7	14.7	23.9
SWRT2004-03-01-02-14-23S	302.4	5.6	7.7	14.0	20.9
SWRT2004-03-01-02-43-12S	259.3	1.2	6.0	12.1	19.8
SWRT2004-03-01-03-12-03S	212.0	0.1	4.0	10.4	18.5
SWRT2004-03-01-03-51-06S	231.1	0.2	5.0	11.2	19.7
SWRT2004-03-01-04-30-07S	201.2	0.5	3.5	9.9	18.6
SWRT2004-03-01-05-09-09S	207.6	0.1	3.9	10.2	18.7
SWRT2004-03-01-05-38-01S	212.7	0.1	4.0	10.2	18.4
SWRT2004-03-01-06-17-01S	196.6	0.0	3.3	9.8	19.1
SWRT2004-03-01-07-06-14S	166.9	0.0	2.1	8.5	18.0
SWRT2004-03-09-18-46-28S	191.6	0.1	3.0	9.6	19.1
SWRT2004-03-09-19-15-14S	218.1	0.1	4.1	10.8	19.1
SWRT2004-03-09-22-47-20S	216.2	0.3	4.2	11.0	19.1
SWRT2004-03-09-23-16-03S	366.0	9.6	9.3	17.2	23.3
SWRT2004-03-09-23-44-50S	252.0	0.7	5.7	12.5	20.5
SWRT2004-03-19-10-34-16S	189.4	0.2	2.9	9.5	
SWRT2004-03-19-13-25-15S	183.4	0.2	2.7	9.5	
SWRT2004-03-19-13-53-46S	150.1	0.1	1.5	7.9	
SWRT2004-03-23-17-56-19S	313.7	2.4	8.3	14.5	
SWRT2004-03-26-22-06-56S	280.1	1.7	7.0	13.5	20.6
SWRT2004-03-26-22-35-34S	293.8	1.0	7.7	14.0	21.0
SWRT2004-03-26-23-04-20S	275.9	0.8	7.1	13.3	20.5
SWRT2004-03-27-04-38-47S	302.6	3.8	7.8	14.0	21.4
SWRT2004-03-27-05-07-30S	362.8	20.4	9.6	17.3	

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-03-27-15-16-52S	271.4	4.4	6.7	12.8	21.6
SWRT2004-03-27-16-56-53S	285.1	3.3	7.5	13.7	21.1
SWRT2004-03-27-17-25-36S	315.7	5.7	8.4	14.4	22.4
SWRT2004-03-27-17-55-37S	279.4	10.4	7.0	13.8	24.7

Table D-2. Configuration A Data Sets with No B3 Edge Bending Moment

Files w/B3 mean edge deleted
SWRT2004-03-19-13-25-15S
SWRT2004-03-19-13-53-46S
SWRT2004-03-23-17-56-19S
SWRT2004-03-26-22-06-56S
SWRT2004-03-26-22-35-34S
SWRT2004-03-26-23-04-20S
SWRT2004-03-27-04-38-47S
SWRT2004-03-27-05-07-30S
Files w/ B3 edge min deleted
SWRT2004-03-19-13-25-15S
SWRT2004-03-19-13-53-46S
SWRT2004-03-26-22-06-56S
SWRT2004-03-26-22-35-34S
SWRT2004-03-26-23-04-20S
Files w/B3 edge Max deleted
SWRT2004-01-23-09-33-57S
SWRT2004-01-23-14-32-33S
SWRT2004-01-25-03-51-41S
SWRT2004-01-27-10-42-15S
SWRT2004-01-30-00-24-53S
SWRT2004-01-30-01-22-25S
SWRT2004-03-01-02-14-23S
SWRT2004-03-09-23-16-03S
SWRT2004-03-19-13-25-15S
SWRT2004-03-19-13-53-46S
SWRT2004-03-23-17-56-19S
SWRT2004-03-26-22-06-56S
SWRT2004-03-26-22-35-34S
SWRT2004-03-26-23-04-20S
SWRT2004-03-27-04-38-47S
SWRT2004-03-27-05-07-30S
SWRT2004-03-27-15-16-52S
SWRT2004-03-27-16-56-53S
SWRT2004-03-27-17-25-36S
SWRT2004-03-27-17-55-37S

Both B1 edge and flap and B2 edge and flap signals are deleted for Configuration A because of strain gauge failures. Table D-3 lists the data sets that have the B3 flap channel deleted.

Table D-3. Configuration A Files with B3 Flap Deleted

B3 flap mean channels deleted
SWRT2004-02-16-08-37-48S
SWRT2004-03-19-13-25-15S
SWRT2004-03-19-13-53-46S
SWRT2004-03-23-17-56-19S
SWRT2004-03-26-22-06-56S
SWRT2004-03-26-22-35-34S
SWRT2004-03-26-23-04-20S
SWRT2004-03-27-04-38-47S
SWRT2004-03-27-05-07-30S

Meteorological data from the M2 tower was not available for all of the SWRT data sets. Shown below in Table D-4 are those data sets from Configuration A that do not have inflow parameters.

Table D-4. Configuration A Files Without Inflow Parameters

Config A no Inflow
SWRT2004-01-19-07-40-28S
SWRT2004-01-22-00-50-16S
SWRT2004-01-22-03-51-54S
SWRT2004-01-22-04-31-04S
SWRT2004-01-22-04-59-58S
SWRT2004-01-22-05-28-58S
SWRT2004-01-22-06-38-33S
SWRT2004-01-25-11-46-15S
SWRT2004-01-26-18-27-44S
SWRT2004-01-26-18-56-31S
SWRT2004-01-26-19-55-49S
SWRT2004-01-26-20-24-33S
SWRT2004-01-26-21-21-59S
SWRT2004-01-27-01-43-10S
SWRT2004-01-27-02-22-12S
SWRT2004-01-27-02-50-58S
SWRT2004-01-27-03-19-47S
SWRT2004-01-27-03-48-33S
SWRT2004-01-27-04-46-03S
SWRT2004-01-27-10-13-29S
SWRT2004-01-27-10-42-15S
SWRT2004-01-27-11-32-32S
SWRT2004-01-27-12-11-25S
SWRT2004-01-27-13-49-27S
SWRT2004-01-27-14-57-02S
SWRT2004-01-27-17-07-12S
SWRT2004-01-27-17-35-56S
SWRT2004-01-27-18-04-41S
SWRT2004-01-27-18-33-30S
SWRT2004-01-27-19-02-13S
SWRT2004-01-27-19-30-59S
SWRT2004-01-27-20-28-28S

Config A no Inflow		
SWRT2004-01-27-21-07-27S		
SWRT2004-01-28-14-42-22S		
SWRT2004-01-29-00-28-18S		
SWRT2004-01-29-00-57-06S		
SWRT2004-01-29-01-54-39S		
SWRT2004-01-29-02-23-26S		
SWRT2004-01-29-02-52-16S		
SWRT2004-01-29-03-21-04S		
SWRT2004-01-29-11-39-02S		
SWRT2004-01-29-12-07-36S		
SWRT2004-01-29-14-08-10S		
SWRT2004-01-29-17-47-01S		
SWRT2004-01-29-18-15-45S		
SWRT2004-01-29-18-44-30S		
SWRT2004-01-29-19-13-18S		
SWRT2004-01-29-19-52-14S		
SWRT2004-01-29-22-19-34S		
SWRT2004-01-29-22-58-34S		
SWRT2004-01-29-23-27-22S		
SWRT2004-01-30-00-24-53S		
SWRT2004-01-30-00-53-39S		
SWRT2004-01-30-01-22-25S		
SWRT2004-01-30-01-51-13S		
SWRT2004-01-30-02-19-59S		
SWRT2004-01-30-06-41-23S		
SWRT2004-01-30-07-10-09S		
SWRT2004-01-30-10-33-47S		
SWRT2004-01-30-11-14-13S		
SWRT2004-01-30-12-57-32S		
SWRT2004-01-30-14-07-05S		
SWRT2004-01-31-09-19-56S		
SWRT2004-03-01-01-16-44S		
SWRT2004-03-19-10-34-16S		
SWRT2004-03-19-13-25-15S		
SWRT2004-03-19-13-53-46S		
SWRT2004-03-27-05-07-30S		

Table D-5 shows a data set summary for Configuration B, along with the 10-minute means for each file for rotor speed (RotorSpd), furl, electric power (Epower), wind speed (SonicWSMet), and yaw error. There were problems with the yaw sensor after power outages during high winds at the NWTC, because it could not be reset until the winds became calm. Hence there are several data sets without yaw position and yaw error for these data sets is blank in the Table D-5. There are no blade edge or flap signals available for Configuration B due to strain gages reaching their rated cycles and failing. There are additional data sets available in the data archive that are not included in the summary table below. These data sets have periods of at least two minutes when the inverter is off-line, mostly due to a low wind inverter cut-out. Hence, most of these data sets are low wind files.

Table D-5. Configuration B Data Set Summary with Selected 10- Minute Means

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-04-05-12-24-53S	133.8	0.4	1.3	8.4	
SWRT2004-04-05-12-53-52S	155.9	0.2	1.8	8.2	
SWRT2004-04-05-13-22-44S	151.4	0.2	1.7	8.2	
SWRT2004-04-05-14-48-06S	136.7	0.1	1.3	7.3	
SWRT2004-04-05-15-45-48S	141.2	0.1	1.4	6.8	
SWRT2004-04-05-17-41-12S	177.6	0.2	2.5	9.2	
SWRT2004-04-05-18-10-08S	171.2	0.2	2.3	9.3	
SWRT2004-04-05-18-39-03S	154.4	0.2	1.7	7.9	
SWRT2004-04-05-19-08-01S	214.2	0.3	4.1	10.9	
SWRT2004-04-05-19-36-58S	231.5	0.3	5.0	11.5	
SWRT2004-04-05-20-05-51S	193.5	0.3	3.2	9.8	13.3
SWRT2004-04-05-20-34-46S	224.9	0.4	4.6	10.8	15.8
SWRT2004-04-05-21-03-47S	165.6	0.2	2.1	8.3	14.7
SWRT2004-04-05-22-01-41S	137.7	0.2	1.3	7.3	13.8
SWRT2004-04-06-01-30-26S	123.1	0.2	1.0	6.6	
SWRT2004-04-06-02-38-19S	114.0	0.2	0.8	6.7	12.6
SWRT2004-04-06-03-17-24S	115.0	0.2	0.8	6.2	9.8
SWRT2004-04-07-07-33-45S	129.4	0.1	1.2	7.0	13.7
SWRT2004-04-07-09-01-56S	119.8	0.1	0.9	6.7	
SWRT2004-04-07-11-46-52S	165.3	0.2	2.1	8.9	
SWRT2004-04-07-12-15-44S	159.3	0.2	1.9	8.8	
SWRT2004-04-07-12-44-49S	167.5	0.2	2.2	9.2	
SWRT2004-04-07-13-13-41S	173.7	0.2	2.3	9.3	
SWRT2004-04-07-14-21-37S	135.0	0.2	1.3	7.2	13.0
SWRT2004-04-07-17-18-13S	127.8	0.2	1.1	6.9	
SWRT2004-04-07-17-47-04S	126.6	0.2	1.0	6.8	
SWRT2004-04-11-21-18-18S	260.9	1.0	6.4	12.7	
SWRT2004-04-11-21-47-18S	221.9	0.4	4.7	11.4	
SWRT2004-04-11-22-16-12S	281.2	0.7	7.6	13.9	
SWRT2004-04-11-22-45-04S	177.5	0.3	2.8	9.2	
SWRT2004-04-11-23-13-57S	199.5	0.4	3.5	10.3	
SWRT2004-04-14-07-54-59S	220.2	0.2	4.4	11.2	15.0
SWRT2004-04-15-05-04-59S	236.6	0.4	5.3	11.4	14.5
SWRT2004-04-18-08-03-32S	226.7	0.4	4.8	10.8	14.7
SWRT2004-04-18-08-32-30S	281.0	0.7	7.4	13.1	15.9
SWRT2004-04-18-09-01-23S	262.7	0.4	6.4	12.4	15.3
SWRT2004-04-18-10-31-21S	228.3	0.3	5.0	11.4	14.8
SWRT2004-04-18-11-30-43S	258.6	0.5	6.0	12.3	14.4
SWRT2004-04-18-12-28-25S	383.0	15.7	9.6	18.2	
SWRT2004-04-18-12-57-13S	369.0	5.7	9.3	17.6	17.5
SWRT2004-04-18-13-54-59S	340.9	12.9	8.6	16.8	22.3
SWRT2004-04-18-14-23-56S	324.3	1.6	8.4	14.7	15.8
SWRT2004-04-18-17-31-57S	374.6	18.4	9.3	18.9	
SWRT2004-04-18-18-00-48S	391.3	9.6	9.5	18.6	19.6
SWRT2004-04-18-18-29-46S	387.7	7.6	9.6	17.9	18.3
SWRT2004-04-18-19-37-36S	374.7	9.6	9.4	17.9	19.6
SWRT2004-04-18-20-06-24S	343.0	4.9	8.9	15.8	17.6

Table D-6 shows a data set summary for Configuration C, along with the 10-minute means for each data set for rotor speed (RotorSpd), furl, electric power (Epower), wind speed (SonicWSMet), and yaw error. There were problems with the yaw sensor after power outages during high winds at the NWTC, because it could not be reset until the winds became calm. Hence, there are several data sets without yaw position and for these, yaw error is blank in the Table below. Similarly, there are a few files with bad furl data and they are also shown as blank. Parameters that are not available in certain data sets are summarized at the end of each data set summary. There are additional data sets available in the data archive that are not included in the summary table below. These data sets have periods of at least two minutes when the inverter is off-line, mostly due to a low wind inverter cut-out. Hence, most of these data sets are low wind files.

Table D-6. Configuration C Data Set Summary with Selected 10- Minute Means

File Name	RotorSpd	Furl	Epower	SonicWSMet	yaw error
SWRT2004-04-20-09-39-3	233.3	1.6	4.9	10.5	16.4
SWRT2004-04-20-10-08-3	209.7	0.0	3.9	9.4	16.0
SWRT2004-04-20-11-06-1	181.5	0.0	2.7	8.4	15.3
SWRT2004-04-20-12-03-5	165.3	0.0	2.1	7.7	16.8
SWRT2004-04-20-13-11-4	224.5	0.0	4.6	10.3	16.7
SWRT2004-04-20-13-40-4	217.2	0.0	4.2	10.0	17.3
SWRT2004-04-20-14-09-3	274.6	0.1	7.1	12.3	17.1
SWRT2004-04-20-14-38-4	270.3	0.0	6.5	12.0	
SWRT2004-04-20-14-57-0	261.8	0.1	6.5	11.5	18.1
SWRT2004-04-20-15-54-4	222.6	0.1	4.5	10.0	16.1
SWRT2004-04-20-16-23-4	169.8	0.0	2.4	7.9	17.3
SWRT2004-04-20-16-52-3	320.8	1.7	8.5	13.8	19.5
SWRT2004-04-20-17-21-3	193.4	0.0	3.1	8.7	16.0
SWRT2004-04-20-18-19-1	198.7	0.0	3.2	9.2	16.2
SWRT2004-04-20-18-48-1	285.7	0.1	7.7	12.7	17.4
SWRT2004-04-20-19-17-0	368.0	27.7	9.2	17.6	
SWRT2004-04-20-19-45-5	352.8	3.3	9.1	15.6	21.5
SWRT2004-04-20-20-14-5	289.2	0.3	7.4	13.0	16.9
SWRT2004-04-20-20-43-4	275.5	1.3	6.6	12.0	18.9
SWRT2004-04-20-21-41-2	234.8	0.2	5.0	10.8	16.5
SWRT2004-04-21-01-30-2	157.9	0.1	1.9	7.6	16.7
SWRT2004-04-21-01-59-0	154.3	0.0	1.8	7.6	16.1
SWRT2004-04-21-02-27-5	188.9	0.1	2.9	9.0	15.4
SWRT2004-04-21-02-56-4	198.3	0.1	3.4	9.4	15.4
SWRT2004-04-21-03-25-3	116.4	0.0	0.8	5.8	16.5
SWRT2004-04-21-09-10-0	117.3	0.0	0.9	5.8	
SWRT2004-04-21-09-38-5	154.7	0.0	1.8	7.6	
SWRT2004-04-21-10-20-4	192.0	0.0	3.0	9.3	
SWRT2004-04-21-10-55-0	175.6	0.1	2.5	8.3	
SWRT2004-04-21-11-23-5	187.3	0.1	2.9	9.0	
SWRT2004-04-21-11-52-4	148.4	0.1	1.6	7.1	
SWRT2004-04-21-12-21-3	124.9	0.1	1.0	6.1	
SWRT2004-04-21-13-10-4	126.9	0.1	1.1	6.4	
SWRT2004-04-21-13-39-2	127.3	0.1	1.1	6.5	
SWRT2004-04-21-14-08-2	139.7	0.1	1.4	6.7	
SWRT2004-04-21-14-37-1	120.5	0.1	0.9	5.9	
SWRT2004-04-21-15-06-0	133.9	0.1	1.2	6.6	
SWRT2004-04-21-15-34-5	123.8	0.1	1.0	6.2	
SWRT2004-04-22-16-43-5	171.6	-0.1	2.3	8.8	
SWRT2004-04-22-17-12-4	145.5	-0.1	1.6	7.4	
SWRT2004-04-22-17-41-3	174.3	-0.1	2.4	8.3	
SWRT2004-04-22-18-10-3	170.0	-0.1	2.3	8.2	
SWRT2004-04-22-18-39-2	205.8	-0.1	3.7	9.6	
SWRT2004-04-22-19-08-1	158.6	-0.1	1.9	7.4	
SWRT2004-04-22-19-37-0	153.1	-0.1	1.7	7.7	
SWRT2004-04-22-20-06-0	214.0	-0.1	4.1	9.8	
SWRT2004-04-22-20-34-5	207.4	-0.1	3.8	9.8	
SWRT2004-04-22-21-03-5	180.6	-0.1	2.7	8.6	
SWRT2004-04-22-21-32-4	157.0	-0.1	1.9	7.6	
SWRT2004-04-22-22-01-3	201.7	-0.1	3.5	9.3	
SWRT2004-04-22-22-30-2	183.9	-0.1	2.8	8.6	
SWRT2004-04-22-22-59-2	146.3	-0.1	1.5	7.4	
SWRT2004-04-22-23-48-3	121.7	-0.1	0.9	6.2	
SWRT2004-04-24-15-57-1	257.4	0.0	6.2	11.7	17.3
SWRT2004-04-24-16-26-1	273.7	0.1	6.8	12.2	19.1
SWRT2004-04-24-16-55-0	238.7	0.0	5.3	10.6	17.1
SWRT2004-04-24-17-24-0	146.8	-0.1	1.6	7.0	16.7
SWRT2004-04-25-04-41-3	119.0	0.0	0.9	6.2	
SWRT2004-04-27-03-31-0	147.4	-0.1	1.6	7.2	15.7
SWRT2004-04-27-08-14-2	155.1	-0.1	1.8	7.3	15.0
SWRT2004-04-27-10-11-4	202.0	-0.1	3.5	9.4	15.9
SWRT2004-04-27-10-40-4	220.7	-0.1	4.4	9.9	16.5
SWRT2004-04-27-11-09-4	273.5	0.0	7.0	12.6	16.3
SWRT2004-04-27-14-42-0	195.3	-0.1	3.4	8.9	15.3
SWRT2004-04-27-15-31-2	192.5	-0.1	3.1	9.0	13.6
SWRT2004-04-27-16-00-2	209.2	-0.1	3.9	9.6	14.3

There are several files for Configuration C that have bad torque signals and those are listed below in Table D-7.

Table D-7. Configuration C files with Bad Torque Signal

Files with Bad Torque Signals
SWRT2004-06-02-18-57-46S
SWRT2004-06-03-15-23-57S
SWRT2004-06-03-16-02-57S
SWRT2004-06-04-17-49-33S
SWRT2004-06-06-15-17-54S
SWRT2004-06-06-15-46-41S
SWRT2004-06-06-16-35-56S
SWRT2004-06-06-17-04-41S
SWRT2004-06-06-18-44-51S
SWRT2004-06-06-20-35-09S
SWRT2004-06-06-23-16-27S
SWRT2004-06-07-03-49-47S
SWRT2004-06-07-10-42-57S
SWRT2004-06-07-23-42-22S
SWRT2004-06-08-20-54-06S
SWRT2004-06-08-21-22-55S

Hysteresis in the inverter controller software for torque control resulted in some scatter in the torque-RPM curves. For comparison purposes, a few files were taken with a fixed resistor load. Table D-8 shows those files taken with a fixed resistor load.

Table D-8. Resistor Files

File	Configuration
SWRT2004-03-26-16-46-41S	A
SWRT2004-03-26-17-15-15S	A
SWRT2004-04-01-16-56-32S	B
SWRT2004-04-01-18-17-54	B
SWRT2004-04-01-18-46-50S	B
SWRT2004-04-01-19-44-35S	B
SWRT2004-04-01-21-11-14S	B
SWRT2004-04-01-21-40-06S	B
SWRT2004-04-01-22-09-02S	B
SWRT2004-04-01-22-37-51S	B
SWRT2004-04-02-04-59-53S	B
SWRT2004-04-18-15-34-49S	B
SWRT2004-04-18-16-03-36	B
SWRT2004-04-18-22-50-51S	B
SWRT2004-05-26-12-44-36S	C

Appendix E – Modeling Summary Configurations A and B

Appendix E lists the files used for Configurations A and B (they only differ by the lateral offset of the axis of rotation). Appendix F lists files used for Configuration C.

Appendix E - Files Used for Configurations A and B

AERODYN INPUT FILE:

```
SWRT rotor Config A and B.  Jan., 2004
SI             SysUnits - System of units for used for input and output [must be SI for
FAST] (unquoted string)
BEDDOES        StallMod - Dynamic stall included [BEDDOES or STEADY] (unquoted string)
```

**NO_CM UseCm - Use aerodynamic pitching moment model?
[USE_CM or NO_CM] (unquoted string)**

```
DYNIN          InfModel - Inflow model [DYNIN or EQUIL] (unquoted string)
SWIRL          IndModel - Induction-factor model [NONE or WAKE or SWIRL] (unquoted
string)
0.005          AToler   - Induction-factor tolerance (convergence criteria) (-)
PRANDtl        TLModel  - Tip-loss model (EQUIL only) [PRANDtl, GTECH, or NONE] (unquoted
string)
NONE           HLModel  - Hub-loss model (EQUIL only) [PRANdtl or NONE] (unquoted string)
" //Mongo/ddrive/Data/WindFiles/Turb_A/34m_hub_height/8m_grid/10ms/Seed1/SNWind"   Wind
file (quoted string)
34.6189        Wind reference (hub) height
0.0            TwrShad  - Tower-shadow velocity deficit (-)
9999.9         ShadHWid - Tower-shadow half width (m)
9999.9         T_Shad_Refpt - Tower-shadow reference point (m)
0.99   *******************Air density for Jan04 data
1.5100E-05     KinVisc  - Kinematic air viscosity
1.0000E-03     Time interval for aerodynamic calculations.
4      Number of airfoil files used. Files listed below:
"D:\Data\NREL\SWRT\ADAMSModel_Nov03\AIRFOILS\TailPlate.dat"
"D:\Data\NREL\SWRT\ADAMSModel_Nov03\AIRFOILS\SH3052Mod_AllRe_Hanley.dat"
"D:\Data\NREL\SWRT\ADAMSModel_Nov03\AIRFOILS\SH3052Mod_AllRe_Elem14_Hanley.dat"
"D:\Data\NREL\SWRT\ADAMSModel_Nov03\AIRFOILS\SH3052Mod_AllRe_Elem15_Hanley.dat"
15     BldNodes - Number of blade nodes used for analysis (-)
Rnodes Twist   DR     Chord  File ID Elem Data      RELM and Twist ignored by ADAMS (but
placeholders must be present)
0.3896 0.00    0.1731 0.213  2       NOPRINT
0.5627 0.00    0.1731 0.213  2       PRINT
0.7358 0.00    0.1731 0.213  2       NOPRINT
0.9090 0.00    0.1731 0.213  2       NOPRINT
1.0821 0.00    0.1731 0.213  2       NOPRINT
1.2552 0.00    0.1731 0.213  2       PRINT
1.4284 0.00    0.1731 0.213  2       NOPRINT
1.6015 0.00    0.1731 0.213  2       NOPRINT
1.7746 0.00    0.1731 0.213  2       NOPRINT
1.9478 0.00    0.1731 0.213  2       PRINT
2.1209 0.00    0.1731 0.213  2       NOPRINT
2.2940 0.00    0.1731 0.213  2       NOPRINT
2.4672 0.00    0.1731 0.213  2       NOPRINT
2.6403 1.60    0.1731 0.201  3       PRINT
2.8134 3.20    0.1731 0.181  4       NOPRINT
ReNu
```

Airfoil File SH3052Mod_AllRe_Hanley.dat:

```
SH3052 data from T Hanley XFOIL predictions
Reinterpolated and foilchecked by CH Feb04
3      Number of airfoil tables in this file
0.3    0.5    1.2    Table ID parameter, typically Re in millions
11.0   10.0   9.0    Stall angle (deg)
0      0      0      No longer used, enter zero
0      0      0      No longer used, enter zero
0      0      0      No longer used, enter zero
-10.152 -10.285 -10.251 Zero Cn angle of attack (deg)
6.249  6.261  6.372  Cn slope for zero lift (dimensionless)
```

```
2.307   2.217   2.141   Cn extrapolated to value at positive stall angle of attack
-0.8    -0.8    -0.8    Cn at stall value for negative angle of attack
-3.0    -3.0    -3.0    Angle of attack for minimum CD (deg)
0.0171  0.01335 0.01155 Minimum CD value
-180    0            0.04485    0            0.02745  0           0.054
-170    0.41544      0.1026     0.42561      0.0855   0.42471     0.1116
-160    0.83097      0.2685     0.85122      0.25215  0.84942     0.2772
-150    0.91332      0.5226     0.93285      0.5076   0.93105     0.53055
-140    0.74187      0.83385    0.75375      0.8205   0.75267     0.8409
-130    0.60201      1.16445    0.60903      1.1532   0.6084      1.1703
-120    0.45999      1.47375    0.46368      1.46505  0.46341     1.47825
-110    0.3078       1.72395    0.30942      1.7181   0.30924     1.7271
-100    0.15048      1.88445    0.15084      1.88145  0.15084     1.8861
-90     0            1.935      0            1.935    0           1.935
-80     -0.15048     1.88445    -0.15084     1.88145  -0.15084    1.8861
-70     -0.3078      1.72395    -0.30942     1.7181   -0.30924    1.7271
-60     -0.45999     1.47375    -0.46368     1.46505  -0.46341    1.47825
-50     -0.60201     1.16445    -0.60903     1.1532   -0.6084     1.1703
-40     -0.74187     0.83385    -0.75375     0.8205   -0.75267    0.8409
-30     -1.0148      0.3484     -1.0365      0.3384   -1.0345     0.3537
-20     -0.7899      0.1969     -0.7974      0.1880   -0.7912     0.1996
-10     -0.0575      0.1260     -0.0260      0.1165   -0.0133     0.1212
-5      0.3891       0.0298     0.4589       0.0218   0.4812      0.0184
-4      0.5716       0.0232     0.5877       0.0196   0.5967      0.0174
-3      0.6950       0.0228     0.7100       0.0178   0.7187      0.0154
-2      0.7940       0.0246     0.8094       0.0188   0.8212      0.0158
-1      0.8946       0.0254     0.9087       0.0198   0.9219      0.0166
0       0.9932       0.0262     1.0072       0.0206   1.0216      0.0172
1       1.0899       0.0270     1.1038       0.0214   1.1195      0.0182
2       1.1838       0.0282     1.1981       0.0226   1.2155      0.0192
3       1.2741       0.0296     1.2896       0.0238   1.3091      0.0204
4       1.3608       0.0314     1.3780       0.0254   1.4001      0.0218
5       1.4429       0.0334     1.4621       0.0272   1.4875      0.0234
6       1.5190       0.0358     1.5411       0.0294   1.5691      0.0254
7       1.5857       0.0386     1.6109       0.0322   1.6397      0.0288
8       1.6325       0.0424     1.6631       0.0360   1.6947      0.0332
9       1.6392       0.0463     1.6697       0.0407   1.6715      0.0407
10      1.6247       0.0517     1.6497       0.0485   1.6126      0.0535
11      1.5964       0.0617     1.5840       0.0639   1.5701      0.0660
12      1.5398       0.0778     1.4960       0.0867   1.5398      0.0782
13      1.4550       0.1037     1.4337       0.1094   1.4956      0.0952
14      1.3557       0.1382     1.3788       0.1328   1.4424      0.1157
15      1.2786       0.1707     1.3242       0.1579   1.3777      0.1419
16      1.2196       0.1991     1.2683       0.1841   1.3114      0.1705
17      1.1720       0.2242     1.2147       0.2105   1.2577      0.1958
18      1.1271       0.2479     1.1626       0.2368   1.2062      0.2207
19      1.0907       0.2654     1.1153       0.2609   1.1591      0.2436
20      1.1479       0.2723     1.1557       0.2777   1.1974      0.2640
21      1.2120       0.2734     1.2098       0.2872   1.2362      0.2832
22      1.2787       0.2720     1.2672       0.2943   1.2813      0.2981
23      1.3408       0.2735     1.3271       0.2978   1.3310      0.3092
24      1.3958       0.2794     1.3866       0.3005   1.3846      0.3173
25      1.4089       0.3160     1.4432       0.3031   1.4402      0.3229
30      1.4497       0.3484     1.4807       0.3384   1.4779      0.3537
40      1.05975      0.83385    1.07676      0.8205   1.07523     0.8409
50      0.86004      1.16445    0.87012      1.1532   0.86922     1.1703
60      0.65709      1.47375    0.6624       1.46505  0.66195     1.47825
70      0.43965      1.72395    0.44199      1.7181   0.44181     1.7271
80      0.21492      1.88445    0.21546      1.88145  0.21546     1.8861
90      0            1.935      0            1.935    0           1.935
100     -0.15048     1.88445    -0.15084     1.88145  -0.15084    1.8861
110     -0.3078      1.72395    -0.30942     1.7181   -0.30924    1.7271
120     -0.45999     1.47375    -0.46368     1.46505  -0.46341    1.47825
130     -0.60201     1.16445    -0.60903     1.1532   -0.6084     1.1703
140     -0.74187     0.83385    -0.75375     0.8205   -0.75267    0.8409
150     -0.91332     0.5226     -0.93285     0.5076   -0.93105    0.53055
160     -0.83097     0.2685     -0.85122     0.25215  -0.84942    0.2772
170     -0.41544     0.1026     -0.42561     0.0855   -0.42471    0.1116
180     0            0.04485    0            0.02745  0           0.054
```

Airfoil File SH3052Mod_AllRe_Elem14_Hanley.dat:

```
SH3052 _6te (14th element) data from T Hanley XFOIL predictions
Reinterpolated and foilchecked by CH Feb04
3       Number of airfoil tables in this file
0.3     0.6     1.2     Table ID parameter, Re in millions
12.0    11.0    10.0    Stall angle (deg)
0       0       0       No longer used, enter zero
0       0       0       No longer used, enter zero
0       0       0       No longer used, enter zero
-7.300  -7.265  -7.214  Zero Cn angle of attack (deg)
6.075   6.127   6.228   Cn slope for zero lift (dimensionless)
2.046   1.953   1.871   Cn extrapolated to value at positive stall angle of attack
-0.8    -0.8    -0.8    Cn at stall value for negative angle of attack
-3.0    -2.0    -2.0    Angle of attack for minimum CD (deg)
0.01058 0.00829 0.00678 Minimum CD value
-180.0   0.0000      -0.0261   0.0000     -0.0203    0.0000      -0.0015
-170.0   0.3963      0.0132    0.3975     0.0189     0.3919      0.0375
-160.0   0.7926      0.1263    0.7950     0.1319     0.7837      0.1495
-150.0   0.9401      0.2999    0.9427     0.3049     0.9307      0.3212
-140.0   0.7788      0.5130    0.7804     0.5175     0.7731      0.5319
-130.0   0.6421      0.7402    0.6430     0.7440     0.6387      0.7561
-120.0   0.4967      0.9544    0.4972     0.9574     0.4949      0.9668
-110.0   0.3358      1.1302    0.3360     1.1322     0.3350      1.1386
-100.0   0.1656      1.2466    0.1657     1.2476     0.1654      1.2508
-90.0    0.0000      1.2900    0.0000     1.2900     0.0000      1.2900
-80.0    -0.1656     1.2466    -0.1657    1.2476     -0.1654     1.2508
-70.0    -0.3358     1.1302    -0.3360    1.1322     -0.3350     1.1386
-60.0    -0.4967     0.9544    -0.4972    0.9574     -0.4949     0.9668
-50.0    -0.6421     0.7402    -0.6430    0.7440     -0.6387     0.7561
-40.0    -0.7788     0.5130    -0.7804    0.5175     -0.7731     0.5319
-30      -0.9401     0.2999    -0.9427    0.3049     -0.9307     0.3212
-20      -0.7243     0.1732    -0.7175    0.1642     -0.7070     0.1671
-10      -0.1999     0.1465    -0.1780    0.0918     -0.1747     0.0575
-9       -0.2293     0.1375    -0.1938    0.0766     -0.1900     0.0369
-8       -0.1327     0.0972    -0.0817    0.0646     -0.0862     0.0299
-7       -0.0123     0.0584    0.0146     0.0319     0.0202      0.0269
-6       0.1063      0.0365    0.1203     0.0265     0.1226      0.0213
-5       0.2000      0.0300    0.2085     0.0232     0.2109      0.0188
-4       0.3032      0.0256    0.3079     0.0200     0.3101      0.0172
-3       0.4048      0.0212    0.4060     0.0172     0.4090      0.0160
-2       0.5033      0.0224    0.5031     0.0166     0.5064      0.0136
-1       0.5988      0.0232    0.6003     0.0172     0.6049      0.0138
0        0.6939      0.0234    0.6966     0.0176     0.7021      0.0144
1        0.7879      0.0238    0.7912     0.0182     0.7982      0.0150
2        0.8801      0.0244    0.8839     0.0190     0.8934      0.0156
3        0.9701      0.0254    0.9749     0.0198     0.9867      0.0164
4        1.0573      0.0266    1.0640     0.0208     1.0776      0.0174
5        1.1409      0.0280    1.1499     0.0222     1.1657      0.0186
6        1.2204      0.0296    1.2319     0.0236     1.2508      0.0200
7        1.2972      0.0316    1.3081     0.0254     1.3299      0.0218
8        1.3710      0.0336    1.3714     0.0278     1.3977      0.0242
9        1.3932      0.0362    1.4126     0.0299     1.4213      0.0274
10       1.4025      0.0399    1.4239     0.0342     1.4192      0.0332
11       1.3968      0.0457    1.4113     0.0412     1.3882      0.0429
12       1.3739      0.0544    1.3633     0.0538     1.3289      0.0576
13       1.3241      0.0691    1.2939     0.0729     1.3035      0.0695
14       1.2568      0.0905    1.2235     0.0967     1.2649      0.0857
15       1.1758      0.1191    1.1763     0.1179     1.2265      0.1034
16       1.0962      0.1512    1.1287     0.1407     1.1810      0.1242
17       1.0393      0.1785    1.0739     0.1669     1.1300      0.1476
18       0.9932      0.2028    1.0200     0.1932     1.0787      0.1717
19       0.9485      0.2264    0.9772     0.2159     1.0291      0.1955
20       0.9872      0.2406    1.0074     0.2358     1.0529      0.2180
21       1.0355      0.2491    1.0434     0.2514     1.0784      0.2390
22       1.0912      0.2521    1.0868     0.2625     1.1057      0.2580
23       1.1578      0.2468    1.1366     0.2693     1.1402      0.2717
24       1.2232      0.2421    1.1902     0.2729     1.1874      0.2794
25       1.2729      0.2469    1.2468     0.2736     1.2368      0.2860
```

```
26       1.3006       0.2652   1.3047      0.2715     1.2861       0.2914
30       1.3430       0.2999   1.3467      0.3049     1.3296       0.3212
40.0     1.1126       0.5130   1.1149      0.5175     1.1045       0.5319
50.0     0.9172       0.7402   0.9186      0.7440     0.9124       0.7561
60.0     0.7095       0.9544   0.7103      0.9574     0.7070       0.9668
70.0     0.4797       1.1302   0.4800      1.1322     0.4786       1.1386
80.0     0.2366       1.2466   0.2367      1.2476     0.2363       1.2508
90.0     0.0000       1.2900   0.0000      1.2900     0.0000       1.2900
100.0    -0.1656      1.2466   -0.1657     1.2476     -0.1654      1.2508
110.0    -0.3358      1.1302   -0.3360     1.1322     -0.3350      1.1386
120.0    -0.4967      0.9544   -0.4972     0.9574     -0.4949      0.9668
130.0    -0.6421      0.7402   -0.6430     0.7440     -0.6387      0.7561
140.0    -0.7788      0.5130   -0.7804     0.5175     -0.7731      0.5319
150.0    -0.9401      0.2999   -0.9427     0.3049     -0.9307      0.3212
160.0    -0.7926      0.1263   -0.7950     0.1319     -0.7837      0.1495
170.0    -0.3963      0.0132   -0.3975     0.0189     -0.3919      0.0375
180.0    0.0000       -0.0261  0.0000      -0.0203    0.0000       -0.0015
```

Airfoil File SH3052Mod_AllRe_Elem14_Hanley.dat:

```
SH3052 _15te (15th element) data from T Hanley XFOIL predictions
Reinterpolated and foilchecked by CH Feb04
3      Number of airfoil tables in this file
0.3    0.6    1.2    Table ID parameter, Re in millions
12.0   12.0   11.0   Stall angle (deg)
0      0      0      No longer used, enter zero
0      0      0      No longer used, enter zero
0      0      0      No longer used, enter zero
-6.093 -6.076 -6.032 Zero Cn angle of attack (deg)
5.977  6.002  6.108  Cn slope for zero lift (dimensionless)
1.887  1.894  1.816  Cn extrapolated to value at positive stall angle of attack
-0.8   -0.8   -0.8   Cn at stall value for negative angle of attack
-3.0   -2.0   -2.0   Angle of attack for minimum CD (deg)
0.01075       0.00822       0.00673       Minimum CD value
-180.0   0.0000       -0.0432  0.0000      -0.0476  0.0000     -0.0224
-170.0   0.3508       -0.0036  0.3571      -0.0080  0.3510     0.0168
-160.0   0.7015       0.1103   0.7142      0.1061   0.7019     0.1298
-150.0   0.8900       0.2851   0.9047      0.2812   0.8905     0.3031
-140.0   0.7484       0.4999   0.7573      0.4965   0.7486     0.5158
-130.0   0.6241       0.7293   0.6294      0.7264   0.6242     0.7426
-120.0   0.4870       0.9459   0.4899      0.9437   0.4871     0.9563
-110.0   0.3316       1.1243   0.3329      1.1228   0.3317     1.1314
-100.0   0.1646       1.2436   0.1649      1.2428   0.1646     1.2472
-90.0    0.0000       1.2900   0.0000      1.2900   0.0000     1.2900
-80.0    -0.1646      1.2436   -0.1649     1.2428   -0.1646    1.2472
-70.0    -0.3316      1.1243   -0.3329     1.1228   -0.3317    1.1314
-60.0    -0.4870      0.9459   -0.4899     0.9437   -0.4871    0.9563
-50.0    -0.6241      0.7293   -0.6294     0.7264   -0.6242    0.7426
-40.0    -0.7484      0.4999   -0.7573     0.4965   -0.7486    0.5158
-30      -0.8900      0.2851   -0.9047     0.2812   -0.8905    0.3031
-20      -0.6574      0.1601   -0.6568     0.1484   -0.6464    0.1609
-10      -0.2275      0.1065   -0.2033     0.0687   -0.2018    0.0657
-8       -0.2222      0.0803   -0.1795     0.0356   -0.1798    0.0274
-7       -0.1122      0.0437   -0.0827     0.0295   -0.0861    0.0246
-6       0.0080       0.0344   0.0139      0.0257   0.0061     0.0205
-5       0.1004       0.0296   0.1031      0.0232   0.0991     0.0188
-4       0.1933       0.0258   0.1954      0.0204   0.1941     0.0174
-3       0.2844       0.0216   0.2853      0.0166   0.2901     0.0160
-2       0.3822       0.0224   0.3813      0.0164   0.3824     0.0134
-1       0.4762       0.0226   0.4770      0.0168   0.4793     0.0136
0        0.5709       0.0228   0.5716      0.0172   0.5754     0.0140
1        0.6641       0.0230   0.6642      0.0176   0.6710     0.0144
2        0.7556       0.0236   0.7555      0.0182   0.7647     0.0150
3        0.8425       0.0242   0.8446      0.0190   0.8561     0.0158
4        0.9266       0.0250   0.9308      0.0198   0.9447     0.0168
5        1.0058       0.0256   1.0127      0.0208   1.0315     0.0176
```

6	1.0857	0.0274	1.0850	0.0218	1.1113	0.0188
7	1.1651	0.0292	1.1474	0.0246	1.1860	0.0202
8	1.2249	0.0316	1.2096	0.0276	1.2494	0.0228
9	1.2528	0.0340	1.2474	0.0297	1.2876	0.0248
10	1.2658	0.0372	1.2826	0.0317	1.3031	0.0286
11	1.2653	0.0421	1.2854	0.0371	1.2815	0.0365
12	1.2518	0.0495	1.2609	0.0462	1.2358	0.0485
13	1.2221	0.0601	1.2111	0.0606	1.1852	0.0640
14	1.1718	0.0765	1.1438	0.0814	1.1618	0.0769
15	1.1099	0.0984	1.0840	0.1043	1.1275	0.0933
16	1.0329	0.1273	1.0433	0.1245	1.0930	0.1109
17	0.9670	0.1558	0.9999	0.1464	1.0522	0.1311
18	0.9182	0.1804	0.9509	0.1708	1.0073	0.1527
19	0.8786	0.2021	0.9035	0.1949	0.9621	0.1749
20	0.9022	0.2217	0.9296	0.2147	0.9830	0.1967
21	0.9442	0.2318	0.9602	0.2314	1.0025	0.2183
22	0.9952	0.2365	0.9975	0.2440	1.0216	0.2386
23	1.0526	0.2370	1.0424	0.2520	1.0527	0.2530
24	1.1203	0.2309	1.0920	0.2570	1.0944	0.2631
25	1.1776	0.2301	1.1498	0.2555	1.1398	0.2704
26	1.2083	0.2431	1.2127	0.2487	1.1873	0.2755
27	1.2348	0.2584	1.2572	0.2539	1.2356	0.2794
30	1.2715	0.2851	1.2925	0.2812	1.2722	0.3031
40.0	1.0691	0.4999	1.0819	0.4965	1.0695	0.5158
50.0	0.8915	0.7293	0.8991	0.7264	0.8918	0.7426
60.0	0.6958	0.9459	0.6998	0.9437	0.6959	0.9563
70.0	0.4738	1.1243	0.4755	1.1228	0.4738	1.1314
80.0	0.2352	1.2436	0.2356	1.2428	0.2352	1.2472
90.0	0.0000	1.2900	0.0000	1.2900	0.0000	1.2900
100.0	-0.1646	1.2436	-0.1649	1.2428	-0.1646	1.2472
110.0	-0.3316	1.1243	-0.3329	1.1228	-0.3317	1.1314
120.0	-0.4870	0.9459	-0.4899	0.9437	-0.4871	0.9563
130.0	-0.6241	0.7293	-0.6294	0.7264	-0.6242	0.7426
140.0	-0.7484	0.4999	-0.7573	0.4965	-0.7486	0.5158
150.0	-0.8900	0.2851	-0.9047	0.2812	-0.8905	0.3031
160.0	-0.7015	0.1103	-0.7142	0.1061	-0.7019	0.1298
170.0	-0.3508	-0.0036	-0.3571	-0.0080	-0.3510	0.0168
180.0	0.0000	-0.0432	0.0000	-0.0476	0.0000	-0.0224

Speed- Torque File for Resistor Load:

```
RPM and Torque (Nm) for SWRT rotor mod by CH Aug 18, 2004 with **RESISTOR LOAD**
0       0.63447
12      20.13909
24      39.18996
36      57.78609
48      75.92652
60      93.61026
72      110.83632
84      127.60374
96      143.91151
108     159.75867
120     175.14423
132     190.06722
144     204.52664
156     218.52152
168     232.05088
180     245.11374
192     257.70912
204     269.83603
216     281.49349
228     292.68053
240     303.39615
252     313.63939
264     323.40926
276     332.70477
288     341.52496
300     349.86882
312     357.7354
```

```
324     365.12369
336     372.03273
348     378.46153
360     384.40912
372     389.8745
384     394.85669
396     399.35473
408     403.36762
420     406.89439
432     409.93405
444     412.48562
456     414.54812
468     416.12058
480     417.202
492     417.79141
504     417.88783
516     417.49027
528     416.59776
540     415.20931
552     413.32395
564     410.94068
576     408.05854
588     404.67653
600     400.79369
612     396.40902
624     391.52154
636     386.13028
648     380.23426
660     373.83248
```

Speed- Torque File for Inverter Load:

```
RPM and Torque (Nm) for SWRT rotor mod by CH Aug 9, 2004 with new test data.  See Config
B Torque vs RPM.xls
0       0.00
10      0.00
20      0.00
30      0.00
40      0.00
50      4.17
60      18.13
70      32.08
80      46.01
90      59.88
100     73.69
110     87.41
120     101.03
130     114.51
140     127.86
150     141.03
160     154.02
170     166.81
180     179.37
190     191.69
200     207.0
210     224.0
220     239.8
230     254.5
240     268.0
250     280.3
260     291.2
270     300.7
280     308.9
290     315.5
300     320.6
310     324.1
320     326.0
330     326.2
340     324.6
```

```
350     321.3
360     316.1
370     308.9
380     299.9
390     288.8
400     275.6
410     260.3
420     242.8
430     223.2
440     201.2
450     176.9
460     150.2
470     121.0
480     89.4
490     55.2
500     18.4
504.75  0.0
1000    0.0
```

FAST Input File:

```
----FAST INPUT FILE -for v5.10d-jmj  --------------------------------------
FAST model of a SWRT 3-bladed upwind turbine.  Note- SWRT rotates in CCW direction- some
inputs will be mirror image of the actual turbine.
Model properties from "SWRTv1p2.adm" and SWRT "AdamsWT_MakeBladeDat_v12.xls".  JEM Jan.,
2004. Updated v5.1 Jul 04, ACH.
---------------------- SIMULATION CONTROL --------------------------------------
False   Echo        - Echo input data to "echo.out" (flag)
1       ADAMSPrep   - ADAMS preprocessor mode {1: Run FAST, 2: use FAST as a preprocessor
to create an ADAMS model, 3: do both} (switch)
1       AnalMode    - Analysis mode {1: Run a time-marching simulation, 2: create a
linearized model} (switch)
3       NumBl       - Number of blades (-)
600.0   TMax        - Total run time (s)
0.002   DT          - Integration time step (s)
---------------------- TURBINE CONTROL -----------------------------------------
   0    YCMode      - Yaw control mode {0: none, 1: user-defined from routine UserYawCont,
2: user-defined from Simulink} (switch)
9999.9  TYCOn       - Time to enable active yaw control (s)
0       PCMode      - Pitch control mode {0: none, 1: user-defined from routine
PitchCntrl, 2: user-defined from Simulink} (switch)
9999.9  TPCOn       - Time to enable active pitch control (s)
2       VSContrl    - Variable-speed control {0: none, 1: simple VS, 2: user-defined from
routine UserVSCont, 3: user-defined from Simulink} (switch)
180.0   RatGenSp    - Rated generator speed for simple variable-speed generator control
(HSS side) (rpm) [used only when VSContrl=1]
0.001   Reg2TCon    - Torque constant for simple variable-speed generator control in
Region 2 (HSS side) (N-m/rpm^2) [used only when VSContrl=1]
1       GenModel    - Generator model {1: Simple, 2: Thevenin, 3: User Defined} [used only
when VSContrl=0] (-)
True    GenTiStr    - Method to start the generator {T: timed using TimGenOn, F: generator
speed using SpdGenOn} (flag)
True    GenTiStp    - Method to stop the generator {T: timed using TimGenOf, F: when
generator power = 0} (flag)
9999.9  SpdGenOn    - Generator speed to turn on the generator for a startup (HSS speed)
(rpm)
0.0     TimGenOn    - Time to turn on the generator for a startup (s)
9999.9 TimGenOf    - Time to turn off the generator (s)
9999.9  THSSBrDp    - Time to initiate deployment of the HSS brake (s)
9999.9  TiDynBrk    - Time to initiate deployment of the dynamic generator brake
[CURRENTLY IGNORED] (s)
9999.9  TTpBrDp(1)  - Time to initiate deployment of tip brake 1 (s)
9999.9  TTpBrDp(2)  - Time to initiate deployment of tip brake 2 (s)
9999.9  TTpBrDp(3)  - Time to initiate deployment of tip brake 3 (s) [unused for 2 blades]
9999.9  TBDepISp(1) - Deployment-initiation speed for the tip brake on blade 1 (rpm)
9999.9  TBDepISp(2) - Deployment-initiation speed for the tip brake on blade 2 (rpm)
9999.9  TBDepISp(3) - Deployment-initiation speed for the tip brake on blade 3 (rpm)
[unused for 2 blades]
```

```
9999.9  TYawManS    - Time to start override yaw maneuver and end standard yaw control (s)
9999.9  TYawManE    - Time at which override yaw maneuver reaches final yaw angle (s)
   0.0  NacYawF     - Final yaw angle for yaw maneuvers (degrees)
9999.9  TPitManS(1) - Time to start override pitch maneuver for blade 1 and end standard
pitch control (s)
9999.9  TPitManS(2) - Time to start override pitch maneuver for blade 2 and end standard
pitch control (s)
9999.9  TPitManS(3) - Time to start override pitch maneuver for blade 3 and end standard
pitch control (s) [unused for 2 blades]
9999.9  TPitManE(1) - Time at which override pitch maneuver for blade 1 reaches final
pitch (s)
9999.9  TPitManE(2) - Time at which override pitch maneuver for blade 2 reaches final
pitch (s)
9999.9  TPitManE(3) - Time at which override pitch maneuver for blade 3 reaches final
pitch (s) [unused for 2 blades]
11.44   BlPitch(1)  - Blade 1 initial pitch (degrees)
11.44   BlPitch(2)  - Blade 2 initial pitch (degrees)
11.44   BlPitch(3)  - Blade 3 initial pitch (degrees) [unused for 2 blades]
11.44   BlPitchF(1) - Blade 1 final pitch for pitch maneuvers (degrees)
11.44   BlPitchF(2) - Blade 2 final pitch for pitch maneuvers (degrees)
11.44   BlPitchF(3) - Blade 3 final pitch for pitch maneuvers (degrees) [unused for 2
blades]
---------------------- ENVIRONMENTAL CONDITIONS --------------------------------
9.81           Gravity     - Gravitational acceleration (m/s^2)
---------------------- FEATURE FLAGS -------------------------------------------
True    FlapDOF1    - First flapwise blade mode DOF (flag)
True    FlapDOF2    - Second flapwise blade mode DOF (flag)
True    EdgeDOF     - First edgewise blade mode DOF (flag)
False   TeetDOF     - Rotor-teeter DOF (flag) [unused for 3 blades]
False   DrTrDOF     - Drivetrain rotational-flexibility DOF (flag)
True    GenDOF      - Generator DOF (flag)
True    YawDOF      - Yaw DOF (flag)
False   TwFADOF1    - First fore-aft tower bending-mode DOF (flag)
False   TwFADOF2    - Second fore-aft tower bending-mode DOF (flag)
False   TwSSDOF1    - First side-to-side tower bending-mode DOF (flag)
False   TwSSDOF2    - Second side-to-side tower bending-mode DOF (flag)
True    CompAero    - Compute aerodynamic forces (flag)
False   CompNoise   - Compute aerodynamic noise (flag)
---------------------- INITIAL CONDITIONS --------------------------------------
0.0     OoPDefl     - Initial out-of-plane blade-tip displacement, (meters)
0.0     IPDefl      - Initial in-plane blade-tip deflection, (meters)
0.0     TeetDefl    - Initial or fixed teeter angle (degrees) [unused for 3 blades]
0.0     Azimuth     - Initial azimuth angle for blade 1 (degrees)
188.0   RotSpeed    - Initial or fixed rotor speed (rpm)
0.0     NacYaw      - Initial or fixed nacelle-yaw angle (degrees)
0.0     TTDspFA     - Initial fore-aft tower-top displacement (meters)
0.0     TTDspSS     - Initial side-to-side tower-top displacement (meters)
---------------------- TURBINE CONFIGURATION -----------------------------------
2.90    TipRad      - The distance from the rotor apex to the blade tip (meters)
0.303   HubRad      - The distance from the rotor apex to the blade root (meters)
1       PSpnElN     - Number of the innermost blade element which is still part of the
pitchable portion of the blade for partial-span pitch control [1 to BldNodes] [CURRENTLY
IGNORED] (-)
0.0     UndSling    - Undersling length [distance from teeter pin to the rotor apex]
(meters) [unused for 3 blades]
0.1536  HubCM       - Distance from rotor apex to hub mass [positive downwind] (meters)
-0.7456 OverHang    - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2
blades] (meters)
-0.2307 NacCMxn     - Downwind distance from the tower-top to the nacelle CM (meters)
0.0910  NacCMyn     - Lateral  distance from the tower-top to the nacelle CM (meters)
0.5475  NacCMzn     - Vertical distance from the tower-top to the nacelle CM (meters)
34.0    TowerHt     - Height of tower above ground level (meters)
0.515112       Twr2Shft    - Vertical distance from the tower-top to the rotor shaft
(meters)
0.0     TwrRBHt     - Tower rigid base height (meters)
-8.0    ShftTilt    - Rotor shaft tilt angle (degrees).  Negative for an upwind rotor.
0.0     Delta3      - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades]
0.0     PreCone(1)  - Blade 1 cone angle (degrees)
0.0     PreCone(2)  - Blade 2 cone angle (degrees)
0.0     PreCone(3)  - Blade 3 cone angle (degrees) [unused for 2 blades]
0.0     AzimB1Up    - Azimuth value to use for I/O when blade 1 points up (degrees)
```

```
---------------------- MASS AND INERTIA ---------------------------------------
0.0     YawBrMass   - Yaw bearing mass (kg)
260.5   NacMass     - Nacelle mass (kg)
113.0   HubMass     - Hub mass (kg)
0.0     TipMass(1)  - Tip-brake mass, blade 1 (kg)
0.0     TipMass(2)  - Tip-brake mass, blade 2 (kg)
0.0     TipMass(3)  - Tip-brake mass, blade 3 (kg) [unused for 2 blades]
39.81   NacYIner    - Nacelle inertia about yaw axis (kg m^2)
0.5     GenIner     - Generator inertia about HSS (kg m^2)
7.71    HubIner     - Hub inertia about rotor axis [3 blades] or teeter axis [2 blades]
(kg m^2)
---------------------- DRIVETRAIN ---------------------------------------------
100.0   GBoxEff     - Gearbox efficiency (%)
83.0    GenEff      - Generator efficiency [ignored by the Thevenin and user-defined
generator models] (%)
1.0     GBRatio     - Gearbox ratio (-)
False   GBRevers    - Gearbox reversal {T: if rotor and generator rotate in opposite
directions} (flag)
9999.9  HSSBrTqF    - Fully deployed HSS-brake torque (N-m)
9999.9  HSSBrDT     - Time for HSS-brake to reach full deployment once initiated (sec)
"junk.dat"     DynBrkFi    - File containing a mech-gen-torque vs HSS-speed curve for a
dynamic brake [CURRENTLY IGNORED] (quoted string)
9999.9  DTTorSpr    - Drivetrain torsional spring (N-m/rad)
0.0     DTTorDmp    - Drivetrain torsional damper (N-m/s)
---------------------- SIMPLE INDUCTION GENERATOR -----------------------------
99.9    SIG_SlPc    - Rated generator slip percentage [>0] (%)              Now HSS side!
999.9   SIG_SySp    - Synchronous (zero-torque) generator speed [>0] (rpm)  Now HSS side!
999.9   SIG_RtTq    - Rated torque [>0] (N-m)                               Now HSS side!
99.9    SIG_PORt    - Pull-out ratio (Tpullout/Trated) [>1] (-)
---------------------- THEVENIN-EQUIVALENT INDUCTION GENERATOR -----------------
9999.9  TEC_Freq    - Line frequency [50 or 60] (Hz)
9998    TEC_NPol    - Number of poles [even integer > 0] (-)
9999.9  TEC_SRes    - Stator resistance [>0] (ohms)
9999.9  TEC_RRes    - Rotor resistance [>0] (ohms)
9999.9  TEC_VLL     - Line-to-line RMS voltage (volts)
9999.9  TEC_SLR     - Stator leakage reactance (ohms)
9999.9  TEC_RLR     - Rotor leakage reactance (ohms)
9999.9  TEC_MR      - Magnetizing reactance (ohms)
---------------------- TOWER --------------------------------------------------
10      TwrNodes    - Number of tower nodes used for analysis (-)
"SWRT_Tower.dat"  TwrFile - Name of file containing tower properties (quoted string)
---------------------- NACELLE-YAW --------------------------------------------
0.0     YawSpr      - Nacelle-yaw spring constant (N-m/rad)
0.0     YawDamp     - Nacelle-yaw constant (N-m/rad/s)
0.0     YawNeut     - Neutral yaw position--yaw spring force is zero at this yaw (degrees)
---------------------- FURLING ------------------------------------------------
True    Furling     - Read in additional model properties for furling turbine (flag)
"SWRT_Furl.dat"  FurlFile    - Name of file containing furling properties (quoted string)
---------------------- ROTOR-TEETER -------------------------------------------
0       TeetMod     - Rotor-teeter spring/damper model (0: none, 1: standard, 2: user-
defined) (switch) [unused for 3 blades]
0.0     TeetDmpP    - Rotor-teeter damper position (degrees) [unused for 3 blades]
0.0     TeetDmp     - Rotor-teeter damping constant (N-m/rad/s) [unused for 3 blades]
0.0     TeetCDmp    - Rotor-teeter rate-independent Coulomb-damping moment (N-m) [unused
for 3 blades]
0.0     TeetSStP    - Rotor-teeter soft-stop position (degrees) [unused for 3 blades]
0.0     TeetHStP    - Rotor-teeter hard-stop position (degrees) [unused for 3 blades]
0.0     TeetSSSp    - Rotor-teeter soft-stop linear-spring constant (N-m/rad) [unused for
3 blades]
0.0     TeetHSSp    - Rotor-teeter hard-stop linear-spring constant (N-m/rad) [unused for
3 blades]
---------------------- TIP-BRAKE ----------------------------------------------
0.0     TBDrConN    - Tip-brake drag constant during normal operation, Cd*Area (m^2)
0.0     TBDrConD    - Tip-brake drag constant during fully-deployed operation, Cd*Area
(m^2)
9999.9  TpBrDT      - Time for tip-brake to reach full deployment once released (sec)
---------------------- BLADE --------------------------------------------------
"SWRT_Blade.dat"      BldFile(1)  - Name of file containing properties for blade 1
(quoted string)
"SWRT_Blade.dat"      BldFile(2)  - Name of file containing properties for blade 2
(quoted string)
```

```
"SWRT_Blade.dat"      BldFile(3)  - Name of file containing properties for blade 3
(quoted string) [unused for 2 blades]
---------------------- AERODYN -------------------------------------------------
"SWRT_AeroDyn.ipt"    ADFile      - Name of file containing AeroDyn input parameters
(quoted string)
---------------------- NOISE ---------------------------------------------------
"SWRT_Noise.dat"      NoiseFile   - Name of file containing aerodynamic noise input
parameters (quoted string)
---------------------- ADAMS ---------------------------------------------------
"SWRT_ADAMS.dat"      ADAMSFile   - Name of file containing ADAMS-specific input
parameters (quoted string)
---------------------- LINEARIZATION CONTROL -----------------------------------
"SWRT_Linear.dat"     LinFile     - Name of file containing FAST linearazation parameters
(quoted string)
---------------------- OUTPUT --------------------------------------------------
True    SumPrint    - Print summary data to "<RootName>.fsm" (flag)
True    TabDelim    - Generate a tab-delimited tabular output file. (flag)
"ES10.3E2"     OutFmt      - Format used for tabular output except time.  Resulting field
should be 10 characters. (quoted string)  [not checked for validity!]
0.0     TStart      - Time to begin tabular output (s)
4       DecFact     - Decimation factor for tabular output [1: output every time step] (-)
10.0    SttsTime    - Amount of time between screen status messages (sec)
0.535   ShftGagL    - Distance from rotor apex [3 blades] or teeter pin [2 blades] to
shaft strain gages [positive for upwind rotors] (meters)
2       NBlGages    - Number of blade nodes that have strain gages for output [0 to 5] (-)
1, 2    BldGagNd    - List of blade nodes that have strain gages [1 to BldNodes] (-)
        OutList     - The next line(s) contains a list of output parameters.  See
OutList.txt for a listing of available output channels, (-)
"WindVxt, HorWndDir"                  ! Wind speed and direction
"RotPwr, GenPwr"                      ! Rotor (mechanical) power and generator
(electrical) power
"Azimuth, RotSpeed"                   ! Rotor azimuth and speed
"TwrBsMxt, TwrBsMyt, TwrBsMzt"                ! Tower base roll, pitch, and yaw moments
"TailFurl"                                    ! Tail-furl angle (position)
"BldPitch1"                           ! Blade 1 pitch angle
"RootMxb1, RootMyb1, RootMzb1"                ! Blade 1 root moments
"OoPDefl1, IPDefl1"                   ! OoP and IP blade 1 tip deflections
"RootFxb1, RootFyb1, RootFzb1"                ! Blade 1 root forces
"RotThrust"                           ! Rotor thrust
"RotTorq, Gentq, LSSGagMys, LSSGagMzs"               ! Rotor & gen torque, Shaft moments
at gage, nonrotating
"NacYaw"                              ! Nacelle yaw angle
"Spn1MLxb1, Spn1MLyb1, Spn2MLxb1, Spn2MLyb1"         ! Spanwise flap and edge loads
"RootMxc1, RootMyc1"                                        ! Root OP and IP moments
"TFrlBrM"                                                   ! Furl bearing moment
END of FAST input file (the word "END" must appear in the first 3 columns of this last
line).
--------------------------------------------------------------------------------
"YawBrFxp, YawBrFyp, YawBrFzp"                ! Tower-top / yaw bearing axial and shear
forces
"YawBrMxp, YawBrMyp, YawBrMzp"                ! Tower-top / yaw bearing roll, pitch, and
yaw moments
"TwrBsFxt, TwrBsFyt, TwrBsFzt"                ! Tower base axial and shear forces
```

Blade Input File:

```
--------------------------------------------------------------------------------
---------------------- FAST INDIVIDUAL BLADE FILE ------------------------------
SWRT blade.  Windward Engineering. January, 2004.
---------------------- BLADE PARAMETERS ----------------------------------------
21             NBlInpSt    - Number of blade input stations (-)
False          CalcBMode   - Calculate blade mode shapes internally {T: ignore mode
shapes from below, F: use mode shapes from below} [CURRENTLY IGNORED] (flag)
3.0            BldFlDmp(1) - Blade flap mode #1 structural damping in percent of critical
(%)
3.0            BldFlDmp(2) - Blade flap mode #2 structural damping in percent of critical
(%)
5.0            BldEdDmp(1) - Blade edge mode #1 structural damping in percent of critical
(%)
---------------------- BLADE ADJUSTMENT FACTORS --------------------------------
```

```
1.0            FlStTunr(1) - Blade flapwise modal stiffness tuner, 1st mode (-)
1.0            FlStTunr(2) - Blade flapwise modal stiffness tuner, 2nd mode (-)
1.0            AdjBlMs     - Factor to adjust blade mass density (-)
1.0            AdjFlSt     - Factor to adjust blade flap stiffness (-)
1.0            AdjEdSt     - Factor to adjust blade edge stiffness (-)
---------------------- DISTRIBUTED BLADE PROPERTIES ----------------------------
BlFract AeroCent       StrcTwst       BMassDen       FlpStff EdgStff GJStff  EAStff  Alpha
        FlpIner EdgIner PrecrvRef      PreswpRef      FlpcgOf EdgcgOf FlpEAOf EdgEAOf
(-)   (-)  (deg) (kg/m)  (Nm^2)   (Nm^2)   (Nm^2)   (N)      (-)  (kg m)         (kg m)         (m)(m)(m)(m)(m)(m)
0     0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.05  0.25  0   4.192   4.53E+03          1.99E+05          4.48E+03          2.04E+06          0 0.005890117
0.1   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.15  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.2   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.25  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.3   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.35  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.4   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.45  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.5   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.55  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.6   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.65  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.7   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.75  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.8   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.85  0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.9   0.25  0   4.192   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005890117    0.021739021    0 0 0 0 0 0
0.95  0.25  0   4.02    4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005648443    0.020847058    0 0 0 0 0 0
1     0.25  0   3.848   4.53E+03 1.99E+05 4.48E+03 2.04E+06 0   0.005406768    0.019955094    0 0 0 0 0 0
---------------------- BLADE MODE SHAPES---------------------------------------
 2.573         BldFl1Sh(2) - Flap , coeff of x^2
-2.772         BldFl1Sh(3) -      , coeff of x^3
 1.551         BldFl1Sh(4) -      , coeff of x^4
-0.330         BldFl1Sh(5) -      , coeff of x^5
-0.021         BldFl1Sh(6) -      , coeff of x^6
 -9.847        BldFl2Sh(2) - Flap , coeff of x^2
 13.882        BldFl2Sh(3) -      , coeff of x^3
  9.529        BldFl2Sh(4) -      , coeff of x^4
-19.873        BldFl2Sh(5) -      , coeff of x^5
  7.309        BldFl2Sh(6) -      , coeff of x^6
 1.617         BldEdgSh(2) - Edge , coeff of x^2
-0.065         BldEdgSh(3) -      , coeff of x^3
-1.424         BldEdgSh(4) -      , coeff of x^4
 1.201         BldEdgSh(5) -      , coeff of x^5
-0.329         BldEdgSh(6) -      , coeff of x^6
```

Furl Input File:

```
---------------------- FAST FURLING FILE ---------------------------------------
SWRT input properties. Windward Engineering.  updated August, 2004. Config B
offset=0.083m
---------------------- FEATURE FLAGS (CONT) ------------------------------------
False   RFrlDOF     - Rotor-furl DOF (flag)
True    TFrlDOF     - Tail-furl DOF (flag)
---------------------- INITIAL CONDITIONS (CONT) -------------------------------
0.0     RotFurl     - Initial or fixed rotor-furl angle (degrees)
0.0     TailFurl    - Initial or fixed tail-furl angle (degrees)
---------------------- TURBINE CONFIGURATION (CONT) ----------------------------
0.083   Yaw2Shft    - Lateral distance from the yaw axis to the rotor shaft (meters)
0.0     ShftSkew    - Rotor shaft skew angle (degrees)
0.0     RFrlCMxn    - Downwind distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
0.0     RFrlCMyn    - Lateral  distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
```

```
0.0     RFrlCMzn    - Vertical distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
1.7667  BoomCMxn    - Downwind distance from the tower-top to the tail boom CM (meters)
0.083   BoomCMyn    - Lateral  distance from the tower-top to the tail boom CM (meters)
0.2668  BoomCMzn    - Vertical distance from the tower-top to the tail boom CM (meters)
0.0     TFinCMxn    - Downwind distance from the tower-top to the tail fin CM (meters)
0.0     TFinCMyn    - Lateral  distance from the tower-top to the tail fin CM (meters)
0.0     TFinCMzn    - Vertical distance from the tower-top to the tail fin CM (meters)
2.7674  TFinCPxn    - Downwind distance from the tower-top to the tail fin center-of-
pressure (m)
0.083   TFinCPyn    - Lateral  distance from the tower-top to the tail fin center-of-
pressure (m)
0.1262  TFinCPzn    - Vertical distance from the tower-top to the tail fin center-of-
pressure (m)
0.0     TFinSkew    - Tail fin chordline skew angle (degrees)
-8.0    TFinTilt    - Tail fin chordline tilt angle (degrees)
8.0     TFinBank    - Tail fin planform  bank angle (degrees)
0.0     RFrlPntxn   - Downwind distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlPntyn   - Lateral  distance from the tower-top to an arbitrary point on
the rotor-furl axis (meters)
0.0     RFrlPntzn   - Vertical distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlSkew    - Rotor-furl axis skew angle (degrees)
0.0     RFrlTilt    - Rotor-furl axis tilt angle (degrees)
0.318   TFrlPntxn   - Downwind distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
0.083   TFrlPntyn   - Lateral  distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
0.470   TFrlPntzn   - Vertical distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
-45.2802       TFrlSkew    - Tail-furl axis skew angle (degrees)
78.7047 TFrlTilt    - Tail-furl axis tilt angle (degrees).
---------------------- MASS AND INERTIA (CONT) --------------------------------
0.0     RFrlMass    - Mass of structure that furls with the rotor [not including rotor]
(kg)
86.8    BoomMass    - Tail boom mass (kg)
0.0     TFinMass    - Tail fin mass (kg)
0.0     RFrlIner    - Inertia of the structure that furls with the rotor about the rotor-
furl axis (kg m^2) [not including rotor]
264.7   TFrlIner    - Tail boom inertia about tail-furl axis (kg m^2)
---------------------- ROTOR-FURL ---------------------------------------------
0       RFrlMod     - Rotor-furl spring/damper model (0: none, 1: standard, 2: user-
defined) (switch)
0.0     RFrlSpr     - Rotor-furl spring constant (N-m/rad)
0.0     RFrlDmp     - Rotor-furl damping constant (N-m/rad/s)

0.0     RFrlCDmp    - Rotor-furl rate-independent Coulomb-damping moment (N-m)
0.0     RFrlUSSP    - Rotor-furl up-stop spring position (degrees)
0.0     RFrlDSSP    - Rotor-furl down-stop spring position (degrees)
0.0     RFrlUSSpr   - Rotor-furl up-stop spring constant (N-m/rad)
0.0     RFrlDSSpr   - Rotor-furl down-stop spring constant (N-m/rad)
0.0     RFrlUSDP    - Rotor-furl up-stop damper position (degrees)
0.0     RFrlDSDP    - Rotor-furl down-stop damper position (degrees)
0.0     RFrlUSDmp   - Rotor-furl up-stop damping constant (N-m/rad/s)
0.0     RFrlDSDmp   - Rotor-furl down-stop damping constant (N-m/rad/s)
---------------------- TAIL-FURL ----------------------------------------------
2       TFrlMod     - Tail-furl spring/damper model (0: none, 1: standard, 2: user-
defined) (switch)
0.0     TFrlSpr     - Tail-furl spring constant (N-m/rad)
10.0    TFrlDmp     - Tail-furl damping constant (N-m/rad/s)
0.0     TFrlCDmp    - Tail-furl rate-independent Coulomb-damping moment (N-m)
85.0    TFrlUSSP    - Tail-furl up-stop spring position (degrees)
3.0     TFrlDSSP    - Tail-furl down-stop spring position (degrees)
1000.0  TFrlUSSpr   - Tail-furl up-stop spring constant (N-m/rad)
17000.0 TFrlDSSpr   - Tail-furl down-stop spring constant (N-m/rad)
85.0    TFrlUSDP    - Tail-furl up-stop damper position (degrees)
0.0     TFrlDSDP    - Tail-furl down-stop damper position (degrees)
1000.0  TFrlUSDmp   - Tail-furl up-stop damping constant (N-m/rad/s)
137.0   TFrlDSDmp   - Tail-furl down-stop damping constant (N-m/rad/s)
```

```
---------------------- TAIL FIN AERODYNAMICS ----------------------------------
1       TFinMod     - Tail fin aerodynamics model (0: none, 1: standard, 2: user-defined)
(switch)
1       TFinNFoil   - Tail fin airfoil number [1 to NumFoil]
1.017   TFinArea    - Tail fin planform area (m^2)
True    SubAxInd    - Subtract average rotor axial induction when computing relative wind-
inflow at tail fin? (flag)
```

Furl Input File:

```
--------------------------------------------------------------------------------
---------------------- FAST FURLING FILE ---------------------------------------
SWRT input properties. Windward Engineering.  updated August, 2004. **Config B** with
0.083m offset (A has 0.106m)
---------------------- FEATURE FLAGS (CONT) ------------------------------------
False   RFrlDOF     - Rotor-furl DOF (flag)
True    TFrlDOF     - Tail-furl DOF (flag)
---------------------- INITIAL CONDITIONS (CONT) -------------------------------
0.0     RotFurl     - Initial or fixed rotor-furl angle (degrees)
50.0    TailFurl    - Initial or fixed tail-furl angle (degrees)
---------------------- TURBINE CONFIGURATION (CONT) ----------------------------
0.083   Yaw2Shft    - Lateral distance from the yaw axis to the rotor shaft (meters)
0.0     ShftSkew    - Rotor shaft skew angle (degrees)
0.0     RFrlCMxn    - Downwind distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
0.0     RFrlCMyn    - Lateral  distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
0.0     RFrlCMzn    - Vertical distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
1.7667  BoomCMxn    - Downwind distance from the tower-top to the tail boom CM (meters)
0.083   BoomCMyn    - Lateral  distance from the tower-top to the tail boom CM (meters)
0.2668  BoomCMzn    - Vertical distance from the tower-top to the tail boom CM (meters)
0.0     TFinCMxn    - Downwind distance from the tower-top to the tail fin CM (meters)
0.0     TFinCMyn    - Lateral  distance from the tower-top to the tail fin CM (meters)
0.0     TFinCMzn    - Vertical distance from the tower-top to the tail fin CM (meters)
2.7674  TFinCPxn    - Downwind distance from the tower-top to the tail fin center-of-
pressure (m)
0.083   TFinCPyn    - Lateral  distance from the tower-top to the tail fin center-of-
pressure (m)
0.1262  TFinCPzn    - Vertical distance from the tower-top to the tail fin center-of-
pressure (m)
0.0     TFinSkew    - Tail fin chordline skew angle (degrees)
-8.0    TFinTilt    - Tail fin chordline tilt angle (degrees)
8.0     TFinBank    - Tail fin planform  bank angle (degrees)
0.0     RFrlPntxn   - Downwind distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlPntyn   - Lateral  distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlPntzn   - Vertical distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlSkew    - Rotor-furl axis skew angle (degrees)
0.0     RFrlTilt    - Rotor-furl axis tilt angle (degrees)
0.318   TFrlPntxn   - Downwind distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
0.083   TFrlPntyn   - Lateral  distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
0.470   TFrlPntzn   - Vertical distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
-45.2802        TFrlSkew    - Tail-furl axis skew angle (degrees)
78.7047 TFrlTilt    - Tail-furl axis tilt angle (degrees).
---------------------- MASS AND INERTIA (CONT) ---------------------------------
0.0     RFrlMass    - Mass of structure that furls with the rotor [not including rotor]
(kg)
86.64   BoomMass    - Tail boom mass (kg)
0.0     TFinMass    - Tail fin mass (kg)
```

```
0.0     RFrlIner    - Inertia of the structure that furls with the rotor about the rotor-
furl axis (kg m^2) [not including rotor]
264.7   TFrlIner    - Tail boom inertia about tail-furl axis (kg m^2)
---------------------- ROTOR-FURL ---------------------------------------------
0       RFrlMod     - Rotor-furl spring/damper model (0: none, 1: standard, 2: user-
defined) (switch)
0.0     RFrlSpr     - Rotor-furl spring constant (N-m/rad)
0.0     RFrlDmp     - Rotor-furl damping constant (N-m/rad/s)
0.0     RFrlCDmp    - Rotor-furl rate-independent Coulomb-damping moment (N-m)
0.0     RFrlUSSP    - Rotor-furl up-stop spring position (degrees)
0.0     RFrlDSSP    - Rotor-furl down-stop spring position (degrees)
0.0     RFrlUSSpr   - Rotor-furl up-stop spring constant (N-m/rad)
0.0     RFrlDSSpr   - Rotor-furl down-stop spring constant (N-m/rad)
0.0     RFrlUSDP    - Rotor-furl up-stop damper position (degrees)
0.0     RFrlDSDP    - Rotor-furl down-stop damper position (degrees)
0.0     RFrlUSDmp   - Rotor-furl up-stop damping constant (N-m/rad/s)
0.0     RFrlDSDmp   - Rotor-furl down-stop damping constant (N-m/rad/s)
---------------------- TAIL-FURL ----------------------------------------------
1       TFrlMod     - Tail-furl spring/damper model (0: none, 1: standard, 2: user-
defined) (switch)
0.0     TFrlSpr     - Tail-furl spring constant (N-m/rad)
0.0     TFrlDmp     - Tail-furl damping constant (N-m/rad/s)
0.0     TFrlCDmp    - Tail-furl rate-independent Coulomb-damping moment (N-m)
65.0    TFrlUSSP    - Tail-furl up-stop spring position (degrees)
2.0     TFrlDSSP    - Tail-furl down-stop spring position (degrees)
17000.0 TFrlUSSpr   - Tail-furl up-stop spring constant (N-m/rad)
8000.0  TFrlDSSpr   - Tail-furl down-stop spring constant (N-m/rad)
65.0    TFrlUSDP    - Tail-furl up-stop damper position (degrees)
2.0     TFrlDSDP    - Tail-furl down-stop damper position (degrees)
1000.0  TFrlUSDmp   - Tail-furl up-stop damping constant (N-m/rad/s)
500.0   TFrlDSDmp   - Tail-furl down-stop damping constant (N-m/rad/s)
---------------------- TAIL FIN AERODYNAMICS ----------------------------------
1       TFinMod     - Tail fin aerodynamics model (0: none, 1: standard, 2: user-defined)
(switch)
1       TFinNFoil   - Tail fin airfoil number [1 to NumFoil]
1.017   TFinArea    - Tail fin planform area (m^2)
True    SubAxInd    - Subtract average rotor axial induction when computing relative wind-
inflow at tail fin? (flag)
```

Appendix F – Modeling Summary for Configuration C

Files used to model configuration C

Appendix F - Files Used for Configuration C

AERODYN INPUT FILE:

```
SWRT rotor Config C. with SH3055 airfoil May, 2005
SI            SysUnits - System of units for used for input and output [must be SI for
FAST] (unquoted string)
BEDDOES       StallMod - Dynamic stall included [BEDDOES or STEADY] (unquoted string)
USE_CM        UseCm    - Use aerodynamic pitching moment model? [USE_CM or NO_CM]
(unquoted string)
DYNIN         InfModel - Inflow model [DYNIN or EQUIL] (unquoted string)
SWIRL         IndModel - Induction-factor model [NONE or WAKE or SWIRL] (unquoted
string)
0.005         AToler   - Induction-factor tolerance (convergence criteria) (-)
PRANDtl       TLModel  - Tip-loss model (EQUIL only) [PRANDtl, GTECH, or NONE] (unquoted
string)
NONE          HLModel  - Hub-loss model (EQUIL only) [PRANdtl or NONE] (unquoted string)
" //Mongo/ddrive/Data/WindFiles/Turb_A/25m_hub_height/8m_grid/12ms/Seed1/SNWind"
Wind file (quoted string)
25.0          Wind reference (hub) height
0.0           TwrShad  - Tower-shadow velocity deficit (-)
9999.9        ShadHWid - Tower-shadow half width (m)
9999.9        T_Shad_Refpt - Tower-shadow reference point (m)
0.99   *******************Air density for Jan04 data
1.5100E-05    KinVisc  - Kinematic air viscosity
1.0000E-03    Time interval for aerodynamic calculations.
4      Number of airfoil files used. Files listed below:
"D:\Data\NREL\SWRT\AIRFOILS\TailPlate.dat"
"D:\Data\NREL\SWRT\AIRFOILS\SH3055_Rough_20%R.dat"
"D:\Data\NREL\SWRT\AIRFOILS\SH3055_Rough_40%R.dat"
"D:\Data\NREL\SWRT\AIRFOILS\SH3055_roughNEW.dat"
15     BldNodes - Number of blade nodes used for analysis (-)
```

Rnodes Twist DR Chord File IDElem Data RELM and Twist ignored by ADAMS (but placeholders must be present)

```
0.40457 0     0.203133333   0.2794  2     NOPRINT
0.60770 0     0.203133333   0.2794  2     NOPRINT
0.81083 0     0.203133333   0.2794  2     NOPRINT
1.01397 0     0.203133333   0.2794  2     NOPRINT
1.21710 0     0.203133333   0.2794  3     NOPRINT
1.42023 0     0.203133333   0.2794  3     NOPRINT
1.62337 0     0.203133333   0.2794  3     NOPRINT
1.82650 0     0.203133333   0.2794  4     NOPRINT
2.02963 0     0.203133333   0.2794  4     NOPRINT
2.23277 0     0.203133333   0.2794  4     NOPRINT
2.43590 0     0.203133333   0.2794  4     NOPRINT
2.63903 0     0.203133333   0.2794  4     NOPRINT
2.84217 0     0.203133333   0.2794  4     NOPRINT
3.04530 1.6   0.203133333   0.2626  4     NOPRINT
3.24843 3.2   0.203133333   0.2375  4     NOPRINT
ReNum
```

Airfoil File Tailplate.dat

```
TailPlate.dat. Lift and drag on delta wing. See Hoerner Lift page 18-5, Figure 7
Oct. 14, 2003, Foilchecked by Windward Engineering.
   1   Number of airfoil tables in this file
     0.00      Table ID parameter
     0.00      No longer used, enter zero
     0.00      No longer used, enter zero
     0.00      No longer used, enter zero
     0.00      No longer used, enter zero
    -4.23      Zero lift angle of attack (deg)
    2.71555    Cn slope for zero lift (dimensionless)
     1.8588    Cn at stall value for positive angle of attack
```

```
    -0.8000    Cn at stall value for negative angle of attack
     0.0000    Angle of attack for minimum CD (deg)
     0.0100    Minimum CD value
  -180.00        0.000     0.1820      0
  -170.00        0.144     0.2155      0
  -160.00        0.287     0.3114      0
  -150.00        0.431     0.4576      0
  -140.00        0.524     0.6353      0
  -130.00        0.479     0.8212      0
  -120.00        0.398     0.9910      0
  -110.00        0.285     1.1219      0
  -100.00        0.147     1.1954      0
   -90.00        0.000     1.2000      0
   -80.00       -0.147     1.1954      0
   -70.00       -0.285     1.1219      0
   -60.00       -0.398     0.9910      0
   -50.00       -0.479     0.8212      0
   -40.00       -0.524     0.6353      0
   -30.00       -0.404     0.4722      0
   -20.00       -0.223     0.3181      0
   -10.00       -0.041     0.1641      0
     0.00        0.200     0.0100      0
     4.00        0.390     0.0230      0
     8.00        0.576     0.0630      0
    12.00        0.758     0.1280      0
    16.00        0.861     0.2190      0
    20.00        0.963     0.3340      0
    24.00        1.041     0.4730      0
    35.00        1.106     0.7830      0
    37.00        0.759     0.5800      0
    40.00        0.748     0.6353      0
    50.00        0.684     0.8212      0
    60.00        0.569     0.9910      0
    70.00        0.407     1.1219      0
    80.00        0.210     1.1954      0
    90.00        0.000     1.2000      0
   100.00       -0.147     1.1954      0
   110.00       -0.285     1.1219      0
   120.00       -0.398     0.9910      0
   130.00       -0.479     0.8212      0
   140.00       -0.524     0.6353      0
   150.00       -0.431     0.4577      0
   160.00       -0.287     0.3114      0
   170.00       -0.144     0.2155      0
   180.00        0.000     0.1820      0
```

Airfoil File SH3055_Rough_20%R.dat

```
SH3055 rough at 20% Blade Length (zig zag trip type F per p.49 UIUC (Univ. of Ill. Champ.
Urbana) Draft Report 2 2003_7_15.pdf.  Windward Eng. Feb. 17, 2005. JEM
calculated using Low Re # catalog, Selig correction and foilchk software
2       Number of airfoil tables in this file
0.35    0.5     Table ID parameter, typically Re in millions
10.3    10.3    Stall angle (deg)
0       0       No longer used, enter zero
0       0       No longer used, enter zero
0       0       No longer used, enter zero
-8.106  -8.3114 Zero Cn angle of attack (deg)
5.560   5.470   Cn slope for zero lift (dimensionless)
1.786   1.777   Cn extrapolated to value at positive stall angle of attack
-0.8    -0.8    Cn at stall value for negative angle of attack
-7.00   -7.00   Angle of attack for minimum CD (deg)
0.0083  0.0076  Minimum CD value
-180    0.0000   0.5596     0             0.0000       0.5734     0
-170    0.4712   0.5909     0             0.4714       0.6045     0
-160    0.9423   0.6802     0             0.9427       0.6931     0
-150    1.4135   0.8144     0             1.4141       0.8263     0
-140    1.0716   0.9737     0             1.0719       0.9842     0
-130    0.8191   1.1337     0             0.8193       1.1426     0
-120    0.5949   1.2691     0             0.5950       1.2760     0
```

```
-110    0.3809    1.3561      0               0.3809        1.3608      0
-100    0.1786    1.3764      0               0.1786        1.3788      0
-90     0.0000    1.3190      0               0.0000        1.3190      0
-80     -0.1786   1.3764      0               -0.1786       1.3788      0
-70     -0.3809   1.3561      0               -0.3809       1.3608      0
-60     -0.5949   1.2691      0               -0.5950       1.2760      0
-50     -0.8191   1.1337      0               -0.8193       1.1426      0
-40     -1.0716   0.9737      0               -1.0719       0.9842      0
-30     -1.4135   0.8144      0               -1.4141       0.8263      0
-20     -0.7992   0.4639      0               -0.7890       0.4703      0
-10     -0.1850   0.1135      0               -0.1639       0.1144      0
-7      -0.0010   0.0083      -0.194466019    0.0338        0.0076      -0.194466019
-6      0.1427    0.0096      -0.212803738    0.1611        0.0085      -0.212803738
-5      0.2696    0.0115      -0.225637255    0.2853        0.0100      -0.225637255
-4      0.3863    0.0130      -0.23           0.3945        0.0119      -0.23
-3      0.4908    0.0130      -0.230122449    0.5000        0.0130      -0.230122449
-2      0.5941    0.0135      -0.231843137    0.6011        0.0143      -0.231843137
-1      0.6887    0.0150      -0.229888889    0.7000        0.0155      -0.229888889
0       0.7861    0.0160      -0.228037037    0.7949        0.0162      -0.228037037
1       0.8846    0.0170      -0.226          0.8894        0.0170      -0.226
2       0.9816    0.0187      -0.223          0.9842        0.0187      -0.223
3       1.0773    0.0198      -0.219190476    1.0793        0.0197      -0.219190476
4       1.1700    0.0214      -0.21447619     1.1727        0.0206      -0.21447619
5       1.2586    0.0233      -0.208807692    1.2610        0.0231      -0.208807692
6       1.3414    0.0260      -0.204301075    1.3468        0.0254      -0.204301075
7       1.4191    0.0292      -0.19625        1.4247        0.0292      -0.19625
8       1.4906    0.0339      -0.1865         1.4944        0.0347      -0.1865
9       1.5546    0.0418      -0.179278846    1.5553        0.0461      -0.179278846
10      1.6055    0.0608      -0.174914286    1.6024        0.0709      -0.174914286
10.3    1.6196    0.0677      -0.174          1.6149        0.0800      -0.174
20      1.7018    0.3287      0               1.7012        0.3409      0
30      2.0193    0.8144      0               2.0201        0.8263      0
40      1.5309    0.9737      0               1.5313        0.9842      0
50      1.1702    1.1337      0               1.1705        1.1426      0
60      0.8498    1.2691      0               0.8500        1.2760      0
70      0.5441    1.3561      0               0.5442        1.3608      0
80      0.2551    1.3764      0               0.2551        1.3788      0
90      0.0000    1.3190      0               0.0000        1.3190      0
100     -0.1786   1.3764      0               -0.1786       1.3788      0
110     -0.3809   1.3561      0               -0.3809       1.3608      0
120     -0.5949   1.2691      0               -0.5950       1.2760      0
130     -0.8191   1.1337      0               -0.8193       1.1426      0
140     -1.0716   0.9737      0               -1.0719       0.9842      0
150     -1.4135   0.8144      0               -1.4141       0.8263      0
160     -0.9423   0.6802      0               -0.9427       0.6931      0
170     -0.4712   0.5909      0               -0.4714       0.6045      0
180     0.0000    0.5596      0               0.0000        0.5734      0
```

Airfoil File SH3055_Rough_40%R.dat

```
SH3055 rough at 40% Blade Length (zig zag trip type F per p.49 UIUC (Univ. of Ill. Champ.
Urbana) Draft Report 2 2003_7_15.pdf.  Windward Eng. Feb. 17, 2005. JEM
calculated using Low Re # catalog, Selig correction and foilchk software
1       Number of airfoil tables in this file
0.5     Table ID parameter, typically Re in millions
10.3    Stall angle (deg)
0       No longer used, enter zero
0       No longer used, enter zero
0       No longer used, enter zero
-8.386  Zero Cn angle of attack (deg)
5.432   Cn slope for zero lift (dimensionless)
1.771   Cn extrapolated to value at positive stall angle of attack
-0.8    Cn at stall value for negative angle of attack
-5.00   Angle of attack for minimum CD (deg)
0.0122  Minimum CD value
-180    0.0000    0.1756      0
-170    0.2834    0.2127      0
-160    0.5668    0.3193      0
-150    0.8502    0.4818      0
```

```
-140    0.7288   0.6795     0
-130    0.6166   0.8869     0
-120    0.4865   1.0771     0
-110    0.3341   1.2248     0
-100    0.1671   1.3097     0
-90     0.0000   1.3190     0
-80     -0.1671  1.3097     0
-70     -0.3341  1.2248     0
-60     -0.4865  1.0771     0
-50     -0.6166  0.8869     0
-40     -0.7288  0.6795     0
-30     -0.8502  0.4818     0
-20     -0.4819  0.2797     0
-10     -0.1136  0.0776     0
-7      -0.0045  0.0170     -0.194466019
-6      0.1375   0.0139     -0.212803738
-5      0.2749   0.0122     -0.225637255
-4      0.3901   0.0127     -0.23
-3      0.4999   0.0130     -0.230122449
-2      0.6030   0.0140     -0.231843137
-1      0.7029   0.0150     -0.229888889
0       0.7970   0.0160     -0.228037037
1       0.8903   0.0169     -0.226
2       0.9842   0.0187     -0.223
3       1.0785   0.0198     -0.219190476
4       1.1703   0.0208     -0.21447619
5       1.2545   0.0233     -0.208807692
6       1.3351   0.0255     -0.204301075
7       1.4038   0.0291     -0.19625
8       1.4605   0.0340     -0.1865
9       1.5041   0.0442     -0.179278846
10      1.5273   0.0668     -0.174914286
10.3    1.5319   0.0750     -0.174
20      1.2080   0.2256     0
30      1.2146   0.4818     0
40      1.0411   0.6795     0
50      0.8809   0.8869     0
60      0.6950   1.0771     0
70      0.4773   1.2248     0
80      0.2387   1.3097     0
90      0.0000   1.3190     0
100     -0.1671  1.3097     0
110     -0.3341  1.2248     0
120     -0.4865  1.0771     0
130     -0.6166  0.8869     0
140     -0.7288  0.6795     0
150     -0.8502  0.4818     0
160     -0.5668  0.3193     0
170     -0.2834  0.2127     0
180     0.0000   0.1756     0
```

Airfoil File SH3055_RoughNew.dat

```
SH3055 rough (zig zag trip type F per p.49 UIUC (Univ. of Ill. Champ. Urbana) Draft
Report 2 2003_7_15.pdf.  Windward Eng. May 6, 2005. JEM
calculated using Low Re # catalog and foilchk software
1       Number of airfoil tables in this file
0.5     Table ID parameter, typically Re in millions
10.3    Stall angle (deg)
0       No longer used, enter zero
0       No longer used, enter zero
0       No longer used, enter zero
-8.284  Zero Cn angle of attack (deg)
5.489   Cn slope for zero lift (dimensionless)
1.780   Cn extrapolated to value at positive stall angle of attack
-0.8    Cn at stall value for negative angle of attack
-5.01   Angle of attack for minimum CD (deg)
0.013   Minimum CD value
-180      0.0000       0.0524       0
-170      0.9273       0.0913       0
```

```
-160     0.7547       0.2035       0
-150     0.6659       0.3751       0
-140     0.6166       0.5851       0
-130     0.5503       0.8077       0
-120     0.4510       1.0154       0
-110     0.3188       1.1826       0
-100     0.1633       1.2883       0
-90      0.0000       1.3190       0
-80      -0.1633      1.2883       0
-70      -0.3188      1.1826       0
-60      -0.4510      1.0154       0
-50      -0.5503      0.8077       0
-40      -0.6166      0.5851       0
-30      -0.6659      0.3751       0
-20      -0.7547      0.2035       0
-10      -0.5794      0.0724       0
-9.15    -0.3900      0.0530       -0.102876289
-8.13    -0.1980      0.0320       -0.16244898
-7.12    -0.0360      0.0210       -0.192135922
-6.07    0.1190       0.0160       -0.21182243
-5.01    0.2700       0.0130       -0.225588235
-3.97    0.3920       0.0130       -0.23
-2.98    0.5020       0.0130       -0.230163265
-1.92    0.6120       0.0140       -0.231686275
-0.89    0.7150       0.0150       -0.229685185
0.1      0.8070       0.0160       -0.227836735
1.08     0.8980       0.0170       -0.22576
2.19     1.0020       0.0190       -0.22227619
3.2      1.0970       0.0200       -0.218285714
4.15     1.1830       0.0210       -0.213711538
5.22     1.2700       0.0240       -0.207655914
6.22     1.3480       0.0260       -0.20275
7.24     1.4110       0.0300       -0.1941
8.24     1.4600       0.0350       -0.184394231
9.31     1.4960       0.0470       -0.177542857
10.33    1.5020       0.0740       -0.174
11.3     1.4970       0.1020       -0.174097087
20       1.0781       0.2035       0
30       0.9512       0.3751       0
40       0.8808       0.5851       0
50       0.7862       0.8077       0
60       0.6443       1.0154       0
70       0.4555       1.1826       0
80       0.2333       1.2883       0
90       0.0000       1.3190       0
100      -0.1633      1.2883       0
110      -0.3188      1.1826       0
120      -0.4510      1.0154       0
130      -0.5503      0.8077       0
140      -0.6166      0.5851       0
150      -0.6659      0.3751       0
160      -0.7547      0.2035       0
170      -0.9273      0.0913       0
180      0.0000       0.0524       0
```

Speed Torque File (Inverter):

RPM and Torque (Nm) from Mongo E:/NREL/SWRT/...Configuration A, B & C Inverter 1min and 160hzbinned torqurRPM.xls. Inverter.

```
0      0
80     58.259
85     63.704
90     68.967
95     72.46
100    77.77
105    82.162
110    87.707
115    93.721
```

120	100.88
125	107.97
130	115.06
135	122.26
140	128.71
145	134.75
150	140.77
155	146.27
160	150.46
165	155.87
170	162.39
175	169.6
180	177.53
185	184.41
190	190.4
195	195.14
200	199.83
205	205.31
210	212.68
215	220.9
220	228.98
225	237.24
230	245.22
235	253.72
240	261.92
245	269.46
250	278.54
255	287.05
260	295.52
265	303.65
270	311.82
275	320.59
280	327.72
285	332.54
290	334.25
295	334.05
300	332.28
305	330.99
310	328.24
315	325.8
320	322.41
325	320.01
330	316.19
335	313.44
340	310.51
345	307.64
350	304.47
355	301.32
360	298.02
365	295.59
370	292.29
375	289.34
380	286.71
385	283.19
390	280.1
395	277.57
400	274.4
405	271.33
410	269.15
415	266.28
420	263.07
425	260.46
430	258.41
435	256.14
440	254.93
445	252.53
450	251.39
455	249
460	248.44
465	247.28
470	246.21

```
475     244.08
480     242.3
485     243.33
490     242.78

495     243.29
500     243.38
700     243.38
```

FAST Input File:

```
--------------------------------------------------------------------------------
------- FAST INPUT FILE -for v5.10d-jmj  ---------------------------------------
FAST model of a SWRT 3-bladed upwind turbine.  Note- SWRT rotates in CCW direction- some
inputs will be mirror image of the actual turbine.
Model properties from "SWRTv1p2.adm" and SWRT "AdamsWT_MakeBladeDat_v12.xls".  JEM Jan.,
2004. Updated v5.1 Jul 04, ACH.  Update to SH3055 airfoil Nov 04, JEM.
---------------------- SIMULATION CONTROL --------------------------------------
False   Echo        - Echo input data to "echo.out" (flag)
1       ADAMSPrep   - ADAMS preprocessor mode {1: Run FAST, 2: use FAST as a preprocessor
to create an ADAMS model, 3: do both} (switch)
1       AnalMode    - Analysis mode {1: Run a time-marching simulation, 2: create a
linearized model} (switch)
3       NumBl       - Number of blades (-)
600.0   TMax        - Total run time (s)
0.002   DT          - Integration time step (s)
---------------------- TURBINE CONTROL -----------------------------------------
   0    YCMode      - Yaw control mode {0: none, 1: user-defined from routine UserYawCont,
2: user-defined from Simulink} (switch)
9999.9  TYCOn       - Time to enable active yaw control (s)
0       PCMode      - Pitch control mode {0: none, 1: user-defined from routine
PitchCntrl, 2: user-defined from Simulink} (switch)
9999.9  TPCOn       - Time to enable active pitch control (s)
2       VSContrl    - Variable-speed control {0: none, 1: simple VS, 2: user-defined from
routine UserVSCont, 3: user-defined from Simulink} (switch)
180.0   RatGenSp    - Rated generator speed for simple variable-speed generator control
(HSS side) (rpm) [used only when VSContrl=1]
0.001   Reg2TCon    - Torque constant for simple variable-speed generator control in
Region 2 (HSS side) (N-m/rpm^2) [used only when VSContrl=1]
1       GenModel    - Generator model {1: Simple, 2: Thevenin, 3: User Defined} [used only
when VSContrl=0] (-)
True    GenTiStr    - Method to start the generator {T: timed using TimGenOn, F: generator
speed using SpdGenOn} (flag)
True    GenTiStp    - Method to stop the generator {T: timed using TimGenOf, F: when
generator power = 0} (flag)
9999.9  SpdGenOn    - Generator speed to turn on the generator for a startup (HSS speed)
(rpm)
0.0     TimGenOn    - Time to turn on the generator for a startup (s)
9999.9  TimGenOf    - Time to turn off the generator (s)
9999.9  THSSBrDp    - Time to initiate deployment of the HSS brake (s)
9999.9  TiDynBrk    - Time to initiate deployment of the dynamic generator brake
[CURRENTLY IGNORED] (s)
9999.9  TTpBrDp(1)  - Time to initiate deployment of tip brake 1 (s)
9999.9  TTpBrDp(2)  - Time to initiate deployment of tip brake 2 (s)
9999.9  TTpBrDp(3)  - Time to initiate deployment of tip brake 3 (s) [unused for 2 blades]
9999.9  TBDepISp(1) - Deployment-initiation speed for the tip brake on blade 1 (rpm)
9999.9  TBDepISp(2) - Deployment-initiation speed for the tip brake on blade 2 (rpm)
9999.9  TBDepISp(3) - Deployment-initiation speed for the tip brake on blade 3 (rpm)
[unused for 2 blades]
9999.9  TYawManS    - Time to start override yaw maneuver and end standard yaw control (s)
9999.9  TYawManE    - Time at which override yaw maneuver reaches final yaw angle (s)
   0.0  NacYawF     - Final yaw angle for yaw maneuvers (degrees)
9999.9  TPitManS(1) - Time to start override pitch maneuver for blade 1 and end standard
pitch control (s)
9999.9  TPitManS(2) - Time to start override pitch maneuver for blade 2 and end standard
pitch control (s)
9999.9  TPitManS(3) - Time to start override pitch maneuver for blade 3 and end standard
pitch control (s) [unused for 2 blades]
9999.9  TPitManE(1) - Time at which override pitch maneuver for blade 1 reaches final
pitch (s)
```

```
9999.9  TPitManE(2) - Time at which override pitch maneuver for blade 2 reaches final
pitch (s)
9999.9  TPitManE(3) - Time at which override pitch maneuver for blade 3 reaches final
pitch (s) [unused for 2 blades]
9.5     BlPitch(1)  - Blade 1 initial pitch (degrees)
9.5     BlPitch(2)  - Blade 2 initial pitch (degrees)
9.5     BlPitch(3)  - Blade 3 initial pitch (degrees) [unused for 2 blades]
9.5     BlPitchF(1) - Blade 1 final pitch for pitch maneuvers (degrees)
9.5     BlPitchF(2) - Blade 2 final pitch for pitch maneuvers (degrees)
9.5     BlPitchF(3) - Blade 3 final pitch for pitch maneuvers (degrees) [unused for 2
blades]
---------------------- ENVIRONMENTAL CONDITIONS --------------------------------
9.81           Gravity     - Gravitational acceleration (m/s^2)
---------------------- FEATURE FLAGS -------------------------------------------
True    FlapDOF1    - First flapwise blade mode DOF (flag)
True    FlapDOF2    - Second flapwise blade mode DOF (flag)
True    EdgeDOF     - First edgewise blade mode DOF (flag)
False   TeetDOF     - Rotor-teeter DOF (flag) [unused for 3 blades]
False   DrTrDOF     - Drivetrain rotational-flexibility DOF (flag)
True    GenDOF      - Generator DOF (flag)
True    YawDOF      - Yaw DOF (flag)
False   TwFADOF1    - First fore-aft tower bending-mode DOF (flag)
False   TwFADOF2    - Second fore-aft tower bending-mode DOF (flag)
False   TwSSDOF1    - First side-to-side tower bending-mode DOF (flag)
False   TwSSDOF2    - Second side-to-side tower bending-mode DOF (flag)
True    CompAero    - Compute aerodynamic forces (flag)
False   CompNoise   - Compute aerodynamic noise (flag)
---------------------- INITIAL CONDITIONS --------------------------------------
0.0     OoPDefl     - Initial out-of-plane blade-tip displacement, (meters)
0.0     IPDefl      - Initial in-plane blade-tip deflection, (meters)
0.0     TeetDefl    - Initial or fixed teeter angle (degrees) [unused for 3 blades]
0.0     Azimuth     - Initial azimuth angle for blade 1 (degrees)
200.0   RotSpeed    - Initial or fixed rotor speed (rpm)
0.0     NacYaw      - Initial or fixed nacelle-yaw angle (degrees)
0.0     TTDspFA     - Initial fore-aft tower-top displacement (meters)
0.0     TTDspSS     - Initial side-to-side tower-top displacement (meters)
---------------------- TURBINE CONFIGURATION -----------------------------------
3.35    TipRad      - The distance from the rotor apex to the blade tip (meters)
0.30305 HubRad      - The distance from the rotor apex to the blade root (meters)
1       PSpnElN     - Number of the innermost blade element which is still part of the
pitchable portion of the blade for partial-span pitch control [1 to BldNodes] [CURRENTLY
IGNORED] (-)
0.0     UndSling    - Undersling length [distance from teeter pin to the rotor apex]
(meters) [unused for 3 blades]
0.1536  HubCM       - Distance from rotor apex to hub mass [positive downwind] (meters)
-0.7456 OverHang    - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2
blades] (meters)
-0.2307 NacCMxn     - Downwind distance from the tower-top to the nacelle CM (meters)
0.0910  NacCMyn     - Lateral  distance from the tower-top to the nacelle CM (meters)
(0.0910 for A)
0.5475  NacCMzn     - Vertical distance from the tower-top to the nacelle CM (meters)
24.3809 TowerHt     - Height of tower above ground level (meters)
0.515112       Twr2Shft    - Vertical distance from the tower-top to the rotor shaft
(meters)
0.0     TwrRBHt     - Tower rigid base height (meters)
-8.0    ShftTilt    - Rotor shaft tilt angle (degrees).  Negative for an upwind rotor.
0.0     Delta3      - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades]
0.0     PreCone(1)  - Blade 1 cone angle (degrees)
0.0     PreCone(2)  - Blade 2 cone angle (degrees)
0.0     PreCone(3)  - Blade 3 cone angle (degrees) [unused for 2 blades]
0.0     AzimB1Up    - Azimuth value to use for I/O when blade 1 points up (degrees)
---------------------- MASS AND INERTIA ----------------------------------------
0.0     YawBrMass   - Yaw bearing mass (kg)
260.5   NacMass     - Nacelle mass (kg)
113.0   HubMass     - Hub mass (kg)
0.0     TipMass(1)  - Tip-brake mass, blade 1 (kg)
0.0     TipMass(2)  - Tip-brake mass, blade 2 (kg)
0.0     TipMass(3)  - Tip-brake mass, blade 3 (kg) [unused for 2 blades]
39.81   NacYIner    - Nacelle inertia about yaw axis (kg m^2)
0.5     GenIner     - Generator inertia about HSS (kg m^2)
```

```
7.71    HubIner     - Hub inertia about rotor axis [3 blades] or teeter axis [2 blades]
(kg m^2)
---------------------- DRIVETRAIN ----------------------------------------------
100.0   GBoxEff     - Gearbox efficiency (%)
83.0    GenEff      - Generator efficiency [ignored by the Thevenin and user-defined
generator models] (%)
1.0     GBRatio     - Gearbox ratio (-)
False   GBRevers    - Gearbox reversal {T: if rotor and generator rotate in opposite
directions} (flag)
9999.9  HSSBrTqF    - Fully deployed HSS-brake torque (N-m)
9999.9  HSSBrDT     - Time for HSS-brake to reach full deployment once initiated (sec)
"junk.dat"     DynBrkFi    - File containing a mech-gen-torque vs HSS-speed curve for a
dynamic brake [CURRENTLY IGNORED] (quoted string)
9999.9  DTTorSpr    - Drivetrain torsional spring (N-m/rad)
0.0     DTTorDmp    - Drivetrain torsional damper (N-m/s)
---------------------- SIMPLE INDUCTION GENERATOR ------------------------------
99.9    SIG_SlPc    - Rated generator slip percentage [>0] (%)              Now HSS side!
999.9   SIG_SySp    - Synchronous (zero-torque) generator speed [>0] (rpm)  Now HSS side!
999.9   SIG_RtTq    - Rated torque [>0] (N-m)                               Now HSS side!
99.9    SIG_PORt    - Pull-out ratio (Tpullout/Trated) [>1] (-)
---------------------- THEVENIN-EQUIVALENT INDUCTION GENERATOR -----------------
9999.9  TEC_Freq    - Line frequency [50 or 60] (Hz)
9998    TEC_NPol    - Number of poles [even integer > 0] (-)
9999.9  TEC_SRes    - Stator resistance [>0] (ohms)
9999.9  TEC_RRes    - Rotor resistance [>0] (ohms)
9999.9  TEC_VLL     - Line-to-line RMS voltage (volts)
9999.9  TEC_SLR     - Stator leakage reactance (ohms)
9999.9  TEC_RLR     - Rotor leakage reactance (ohms)
9999.9  TEC_MR      - Magnetizing reactance (ohms)
---------------------- TOWER ---------------------------------------------------
10      TwrNodes    - Number of tower nodes used for analysis (-)
"SWRT_Tower.dat"  TwrFile - Name of file containing tower properties (quoted string)
---------------------- NACELLE-YAW ---------------------------------------------
0.0     YawSpr      - Nacelle-yaw spring constant (N-m/rad)
0.0     YawDamp     - Nacelle-yaw constant (N-m/rad/s)
0.0     YawNeut     - Neutral yaw position--yaw spring force is zero at this yaw (degrees)
---------------------- FURLING -------------------------------------------------
True    Furling     - Read in additional model properties for furling turbine (flag)
"SWRT_Furl.dat"  FurlFile    - Name of file containing furling properties (quoted string)
---------------------- ROTOR-TEETER --------------------------------------------
0       TeetMod     - Rotor-teeter spring/damper model (0: none, 1: standard, 2: user-
defined) (switch) [unused for 3 blades]
0.0     TeetDmpP    - Rotor-teeter damper position (degrees) [unused for 3 blades]
0.0     TeetDmp     - Rotor-teeter damping constant (N-m/rad/s) [unused for 3 blades]
0.0     TeetCDmp    - Rotor-teeter rate-independent Coulomb-damping moment (N-m) [unused
for 3 blades]
0.0     TeetSStP    - Rotor-teeter soft-stop position (degrees) [unused for 3 blades]
0.0     TeetHStP    - Rotor-teeter hard-stop position (degrees) [unused for 3 blades]
0.0     TeetSSSp    - Rotor-teeter soft-stop linear-spring constant (N-m/rad) [unused for
3 blades]
0.0     TeetHSSp    - Rotor-teeter hard-stop linear-spring constant (N-m/rad) [unused for
3 blades]
---------------------- TIP-BRAKE -----------------------------------------------
0.0     TBDrConN    - Tip-brake drag constant during normal operation, Cd*Area (m^2)
0.0     TBDrConD    - Tip-brake drag constant during fully-deployed operation, Cd*Area
(m^2)
9999.9  TpBrDT      - Time for tip-brake to reach full deployment once released (sec)
---------------------- BLADE ---------------------------------------------------
"SWRT_Blade.dat"      BldFile(1)  - Name of file containing properties for blade 1
(quoted string)
"SWRT_Blade.dat"      BldFile(2)  - Name of file containing properties for blade 2
(quoted string)
"SWRT_Blade.dat"      BldFile(3)  - Name of file containing properties for blade 3
(quoted string) [unused for 2 blades]
---------------------- AERODYN -------------------------------------------------
"SWRT_AeroDyn.ipt"    ADFile      - Name of file containing AeroDyn input parameters
(quoted string)
---------------------- NOISE ---------------------------------------------------
"SWRT_Noise.dat"      NoiseFile   - Name of file containing aerodynamic noise input
parameters (quoted string)
---------------------- ADAMS ---------------------------------------------------
```

```
"SWRT_ADAMS.dat"      ADAMSFile   - Name of file containing ADAMS-specific input
parameters (quoted string)
---------------------- LINEARIZATION CONTROL -----------------------------------
"SWRT_Linear.dat"     LinFile     - Name of file containing FAST linearazation parameters
(quoted string)
---------------------- OUTPUT --------------------------------------------------
True    SumPrint    - Print summary data to "<RootName>.fsm" (flag)
True    TabDelim    - Generate a tab-delimited tabular output file. (flag)
"ES10.3E2"    OutFmt      - Format used for tabular output except time.  Resulting field
should be 10 characters. (quoted string)  [not checked for validity!]
0.0     TStart      - Time to begin tabular output (s)
4       DecFact     - Decimation factor for tabular output [1: output every time step] (-)
5.0     SttsTime    - Amount of time between screen status messages (sec)
0.535   ShftGagL    - Distance from rotor apex [3 blades] or teeter pin [2 blades] to
shaft strain gages [positive for upwind rotors] (meters)
2       NBlGages    - Number of blade nodes that have strain gages for output [0 to 5] (-)
1, 2    BldGagNd    - List of blade nodes that have strain gages [1 to BldNodes] (-)
        OutList     - The next line(s) contains a list of output parameters.  See
OutList.txt for a listing of available output channels, (-)
"WindVxt,HorWindV, HorWndDir"                ! Wind speed and direction
"RotPwr, GenPwr"                     ! Rotor (mechanical) power and generator
(electrical) power
"Azimuth, RotSpeed"                  ! Rotor azimuth and speed
"TwrBsMxt, TwrBsMyt, TwrBsMzt"               ! Tower base roll, pitch, and yaw moments
"TailFurl"                                   ! Tail-furl angle (position)
"BldPitch1"                          ! Blade 1 pitch angle
"RootMxb1, RootMyb1, RootMzb1"               ! Blade 1 root moments
"OoPDefl1, IPDefl1"                  ! OoP and IP blade 1 tip deflections
"RootFxb1, RootFyb1, RootFzb1"               ! Blade 1 root forces
"RotThrust"                          ! Rotor thrust
"RotTorq, Gentq, LSSGagMys, LSSGagMzs"               ! Rotor & gen torque, Shaft moments
at gage, nonrotating
"NacYaw"                             ! Nacelle yaw angle
"Spn1MLxb1, Spn1MLyb1, Spn2MLxb1, Spn2MLyb1"         ! Spanwise flap and edge loads
"RootMxc1, RootMyc1"                                         ! Root OP and IP moments
"TFrlBrM"                                                    ! Furl bearing moment
END of FAST input file (the word "END" must appear in the first 3 columns of this last
line).
--------------------------------------------------------------------------------
"YawBrFxp, YawBrFyp, YawBrFzp"               ! Tower-top / yaw bearing axial and shear
forces
"YawBrMxp, YawBrMyp, YawBrMzp"               ! Tower-top / yaw bearing roll, pitch, and
yaw moments
"TwrBsFxt, TwrBsFyt, TwrBsFzt"               ! Tower base axial and shear forces
```

SWRT_Blade.dat File:

```
--------------------------------------------------------------------------------
---------------------- FAST INDIVIDUAL BLADE FILE ------------------------------
SWRT blade.  Windward Engineering. June 2005.
---------------------- BLADE PARAMETERS ----------------------------------------
21             NBlInpSt    - Number of blade input stations (-)
False          CalcBMode   - Calculate blade mode shapes internally {T: ignore mode
shapes from below, F: use mode shapes from below} [CURRENTLY IGNORED] (flag)
3.0            BldFlDmp(1) - Blade flap mode #1 structural damping in percent of critical
(%)
3.0            BldFlDmp(2) - Blade flap mode #2 structural damping in percent of critical
(%)
5.0            BldEdDmp(1) - Blade edge mode #1 structural damping in percent of critical
(%)
---------------------- BLADE ADJUSTMENT FACTORS --------------------------------
1.0            FlStTunr(1) - Blade flapwise modal stiffness tuner, 1st mode (-)
1.0            FlStTunr(2) - Blade flapwise modal stiffness tuner, 2nd mode (-)
1.0            AdjBlMs     - Factor to adjust blade mass density (-)
1.0            AdjFlSt     - Factor to adjust blade flap stiffness (-)
1.0            AdjEdSt     - Factor to adjust blade edge stiffness (-)
---------------------- DISTRIBUTED BLADE PROPERTIES ----------------------------
BlFract AeroCent       StrcTwst       BMassDen       FlpStff EdgStff GJStff  EAStff  Alpha
        FlpIner EdgIner PrecrvRef      PreswpRef      FlpcgOf EdgcgOf FlpEAOf EdgEAOf
```

```
   (-)    (-)    (deg)(kg/m)(Nm^2)  (Nm^2)  (Nm^2)      (N)   (-)      (kg m)(kg m)
                            (m)   (m)   (m)     (m)       (m)     (m)
0     0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.05  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.1   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.15  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.2   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.25  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.3   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.35  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.4   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.45  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.5   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.55  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.6   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.65  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.7   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.75  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.8   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.85  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.9   0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
0.95  0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
1     0.25  0   4.955   7.02E+03  3.62E+05  6.50E+03  2.00E+06  0   0   0   0   0   0   0.017  0   0
---------------------- BLADE MODE SHAPES---------------------------------------
 1.586         BldFl1Sh(2) - Flap , coeff of x^2
 0.006         BldFl1Sh(3) -      , coeff of x^3
-1.481         BldFl1Sh(4) -      , coeff of x^4
 1.218         BldFl1Sh(5) -      , coeff of x^5
-0.330         BldFl1Sh(6) -      , coeff of x^6
 -9.707        BldFl2Sh(2) - Flap , coeff of x^2
  9.871        BldFl2Sh(3) -      , coeff of x^3
 20.348        BldFl2Sh(4) -      , coeff of x^4
-30.197        BldFl2Sh(5) -      , coeff of x^5
 10.685        BldFl2Sh(6) -      , coeff of x^6
 1.587         BldEdgSh(2) - Edge , coeff of x^2
 0.004         BldEdgSh(3) -      , coeff of x^3
-1.477         BldEdgSh(4) -      , coeff of x^4
 1.215         BldEdgSh(5) -      , coeff of x^5
-0.329         BldEdgSh(6) -      , coeff of x^6
```

SWRT_Furl.dat

```
--------------------------------------------------------------------------------
---------------------- FAST FURLING FILE ---------------------------------------
SWRT input properties. Windward Engineering.  updated August, 2004. **Config B** with
0.083m offset (A has 0.106m)
---------------------- FEATURE FLAGS (CONT) -----------------------------------
False  RFrlDOF     - Rotor-furl DOF (flag)
True   TFrlDOF     - Tail-furl DOF (flag)
---------------------- INITIAL CONDITIONS (CONT) ------------------------------
0.0    RotFurl     - Initial or fixed rotor-furl angle (degrees)
50.0   TailFurl    - Initial or fixed tail-furl angle (degrees)
---------------------- TURBINE CONFIGURATION (CONT) ---------------------------
0.083  Yaw2Shft    - Lateral distance from the yaw axis to the rotor shaft (meters)
0.0    ShftSkew    - Rotor shaft skew angle (degrees)
0.0    RFrlCMxn    - Downwind distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
0.0    RFrlCMyn    - Lateral  distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
0.0    RFrlCMzn    - Vertical distance from the tower-top to the CM of the structure that
furls with the rotor [not including rotor] (meters)
1.7667 BoomCMxn    - Downwind distance from the tower-top to the tail boom CM (meters)
0.083  BoomCMyn    - Lateral  distance from the tower-top to the tail boom CM (meters)
0.2668 BoomCMzn    - Vertical distance from the tower-top to the tail boom CM (meters)
0.0    TFinCMxn    - Downwind distance from the tower-top to the tail fin CM (meters)
0.0    TFinCMyn    - Lateral  distance from the tower-top to the tail fin CM (meters)
0.0    TFinCMzn    - Vertical distance from the tower-top to the tail fin CM (meters)
```

```
2.7674  TFinCPxn    - Downwind distance from the tower-top to the tail fin center-of-
pressure (m)
0.083   TFinCPyn    - Lateral  distance from the tower-top to the tail fin center-of-
pressure (m)
0.1262  TFinCPzn    - Vertical distance from the tower-top to the tail fin center-of-
pressure (m)
0.0     TFinSkew    - Tail fin chordline skew angle (degrees)
-8.0    TFinTilt    - Tail fin chordline tilt angle (degrees)
8.0     TFinBank    - Tail fin planform  bank angle (degrees)
0.0     RFrlPntxn   - Downwind distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlPntyn   - Lateral  distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlPntzn   - Vertical distance from the tower-top to an arbitrary point on the
rotor-furl axis (meters)
0.0     RFrlSkew    - Rotor-furl axis skew angle (degrees)
0.0     RFrlTilt    - Rotor-furl axis tilt angle (degrees)
0.318   TFrlPntxn   - Downwind distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
0.083   TFrlPntyn   - Lateral  distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
0.470   TFrlPntzn   - Vertical distance from the tower-top to an arbitrary point on the
tail-furl axis (meters)
-45.2802       TFrlSkew    - Tail-furl axis skew angle (degrees)
78.7047 TFrlTilt    - Tail-furl axis tilt angle (degrees).
---------------------- MASS AND INERTIA (CONT) -------------------------------
0.0     RFrlMass    - Mass of structure that furls with the rotor [not including rotor]
(kg)
86.64   BoomMass    - Tail boom mass (kg)
0.0     TFinMass    - Tail fin mass (kg)
0.0     RFrlIner    - Inertia of the structure that furls with the rotor about the rotor-
furl axis (kg m^2) [not including rotor]
264.7   TFrlIner    - Tail boom inertia about tail-furl axis (kg m^2)
---------------------- ROTOR-FURL -------------------------------------------
0       RFrlMod     - Rotor-furl spring/damper model (0: none, 1: standard, 2: user-
defined) (switch)
0.0     RFrlSpr     - Rotor-furl spring constant (N-m/rad)
0.0     RFrlDmp     - Rotor-furl damping constant (N-m/rad/s)
0.0     RFrlCDmp    - Rotor-furl rate-independent Coulomb-damping moment (N-m)
0.0     RFrlUSSP    - Rotor-furl up-stop spring position (degrees)
0.0     RFrlDSSP    - Rotor-furl down-stop spring position (degrees)
0.0     RFrlUSSpr   - Rotor-furl up-stop spring constant (N-m/rad)
0.0     RFrlDSSpr   - Rotor-furl down-stop spring constant (N-m/rad)
0.0     RFrlUSDP    - Rotor-furl up-stop damper position (degrees)
0.0     RFrlDSDP    - Rotor-furl down-stop damper position (degrees)
0.0     RFrlUSDmp   - Rotor-furl up-stop damping constant (N-m/rad/s)
0.0     RFrlDSDmp   - Rotor-furl down-stop damping constant (N-m/rad/s)
---------------------- TAIL-FURL --------------------------------------------
1       TFrlMod     - Tail-furl spring/damper model (0: none, 1: standard, 2: user-
defined) (switch)
0.0     TFrlSpr     - Tail-furl spring constant (N-m/rad)
0.0     TFrlDmp     - Tail-furl damping constant (N-m/rad/s)
0.0     TFrlCDmp    - Tail-furl rate-independent Coulomb-damping moment (N-m)
65.0    TFrlUSSP    - Tail-furl up-stop spring position (degrees)
2.0     TFrlDSSP    - Tail-furl down-stop spring position (degrees)
17000.0 TFrlUSSpr   - Tail-furl up-stop spring constant (N-m/rad)
8000.0  TFrlDSSpr   - Tail-furl down-stop spring constant (N-m/rad)
65.0    TFrlUSDP    - Tail-furl up-stop damper position (degrees)
2.0     TFrlDSDP    - Tail-furl down-stop damper position (degrees)
1000.0  TFrlUSDmp   - Tail-furl up-stop damping constant (N-m/rad/s)
500.0   TFrlDSDmp   - Tail-furl down-stop damping constant (N-m/rad/s)
---------------------- TAIL FIN AERODYNAMICS --------------------------------
1       TFinMod     - Tail fin aerodynamics model (0: none, 1: standard, 2: user-defined)
(switch)
1       TFinNFoil   - Tail fin airfoil number [1 to NumFoil]
1.017   TFinArea    - Tail fin planform area (m^2)
True    SubAxInd    - Subtract average rotor axial induction when computing relative wind-
inflow at tail fin? (flag)
```

FAST to ADAMS Input File:

```
--------------------------------------------------------------------------------
---------------------- FAST 2 ADAMS PREPROCESSOR, ADAMS-SPECIFIC DATA FILE -----
SWRT WAGS ADAMS-specific data.
---------------------- FEATURE FLAGS -------------------------------------------
True       SaveGrphcs  - Save GRAPHICS output (flag)
False       MakeLINacf  - Make an ADAMS/LINEAR control / command file (flag
---------------------- DAMPING PARAMETERS -------------------------------------
   0.01     CRatioTGJ   - Ratio of damping to stiffness for the tower torsion
deflection  (-)
   0.01     CRatioTEA   - Ratio of damping to stiffness for the tower extensional
deflection  (-)
   0.01     CRatioBGJ   - Ratio of damping to stiffness for the blade torsion
deflections (-)
   0.01     CRatioBEA   - Ratio of damping to stiffness for the blade extensional
deflections (-)
---------------------- BLADE PITCH ACTUATOR PARAMETERS -------------------------
   1.0E12   BPActrSpr   - Blade pitch actuator spring stiffness constant (N-m/rad  )
   1.0E11   BPActrDmp   - Blade pitch actuator damping          constant (N-m/rad/s)
---------------------- GRAPHICS PARAMETERS ------------------------------------
  12     NSides      - Number of sides used in GRAPHICS CYLINDER and FRUSTUM statements
(-)
   0.3   TwrBaseRad  - Tower base radius used for linearly tapered tower GRAPHICS
CYLINDERs (m)
   0.3   TwrTopRad   - Tower top  radius used for linearly tapered tower GRAPHICS
CYLINDERs (m)
   1.2   NacLength   - Length of nacelle used for the nacelle GRAPHICS (m)
   0.4   NacRadBot   - Bottom (opposite rotor) radius of nacelle FRUSTUM used for the
nacelle GRAPHICS (m)
   0.4   NacRadTop   - Top    (rotor end)      radius of nacelle FRUSTUM used for the
nacelle GRAPHICS (m)
   0.4      GBoxLength  - Length, width, and height of the gearbox BOX for gearbox
GRAPHICS (m)
   0.5      GenLength   - Length of the generator CYLINDER used for generator GRAPHICS
(m)
   0.4      HSSLength   - Length of the high-speed shaft CYLINDER used for HSS GRAPHICS
(m)
   1.4      LSSLength   - Length of the low-speed shaft CYLINDER used for LSS GRAPHICS
(m)
   0.3      GenRad      - Radius of the generator CYLINDER used for generator GRAPHICS
(m)
   0.05     HSSRad      - Radius of the high-speed shaft CYLINDER used for HSS GRAPHICS
(m)
   0.1      LSSRad      - Radius of the low -speed shaft CYLINDER used for LSS GRAPHICS
(m)
   0.15     HubCylRad   - Radius of hub CYLINDER used for hub GRAPHICS (m)
   0.1      ThkOvrChrd  - Ratio of blade thickness to blade chord used for blade element
BOX GRAPHICS (-)
   0.05     BoomRad     - Radius of the tail boom CYLINDER used for tail boom GRAPHICS
(m)
```

INPUT DESCRIPTION FOR THE IEC WIND GENERATING PROGRAM IECWind

All 12 input lines should be present, although an error will only be generated for incorrect parameters that are actually used in the program session. The first parameter is the condition for which the wind will be generated. A list of the conditions to be used in this line is shown below in Table 1. All letters should be capitalized as they appear below. The option ALL can also be used to generate all conditions and all possible combinations. For more details on each condition see IEC standard 61400-1, 2nd edition.

The second parameter specifies the units; SI or ENGLISH. The units specified should indicate those for the wind speed in lines 5 and 6, and the same will be used for the output. The third parameter is the wind turbine class, 1, 2, 3, or 4, as specified by the IEC standard. This parameter is not used for condition ECG. The fourth parameter identifies the wind turbulence category (should be either A or B). This parameter is also not used for condition ECG. The fifth parameter is Vrated, which is the rated wind speed. The sixth parameter is Vout, or the cut-out wind speed. Either Vrated or Vout can be set to 0.0 (or less) and it will be ignored. If both are used, two wind files will be created–one for Vrated and one for Vout–for most cases. The exceptions are ECG and ECD for which Vout does not apply, and EWM for which neither is used (see the IEC 1400-1 standard for more details). The seventh parameter is the angle of the inflow to the rotor. The IEC standard (section 3.3) specifies a maximum inclination of 8 degrees with respect to the horizontal. This angle is assumed invariant with height. IECWind will print a warning to the screen for angles exceeding 8 degrees absolute value. The eighth parameter is the time in seconds for constant wind before the start of the IEC condition. This allows the turbine to stabilize before the start of the transient condition. This is not used for the steady EWM conditions. The ninth parameter is the time step used for the transient wind period in the wind file. The smaller the time step, the greater the number of points that will be generated, and the smoother the curve. Again, this is not used for the steady EWM conditions. The tenth parameter is used to determine the sign on conditions that require running both positive and negative cases to determine which case causes the most severe loading. The conditions requiring this sign specifier are listed in Table 1. Enter + for the positive cases and - for the negative cases or the word BOTH to generate both positive and negative cases where applicable. This parameter is ignored for cases in which it does not apply, and when ALL cases are generated, in which case both sign conditions are generated. The eleventh and twelfth parameters are the wind turbine hub-height and diameter, respectively, used to determine the turbulence scale parameter and severity of gusts, direction changes, and shears.

Table F-1: Summary of IEC Conditions

IEC Condition	Time duration of transient	Sign	Hub-Height Wind Speed
EOG50	14 sec	NA	rated/cut-out
EOG01	10.5 sec	NA	rated/cut-out
EDC50	6 sec	+/-	rated/cut-out
EDC01	6 sec	+/-	rated/cut-out
ECG	10 sec	NA	rated
ECD	10 sec	+/-	rated
EWSV	12 sec	NA	rated/cut-out
EWSH	12 sec	+/-	rated/cut-out
EWM50	NA	+/-	NA
EWM01	NA	+/-	NA

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6. **AUTHOR(S)** D. Corbus and M. Meadors	5d. **PROJECT NUMBER** NREL/TP-500-38660
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13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT** *(Maximum 200 Words)*

The Small Wind Research Turbine (SWRT) project was initiated to provide reliable test data for model validation of furling wind turbines and to help understand small wind turbine loads. This report will familiarize the user with the scope of the SWRT test and support the use of these data. In addition to describing all the testing details and results, the report presents an analysis of the test data and compares the SWRT test data to simulation results from the FAST aeroelastic simulation model.

15. **SUBJECT TERMS**

small wind research turbine; National Wind Technology Center; small wind turbine; furling; FAST aeroelastic simulation model

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