Power Performance Results Using Wind Turbine Blade Enhancing Devices Developed By Edge Aerodynamix

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Table of Contents

List of Figures

List of Tables

1 Introduction

Figure 1: CART2 wind turbine at the NWTC with black CVG tape shown on the leading edge of the blades. Photo by Lee Jay Fingersh, NREL.

In the wind industry, research is being done to enhance the rotors of horizontal axis wind turbines. These devices look to improve the performance of wind turbines by lower the cost of wind energy by either improving the power capture of the wind turbine, extending the turbine lifetime by reducing damage to the wind turbine, or both. One technology in the wind industry is leading edge tape used to protect wind turbine blades from damage due to debris impacting the blades. This technology has also been used in the helicopter industry for the same purpose. Research in the helicopter industry has shown that leading edge tape can reduce the aerodynamic performance of the blades [1].

Edge Aerodynamix, along with Edge Wind, LLC, has developed a leading edge tape that looks to improve the power performance of the wind turbine rotor as well as provide for protection of the wind turbine blades' leading edge from debris impacts. Additionally, Edge Aerodynamix has a trailing edge tab that in combination with the leading edge tape looks to provide further power performance improvement.

The National Renewable Energy Laboratory (NREL) along with its National Wind Technology Center (NWTC) has provided one of its field testing wind turbines, the Controls Advanced Research Turbine – 2 bladed (CART2), for a power performance field test to show a proof of concept for the leading edge tape and tab. A picture of the CART2 can be seen in Figure 1.

2 Test Objective

This project looks to test the performance of a prototype leading edge tape, as well as a combination of the leading edge tape with a trailing edge tab and compare both configurations to a commercially available leading edge tape. The first configuration that was tested is a commercially available linear leading edge tape. The second configuration that was tested is a prototype conformal vortex generator (CVG) tape developed by Edge Aerodynamix. The third configuration that was tested is a combination of the CVG tape from the second configuration with the addition of a trailing edge tab also developed by Edge Aerodynamix. These three configurations will be compared to each other using the turbine's electrical power output as a measure of power performance for a given inflow wind speed. The first configuration will be considered as a baseline case as it is common practice to use linear leading edge tape for blade protection.

3 Test Description

The wind turbine used for the field testing campaign at the NWTC is located south of Boulder, Colorado, USA. The NWTC at NREL has a rich history of field testing and is well equipped for the field tests needed for this proof of concept. The CART2 wind turbine at the NWTC has been utilized in the past for field testing different wind turbine technologies, and recently has been primarily focused on wind turbine controls research.

3.1 CART2 Wind Turbine Description

The CART2 is a variable speed/variable pitch horizontal axis wind turbine that has an extensive instrumentation suite as well as a dedicated met mast all of which is combined into a single data acquisition system that is capable of recording data at a rate of 400 Hz. For this test, the electrical power output from the power electronics converter will be used as a measure of power from the wind turbine. The CART2 has utilizes LabVIEW for its supervisory controller and operational controller allowing for a highly flexible controller that can be tailored to the specific needs of different field tests. Specifications of the CART2 parameters can be found in Table 1. Note that the rated rotor speed is for normal variable speed operation of the wind turbine. It will later be discussed for this test that the rotor speed parameter was modified. Additionally, more information on the CART2 can be found in [1].

Table 1: Specifications of the CART 2 Wind Turbine

Parameter	Value
Manufacturer	Westinghouse
Model	WWG-0600
Number of Blades	2
Hub Height	36.6 meters
Rotor Diameter	43.28 meters
Rated Electrical Power	600 kW
Rated Rotor Speed	41.7 RPM

3.2 CART2 Meteorological Tower Description

The CART2 wind turbine additionally has a dedicated met mast that is located approximately two rotor diameters upstream of the wind turbine from the predominant wind direction at the NWTC. This met mast is instrumented with Met One Instruments cup anemometers for measuring wind speed and Met One Instruments vanes for measuring wind direction at various heights above the ground. For this project, the hub height wind speed cup anemometer was used to measure the wind speed for the CART 2 wind turbine. The calibration sheet for the anemometer used in this test can be found in Figure 14 – Figure 16 in Appendix A.

3.3 CART2 Controller Description

Normally, the CART2's operational controller uses a variable speed mode, where the controller has been optimized to regulate the demanded generator torque based on the square of the generator rotational speed multiplied by a constant which is based on the rotor's aerodynamic performance [2]. However, this test looks to modify the rotor's aerodynamic performance and hence would invalidate the normal variable speed control law. This would result in suboptimal turbine performance. Instead, for this test, the operational controller was modified to run the turbine in a constant speed control mode. The generator torque controller used to govern the constant speed control is based off of a generator slip curve controller that has been used in region 2.5 for wind turbine control [3]. A 5% slip curve was used, with a rotor speed set point of 30 RPM. Additionally, a saturation value was placed on the maximum allowable torque demanded to protect the wind turbine from excessive electrical and mechanical loads. In higher wind speeds, the maximum torque would not be enough to maintain a constant rotor speed, and the rotor would be allowed to accelerate until it reached the rated rotor speed of 41.7 RPM, where the normal variable pitch controller would regulate the rotor speed to 41.7 RPM.

3.4 Blade Enhancing Device Configurations

As mentioned earlier, two configurations of blade enhancing devices were tested with the CART2 wind turbine and compared to a third baseline configuration. This section will describe each configuration in further detail.

3.4.1 Linear Leading Edge Tape

Commercially available linear leading edge tape was applied on the CART2 wind turbine blades for the first phase of field testing and will be considered as a baseline case for comparison. This phase will be referred to as “Linear Tape”. The linear tape was provided to NREL from Edge Aerodynamix and a sample can be seen in Figure 2. The duration of this testing phase went from June 14, 2016 to July 5, 2016. A total amount of 498 raw five minute data files were collected during this phase of testing.

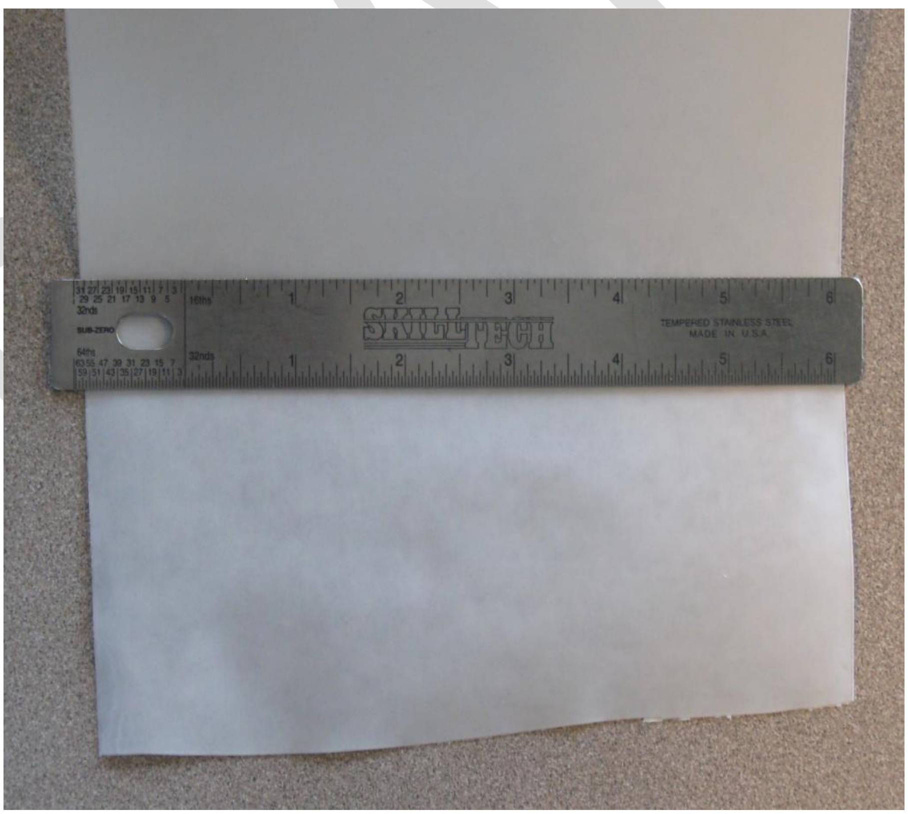

Figure 2: Commercially available linear leading edge tape used in the first phase of testing. Photo by Lee Jay Fingersh, NREL.

3.4.2 Edge Aerodynamix CVG Leading Edge Tape

CVG tape developed and manufactured by Edge Aerodynamix was applied to the CART2 wind turbine blades for the second phase of field testing. This phase will be referred to as “CVG Tape”. The CVG tape was provided to NREL from Edge Aerodynamix and a sample can be seen in Figure 3. A preliminary configuration was tested and it was found out early on that the CVG tape was not sized well for the chord length of the blades. The data from the preliminary configuration was not included in the results. It should be noted that this configuration was not optimized and is a proof of concept. The duration of this testing phase went from August 17, 2016 to April 10, 2017. A total amount of 5,002 raw five minute data files were collected during this phase of testing.

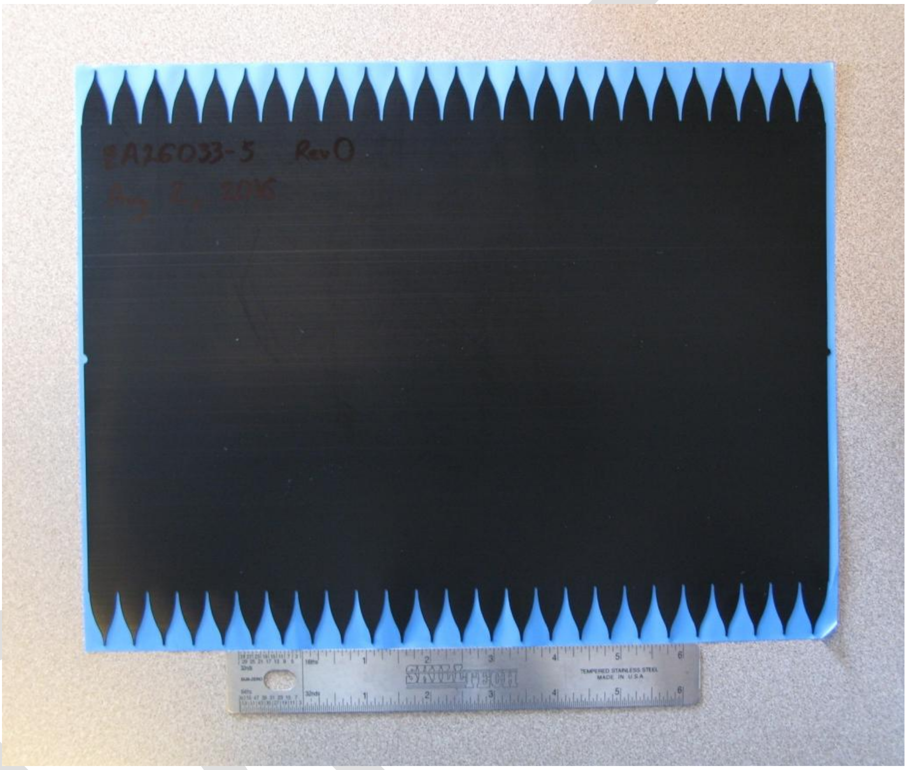

Figure 3: CVG leading edge tape used in the second phase of testing. Photo by Lee Jay Fingersh, NREL.

3.4.3 Edge Aerodynamix CVG Leading Edge Tape and Trailing Edge Tab

For the third phase, the CVG tape applied to the CART2 blades in the second phase remained in place on the turbine blades. A trailing edge tab was applied to the high pressure side of the blade approximately 1/4 of an inch inside of the trailing edge. The dimensions of the cross section of the tab are 1/4 of an inch in height by 1/2 of an inch in width. This phase will be referred to as "CVG Tape + Tab". The tab material was provided to NREL from Edge Aerodynamix and a sample can be seen in Figure 4. It should be noted that this configuration was not optimized and is a proof of concept. The duration of this testing phase went from April 12, 2017 and is currently ongoing. A total amount of 1,397 raw five minute data files were collected during this phase of testing as of May 18, 2017.

Figure 4: Tab material used in the third phase of testing. Photo by Lee Jay Fingersh, NREL.

4 Results

This section presents the results of the three configurations of blade enhancing devices. For the analysis, a single data point represents the mean and standard deviation (where applicable) of a five minute data file which contains five minutes of continuous data. Data files where the transients of the wind turbine starting up and shutting down were not included in the analysis.

The plots produced for the results compare the CART2 wind turbine power output against the hub height wind speed. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in red. Two types of plots are presented: a scatter plot where each data point is shown and a binned plot where the data has been binned according to wind speed and the turbine power averaged over the subset of data within each bin. Each bin has a 1 m/s width, and the bin edges are on whole integers (e.g. 0 – 1 m/s, 1 – 2 m/s, 2 – 3 m/s, etc.). Additionally, the binned plots show error bars that represent the standard deviation of the subset of turbine power data within each bin, and the size of the dot represents how much data is in the bin (a larger dot represents more data than a smaller dot).

Four pairs of plots are shown in Figure 5 – Figure 12. Each pair shows the data with different levels of turbulence intensities filtered out. Figure 5 and Figure 6 show the data with no turbulence intensity filter applied. Figure 7 and Figure 8 show the data with a turbulence intensity greater than 20% filtered out. Figure 9 and Figure 10 show the data with a turbulence intensity greater than 10% filtered out. Figure 11 and Figure 12 show the data with a turbulence intensity greater than 6% filtered out. Finally, a histogram plot is shown in Figure 13 to show the distribution of data for the wind speed bins over the three phases of field testing with no turbulence intensity filter applied.

An annual energy production (AEP) analysis was computed on the data set to get an estimate of the AEP value for each phase of testing. With 498 data points, the linear tape phase had an AEP estimate of 61.8 MW-h, with 5,002 data points the CVG Tape phase had an estimate of 74.7 MW-h, and with 1,397 data points the CVG Tape + Tab phase had an AEP estimate of 75.5 MW-h.

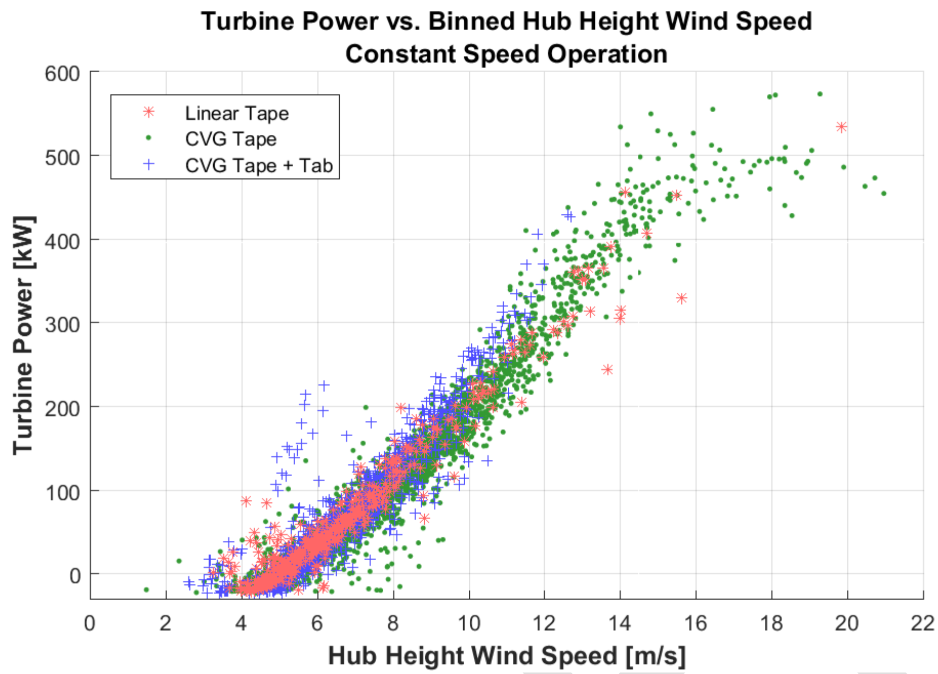

Figure 5: Scatter plot showing the turbine power vs. wind speed data for the three phases of field testing with no turbulence intensity filter applied. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

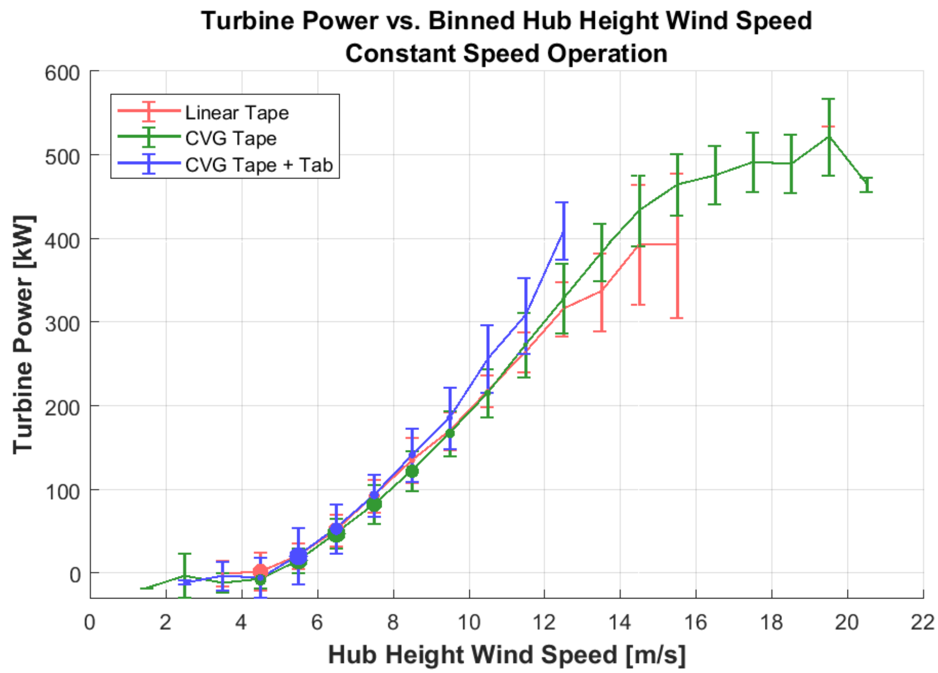

Figure 6: Binned Plot showing the turbine power vs. wind speed data for the three phases of field testing with no turbulence intensity filter applied. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

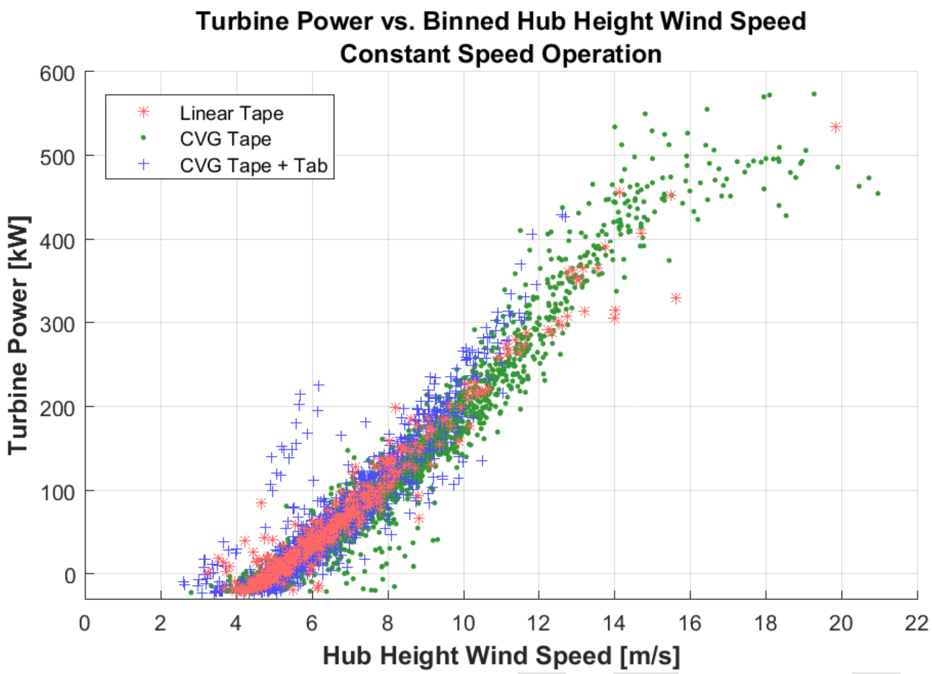

Figure 7: Scatter plot showing the turbine power vs. wind speed data for the three phases of field testing with turbulence intensity greater than 20% filtered out. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

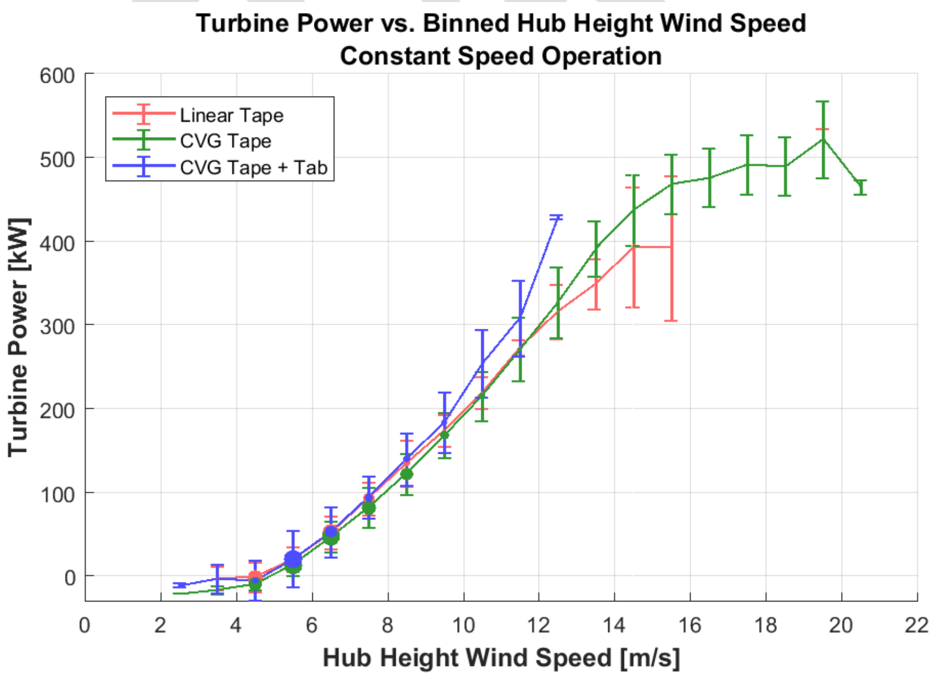

Figure 8: Binned plot showing the turbine power vs. wind speed data for the three phases of field testing with turbulence intensity greater than 20% filtered out. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

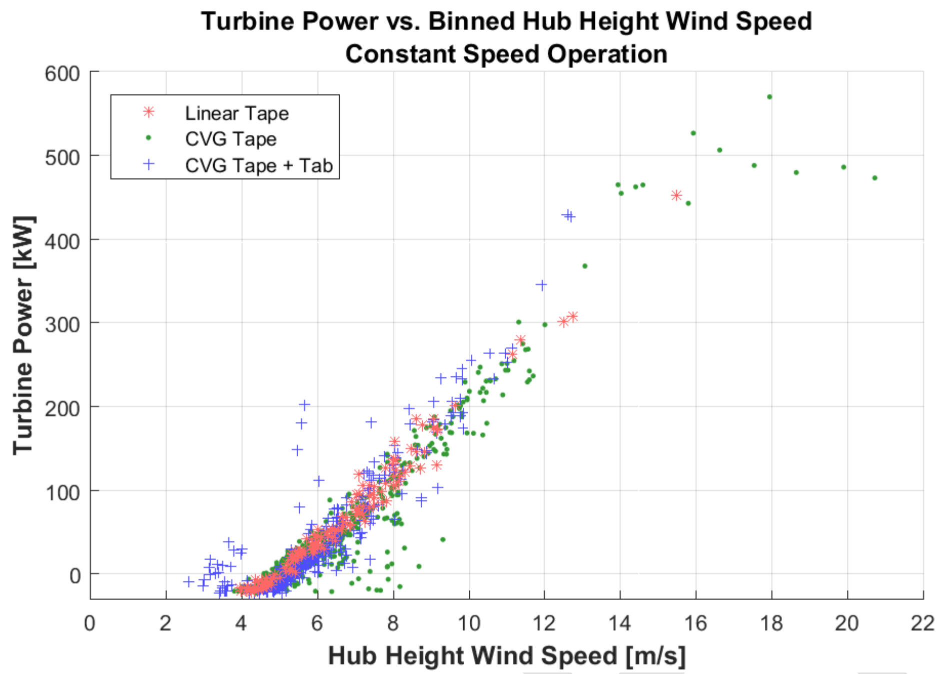

Figure 9: Scatter plot showing the turbine power vs. wind speed data for the three phases of field testing with turbulence intensity greater than 10% filtered out. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

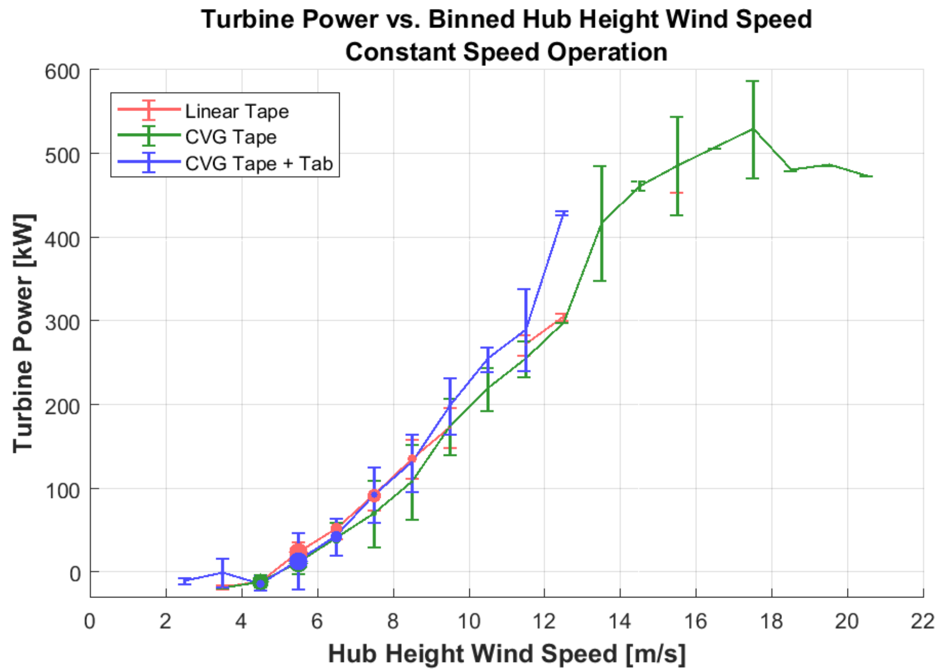

Figure 10: Binned plot showing the turbine power vs. wind speed data for the three phases of field testing with turbulence intensity greater than 10% filtered out. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

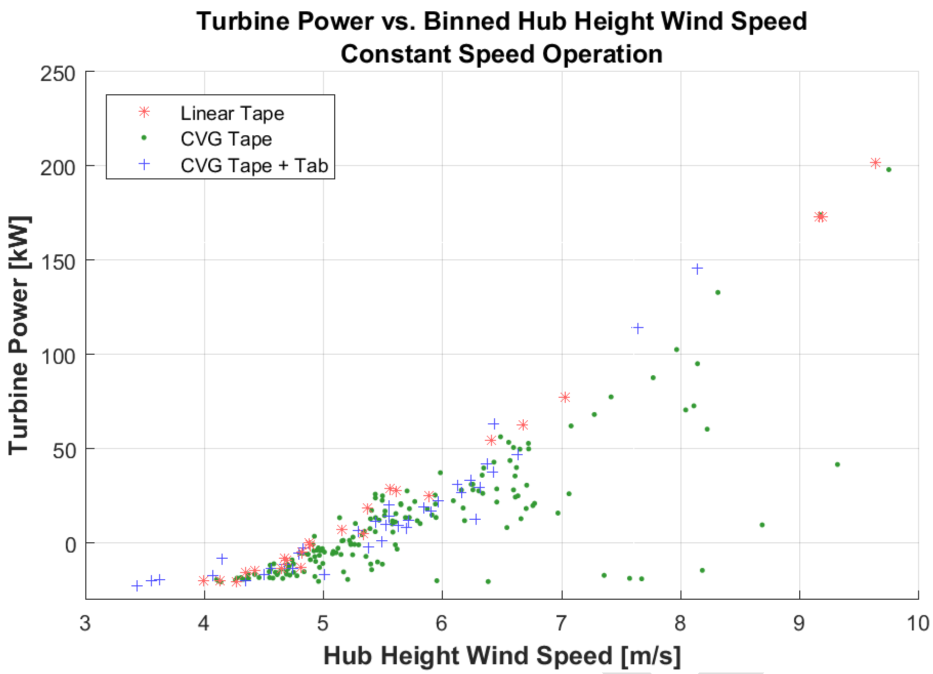

Figure 11: Scatter plot showing the turbine power vs. wind speed data for the three phases of field testing with turbulence intensity greater than 6% filtered out. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

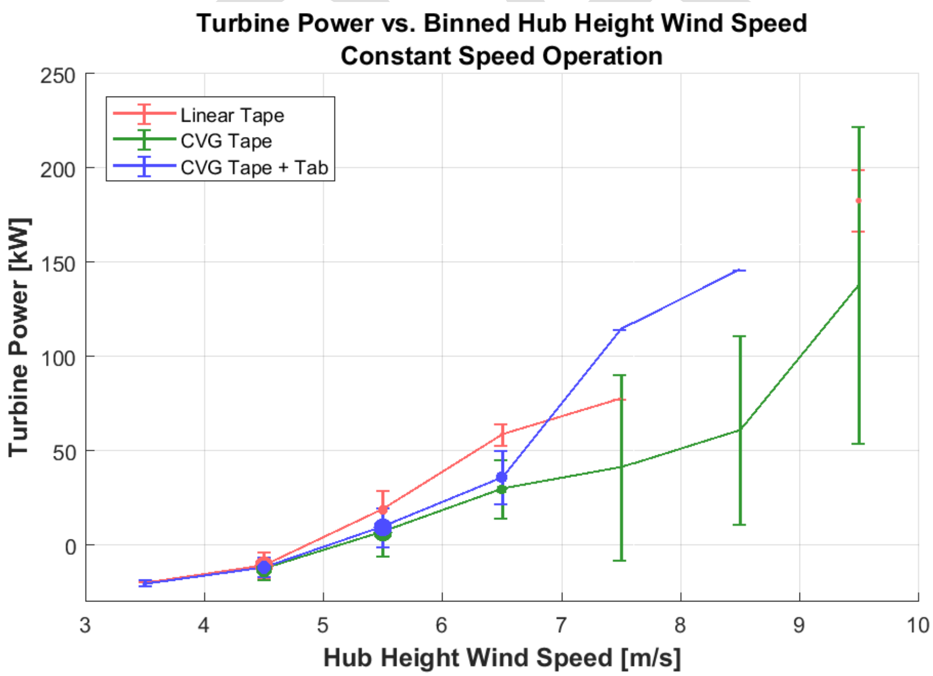

Figure 12: Binned plot showing the turbine power vs. wind speed data for the three phases of field testing with turbulence intensity greater than 6% filtered out. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

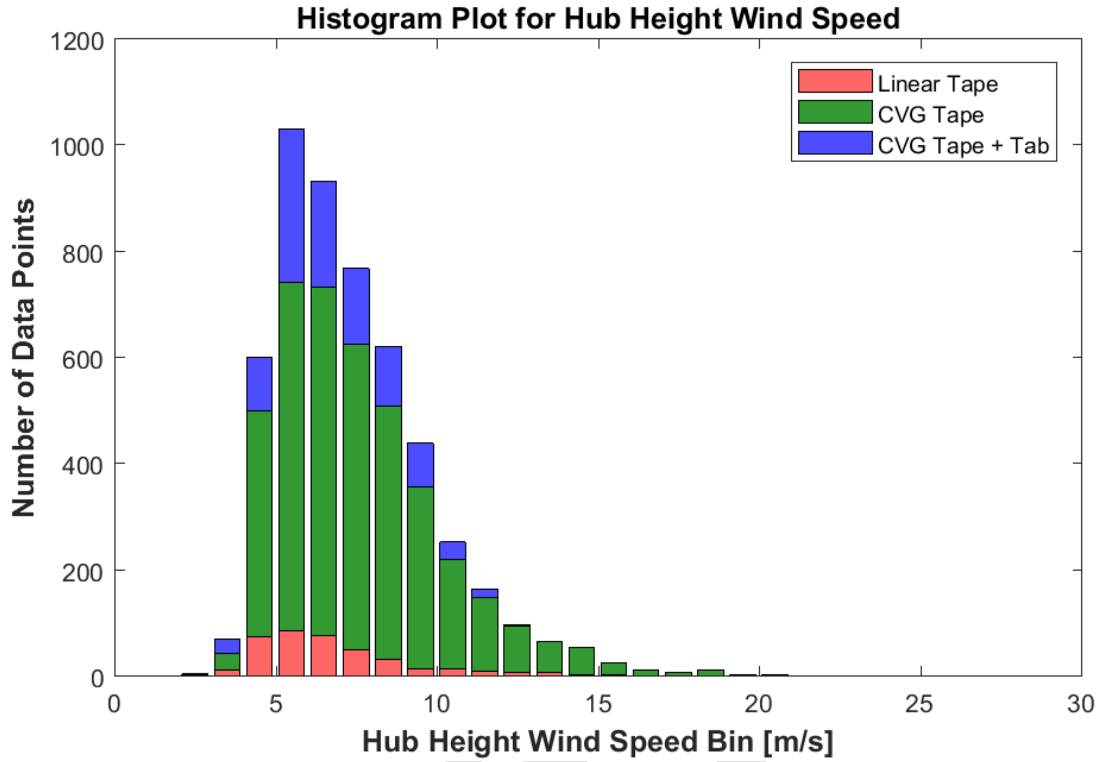

Figure 13: Histogram plot showing the distribution of data for the wind speed bins over the three phases of field testing with no turbulence intensity filter applied. The Linear Tape phase is shown in red, the CVG Tape phase is shown in green, and the CVG Tape + Tab phase is shown in blue.

5 References

[1] M. E. Calvert and T.-C. Wong, "Aerodynamic Impacts of Helicopter Blade Erosion Coatings," in *30th AIAA Applied Aerodynamics Conference*, New Orleans, Louisiana, 2012.

[2] L. J. Fingersh and K. Johnson, "Controls Advanced Research Turbine (CART) Commissioning and Baseline Data Collection," National Renewable Energy Laboratory, Golden, CO, 2002.

[3] P. W. Carlin, A. S. Laxson and E. B. Muljadi, "The History and State of the Art of Variable-Speed Wind Turbine Technology," *Wind Energy*, vol. 6, pp. 129-159, 2003.

[4] J. Jonkman, S. Butterfield, W. Musial and G. Scott, "Definition of a 5-MW Reference Wind Turbine for Offshore System Development," National Renewable Energy Laboratory, Golden, CO, 2009.

6 Appendix A – Calibration sheet for cup anemometer

04104C

Met One Instruments

Certificate of Calibration

Instrument:	Wind Speed Sensor	Model No.:	SS201
Manufacturer:	Met One Instruments	Serial No.:	W1918
Tested per PO:	VISA	Cup Serial No.	W1918A
Customer:	NREL	Sales Order No.:	104310

Instrument Condition Within Tolerance: As Found ___ As Left X

Corrective Action: No Adjustment ___ Adjust ___ Repair ___

Preventative Maintenance X

Quality Control Manual Revision: September 16, 2013 MP42201 Rev. G.
All Work Performed per Customer Purchase Order Requirements.
Calibration Document No. 41663-6101 42061-6101

As Found Test Date: N/A As Left Test Date 08/07/2014

Calibrated by: David Frith Signature: David Frith

Date: 08/07/2014

Test Equipment Used for Calibration of Instruments

Description	Manufacturer	Model No.	Serial No.	Cal Date	Cal Due	Accuracy
Digital Multimeter	Keithley	197A	490833	3/12/2014	3/12/2015	+/- 0.2% of input
Data Acquisition	Campbell Scientific	CR1000	9633	8/19/2013	8/19/2015	+/- 3 mV < 6 ppm timebase
Standard Cup Assembly	Met One Instruments	170.41	3309	4/24/12	4/24/2017	<0.15mph or 1% WS

Environmental Data: Temperature 65 to 80 DegF, Humidity 20% to 70%

The standards used for calibration have accuracies equal to or greater than the instruments tested. These standards are on record and are traceable to NIST to the extent allowed by the institute's calibration facility. Unless otherwise stated hereon, all instruments are calibrated to meet the manufacturer's published specifications. The calibration system complies with MIL-STD-45662A (8/1/88). Instruments accuracy meets the requirements of Regulatory Guide 1.23 (2/72). Compliant with ISO 9001:2008 requirements.

QC Inspection by: [signature] Date: 8/8/14

Figure 14: Calibration sheet (1 of 3) for the wind speed anemometer used for the field test.

Met One Instruments
3206 Main St., Suite 106
Regional Service Center
Rowlett, TX. 75088

Wind Tunnel Calibration
Data Sheet
41663-6101

*Test Cup Model No. C-201 Serial No. W1918A

*Test Sensor Model No. SS201 Serial No. W1918

*Calibrated as a matched pair

NIST Cup Model No. 170.41 Serial No. 3309
NIST Sensor Model No. 50.1B Serial No. 1263

Target Speed mph	NIST Monitor Calibration mph/Hz	NIST Monitor Frequency Hz	NIST Speed mph	Test Cup Frequency Hz	Test Cup Speed mph	Speed Diff mph	Spec +/- mph
5	0.093644	52.62	4.93	42.67	4.28	-0.65	1.00
10	0.087553	114.06	9.99	95.57	9.58	-0.41	1.00
15	0.085985	174.14	14.97	147.00	14.73	-0.24	1.00
20	0.085098	235.06	20.00	198.11	19.85	-0.15	1.00
25	0.084520	295.50	24.98	248.33	24.88	-0.10	1.00

Threshold: 0.89 mph

Instrument Test Condition As Found ____
As Left X

Customer: NREL
Purchase Order: VISA

Test Date: 08/07/2014
Sales Order: 104310

Test Technician David Frith DF

Figure 15: Calibration sheet (2 of 3) for the wind speed anemometer used for the field test.

MET ONE INSTRUMENTS

SS201 Wind Speed Sensor
Production and Repair Data
42061-6101

Date Tested	7/29/2014
Sales Order	104310
Customer	NREL
Customer P.O.	VISA
Serial Number	W1918
Output Vpp (8.0 Vpp Min.) (12.0 Vpp Max.)	10 vpp
Symmetry (% Duty Cycle)	50%
Current Drain (5ma Typical)	2.34 ma
Starting torque (< 1.0 gm-cm)	YES X NO
Shaft End Play (0.006 +/- 0.020)	0.019
Shaft and Hub Runout (< 0.005)	0.001

Instrument Condition: As Found: ____
As Left: X

Test Technician: ____

Figure 16: Calibration sheet (3 of 3) for the wind speed anemometer used for the field test.