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Aerodynamic and Performance Measurements on a SWT-2.3-101 Wind turbine.

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This paper provides an overview of a detailed wind turbine field experiment, which is currently being conducted at the National Wind Technology Centre (NWTC) as part of Combined Research And Development Agreement between Siemens Wind Power and the National Renewable Energy Laboratory (NREL) under U.S. Department of Energy (DOE) sponsorship. The main objective of the current field experiment is to obtain detailed knowledge of wind turbine aerodynamics, performance, noise emission as well as structural characteristics of the Siemens SWT-2.3-101 wind turbine being operated at a severe wind condition site with strong wind shear and high turbulence intensity. Detail of the setup for characterizing the inflow (met mast instrumentation and lidar) are provided. Also, the tests designed to measure loads during operation, structural blade modal tests, noise emissions tests, flow visualization tests as well as a description of the pressure system developed to map the rotor aerodynamics are discussed. Due to the physical environment, the rotation of the measurement equipment, the generated induction field of the turbine as well as the pressure tubing system, several data corrections methods have to be applied to the measured signals. These are described and applied to some selected time series, which are presented here. In general, the initial agreement with computational fluid dynamic computations at similar operational conditions is highly encouraging and provides a good basis for further development of currently used design tools. This resulting data and tools will eventually lead to reduced uncertainty in the design process and result in more cost-effective wind turbines in the future.

I. Introduction

Wind turbine technology is a major contributor to the global energy portfolio. Constant research and development is essential to continuous improvement of wind turbines and maintain a competitive edge over other technologies. Identifying this as a common goal, Siemens Wind Power and National Renewable Energy Lab (NREL) entered into a Combined Research and Development Agreement (CRADA) in December of 2008. Under this agreement a Siemens 2.3 MW turbine was installed on the National Wind Technology Center (NWTC) grounds in Golden, Colorado to support numerous research activities that will result in improved understanding of the wind turbines and provide high quality data that will lead to better and more efficient rotor designs. The site is particularly suitable for this study because of its ability to provide extreme wind conditions with strong shear, high turbulence intensity, severe wind ramps and gust events.

The test turbine erected under the CRADA agreement is a Siemens SWT-2.3-101 turbine. It is a pitch regulated variable speed turbine with a rated power of 2.3 MW and a rotor diameter of 101 m. The tower height is 80 m and the blades are 49m long designed specifically for reducing loads and increasing power at moderate wind speeds. The blades are made of fiberglass-reinforced epoxy using a Siemens' proprietary

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manufacturing process. The turbine is designed to run between wind speeds of 4-25 m/s with nominal power being reached at 12-13 m/s. The rotor speed varies between 6-16 rpm.

The overall objective of the CRADA is to enable a broad range of studies, designed to impact the wind turbine design cycle at multiple stages, including but not limited to

1. inflow characterization,
2. aerodynamic performance characterization,
3. operational loads performance,
4. structural characterization
5. noise emission,
6. turbine wake etc.

The goal of this paper is to provide an overview of studies that are currently underway or are planned to meet the overall objective. The work presented in this paper is more focussed on the aerodynamic tests, which are at a comparatively advanced stage.

II. Inflow Characterization

As the turbine size continues to grow, the interaction of turbine blades with the atmospheric boundary layer (ABL) is increasing in complexity. ABL qualities (shear,turbulence, etc.) have a great influence on the turbine operation and performance. Inflow characterization is thus not only essential to accurately predict the AEP but also the lifetime over which the turbine can be expected to perform without major deterioration. The objective of inflow characterization tests planned as a part of this study is to obtain data that can be used to correlate the power produced and loads acting on a turbine to variables that describe the inflow. Having such correlations will also enable short-term forecasting that can be used to improve the efficiency of the turbine, and avoid overloads by anticipating high load events such as a gust. A brief overview of the tools/equipment that are available for characterizing the inflow to the test turbine are discussed here.

A. Meteorological Towers

The need to accurately characterize the ABL as well as the inflow across the turbine rotor led to the design of a 135m (440 foot) meteorological tower for this project that is placed approximately 2 rotor diameters upwind of the turbine. This tower was based on the tower design used in the NREL Lamar Low Level Jet Project which was designed primarily to be extremely stiff so that tower motions wouldn't be detectable by the sonic anemometers leaving them free to measure only atmospheric conditions. However, this tower is both taller (135m versus 120m) and holds more instrumentation (six sonic levels versus four) thus necessitating some adjustments to the design. Further, the tower ended up having to serve double and triple duty for other projects ultimately leading to the installation of 13 instrumentation booms and several auxiliary devices for other purposes. All of this instrumentation requires substantial maintenance so a service lift was also custom-designed to facilitate frequent trips up the tower in a safe manner.

All of this customization led to substantial delays in the implementation of the 135m primary inflow tower. To help mitigate the effect of these delays, an existing nearby tower approximately 2.5 rotor diameters upwind of the turbine was placed into service for this project. This tower was 58m tall serving the Controls Advanced Research Turbines (CART) and was instrumented with one sonic, four levels of cups and vanes, and two levels of temperature, plus barometric temperature. For this project, the tower was extended to 80m and IEC-class instrumentation was placed at the top at turbine hub height. This included a class-1 cup at 80m, another at 78.5m along with a vane at that level, and a barometric pressure sensor and temperature sensor just below that. The data system was modified to run continuously at 20Hz and data has been collected during turbine pressure instrumentation commissioning procedures.

B. Lidar

In collaboration with University of Colorado, Boulder, a portable Windcube lidar has been installed on-site approximately 2.8 diameters upstream of the turbine in dominant wind direction to characterize the inflow.

The lidar is capable of measuring three velocity components (within 0-60m/s) within a 40-200m range, with scanning cone angle of 15° and 30°. Though the system is capable of producing high temporal resolution data, currently it is being used to acquire averaged data (over 10 minutes) at 40, 50, 60, 80, 100, 120, 140, 160, 180 and 200 meters above the ground.

III. Operational Loads Tests

The main purpose of the operational loads test is to identify how the SWT-2.3-101 wind turbine operates for a wide range of inflow conditions, such as high wind and high turbulence, during normal operation, idling, cut-in and cut-out. The data will also allow validation of in-house aeroelastic tools that are used as an integral part of the blade design process. In order to use the load measurements for validation, wind inflow data is also captured simultaneously. To enable this study each of the three blades is instrumented with four strain gauges. Additional strain gauges are installed in the nacelle and the tower. In addition to the strain gauges the turbine is also instrumented with bi- and tri-axial accelerometers at various locations, which will provide data sufficient to determine the modes of the tower and the blades. Though the system is in place to acquire all the data required to meet the objectives of this test, analysis of the data has not been started yet.

IV. Blade Modal Tests

One of the most important part of the blade design cycle is determination of the structural response of a blade to ensure that modes that can be detrimental to the blade are not excited in the expected range of operation. A series of modal tests are planned as a part of this study to obtain data that will be compared against the structural models that are used in computations. This section provides information about the tests that have been conducted and are planned for the future.

A structural test of the B-49 blade was conducted at the NWTC to verify the structural data used in Siemens' aeroelastic codes. The blade test included a static loads test and a modal test. The static loads test was performed on a smaller 5.4 MN-m Stand and aims to verify the blade stiffness properties. The modal test would be conducted in two phases, on the 5.4 MN-m stand and on a larger and more stiff 16.7 MN-m stand. The goal of the modal test was to identify the modal properties (frequencies, damping, and mode shapes) of the first ten blade modes. Blade adapters were designed and built to allow blade attachment to both blade test stands.

In the static loads test, the blade was mounted in the cantilever position with the leading edge down, and the loads were applied at two blade stations separately (37 m and 48 m). Two wooden saddles were built for each station so the loads can be applied safely to the blade. To simulate the flap loads, a tractor applied a side pull to the blade; the edge loads were simulated using dead weights. For the torsion test, the torsion loads were applied through the saddle with one end supported from above by a crane and the other

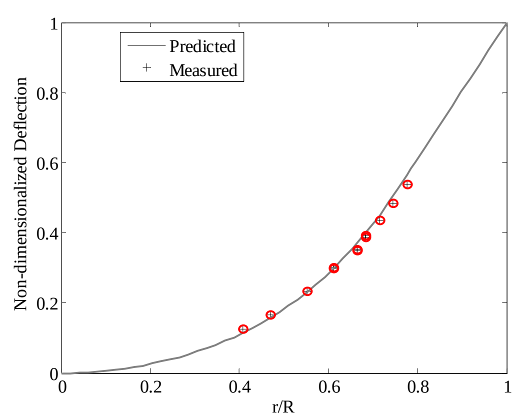

Figure 1. An example of data that was obtained from a modal test.

end hung by dead weights. The static loads were applied at several levels and were measured with load cells. Blade flap and edge deflections were measured using a laser tracker and string pods; inclinometers measured the blade twist. Figure 1 shows a sample test result for the edgewise static load test.

In addition to the static loads test, the first phase of the modal tests was performed on the 5.4 MN-m stand, where the blade was cantilevered with the leading edge facing down. For this test, accelerometers were mounted at ten stations along the blade span at the leading edge, trailing edge, and mid chord. Additionally, accelerometers at the blade roots and on the stand were used to measure their relative motions. Blade excitations were applied using impact hammer at several blade stations. Data acquisition and modal analysis were performed with LMS Test Lab. Modal data were extracted using LMS's PolyMAX method. The modal test was able to identify more than the first ten blade modes, and the preliminary test results correlate fairly well with prediction. However, the measured frequencies were found to be 4-8 percent lower than prediction, probably due to the stand stiffness. Thus, the blade modal test would be repeated on the larger, stiffer 16.7 MN-m stand in the next phase.

V. Noise Tests

The SWT 2.3-101 at the NWTC has also been utilized in noise emission evaluation and mitigation studies since its commissioning. The majority of the testing is based around noise reduction through the use of aerodynamic devices, with the aim of reducing the aero-acoustic noise without forcing the turbine to operate in a curtailed state. Measurements of some preliminary aero-acoustic noise mitigation devices show that a broadband noise reduction of up to at least 2 dB can be achieved at peak noise levels. Figure 2 shows the background corrected sound power levels versus wind speed for the standard turbine blade configuration compared to measurements made after the application of aero-acoustic noise mitigation devices to the blades.

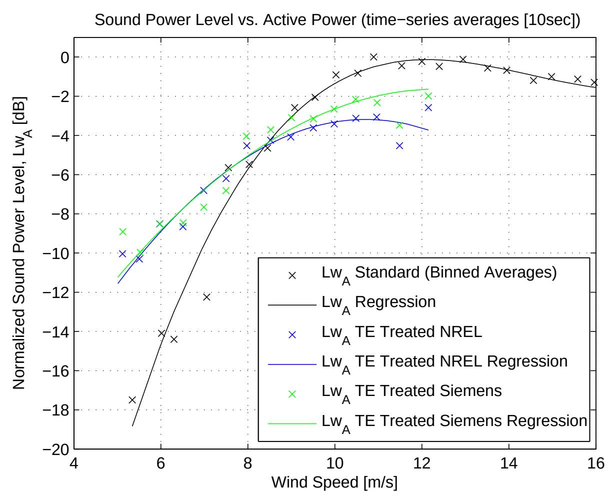

Figure 2. Results from a noise measurement campaign on the turbine that compare baseline and aero-acoustically treated blades.

The measurements shown in figure 2 were made in accordance to the IEC 61400-11 standard [ref.1]. In addition to single microphone measurements, a small acoustic array has been employed in the evaluation of noise to attempt to localize dominate noise emission locations and better understand the directionality of these noise sources. Examples of these measurements can be seen in figure 3.

VI. Flow Visualization

To characterize blade suction surface boundary layer state and flow field topology with high spatial resolution, oil-flow visualization tests were conducted in May 2010. These visualizations were especially well suited to discerning the effect of different vortex generators under varying operating conditions. Due to constraints related to turbine blade access and environmental sensitivity at the NREL/NWTC site, new

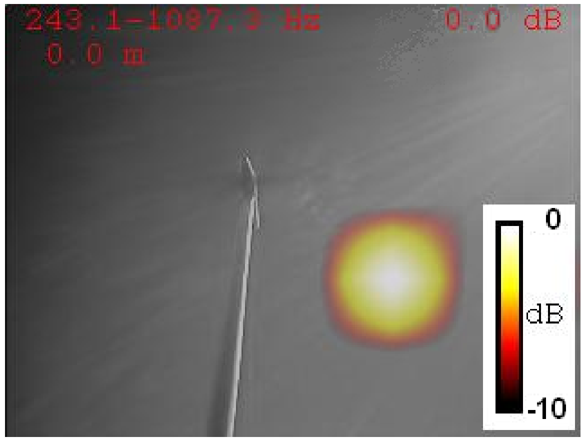

Figure 3. An example of acoustic image from data acquired using the acoustic array.

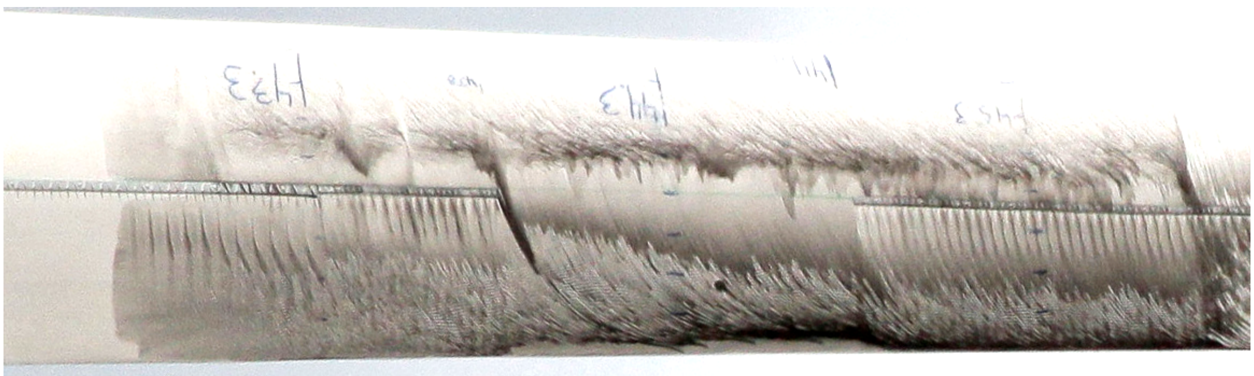

Figure 4. Typical oil flow visualization on wind turbine blade suction surface, through the blade radius range 0.84 ≤ r/R ≤ 0.91. Leading edge is at upper border.

variations on traditional oil-flow techniques were developed. The relatively long time period and possible variation between separate test runs resulted in the use of a vegetable based oil that remained present and fluid throughout the test and was environmentally friendly. Despite inherent challenges and limitations, this new oil flow technique was effective in providing high quality measurements of the surface flow conditions during operation.

Oil flow visualization tests were performed on the blade over the radial region 0.85R ≤ r/R ≤ 0.91R. Vortex generators were installed at 0.60c, from 0.85R to 0.87R and from 0.89R to 0.91R. Two sizes of vortex generators were used, with a height of 8 mm from radius 0.85R to 0.86R and 6 mm from 0.86R to 0.87R and from 0.89R to 0.91R. The blade was left clean in the center region of study between radius 0.87R and 0.89R.

A Grove GMK5275 hydraulic crane with a man basket was used to provide access to the blade, approximately 60 m above ground level. A combination of vegetable based oil and pigment were mixed together and applied to the blade using a standard paint roller. Once the oil pigment mix was applied to the blade, the man basket was lowered and the crane boom was moved clear of the rotor. Finally, the turbine locks necessary for man basket work on the blade were released and the turbine was allowed to operate. This process resulted in a 10 to 20 minute delay from the time the oil was applied until the turbine began operating.

Still photography was taken either from the ground or from the top of a nearby wind turbine at a height of approximately 40m. Distance from camera to test turbine varied somewhat from test to test, but was approximately 200 m. An 18 megapixel APS-c digital SLR was used with a 400mm lens to provide spatial resolution of approximately 3 mm at the blade surface. Because the turbine was rotating and the section of interest was tracked by hand, a fast shutter speed of 1/4000th was selected to minimize motion blur arising from imperfect tracking. An attempt was made to capture approximately five frames per rotor revolution, at the 12, 3, 5, 7, and 9 o'clock positions. The 6 o'clock position was avoided because the tower blocked the view of the rotating blade.

Figure 4 contains a typical suction surface flow visualization photo. Visible in the panel is a planform view of the blade suction surface for the radius range $0.84R \leq r/R \leq 0.91R$. A black border has been drawn around the blade to clearly demarcate its extent. The blade leading edge is located near the top of the panel and the tip lies to the right. The oil visualizing medium is prominent over much of the frame as the dark medium irregularly patterned over the light blade surface. The oil flow pattern in Figure 4 shows well defined, narrow dark bands parallel to the blade trailing edge. The photo shown in Figure 4 represents a low angle of attack that normally would result in negligible trailing edge separation. Clearly, the vortex generators were effective in delaying trailing edge separation, as they shifted separation 0.05c to 0.10c farther aft for the same angle of attack.

VII. Aerodynamic Testing

One of the major research goals of this turbine is to characterize the general aerodynamic behavior of wind turbine blades and more specifically those that are used on the SWT-2.3-101 turbine. The data resulting from this study will be used to validate the CFD tools and develop robust analytical models that are essential part of the blade design procedure. The data will thus play a critical role in producing tools that will lead to better and more efficient blades. This section describes the relevant instrumentation, methodology being used for the aerodynamic measurements, and initial results obtained so far.

A. Pressure Instrumentation

In order to obtain useful surface pressure data, one of the blades is extensively instrumented to provide the pressure measurements at nine span-wise locations. Each of the nine span-wise locations has approximately 60-64 pressure taps, distributed based on surface curvature, that provide sufficient resolution to develop reliable models and CFD comparisons. Figure 5 depicts the span-wise locations used on the blade for pressure measurements and 5-hole pitot probes. The pressure at each of these stations is acquired using a combination of ZOC33 and ERAD-4000 modules from Scanivalve Corporation at 25 Hz and is transmitted wirelessly to a remote computer for storage and post-processing. To avoid the sensor drifts due to variation in temperature, the pressure modules are housed in a Temperature Control Unit(TCU) that maintains the temperature of the modules at $\approx 25°C$. Additionally, in an attempt to reduce operational damage, the instruments are mounted within 25 m blade radius and aligned appropriately as suggested by the manufacturer. Furthermore, four 5-hole pitot probes manufactured by Aeroprobe are installed to measure inflow angles and velocities and are also shown in figure 5. These probes extend approximately 0.6m into the flow and the setup for the data acquisition is essentially the same as that was described for the pressure measurements. A standard data reduction scheme is used for post-processing of the acquired data.

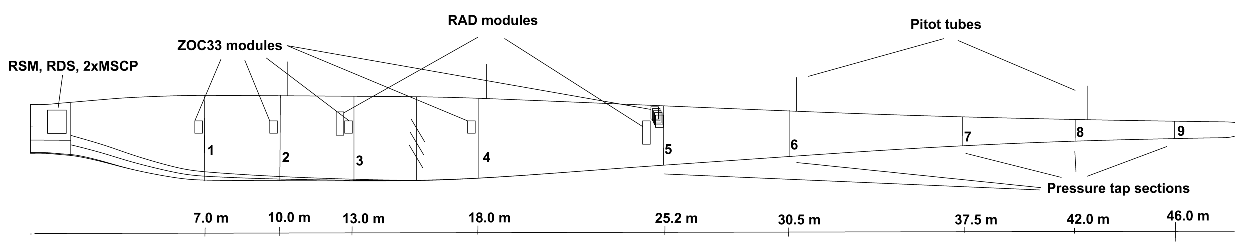

Figure 5. Schematic of the instrumented blade showing the locations of measurements stations and 5-hole pitot probes.

B. Post-Processing: Data Corrections

Past studies[1,2] have shown that certain physical phenomenon manifest themselves on the actual pressure distribution and must be accounted for in the pressure measurements conducted on a turbine. While, most of these corrections are well understood and have been successfully implemented previously, the nature of measurements being conducted here also require an additional correction that have not been used on turbine scale experiments previously. As will be evident, validation tests for some of these corrections were conducted using actual measurement configuration for increased confidence. For the remaining corrections, validations test are planned and will be carried out in near future. To summarize (for details, references 1–3 are suggested), the corrections implemented for this work are,

1. Centrifugal correction: The column of air trapped between the sensor and the port exerts a net negative force on the sensor diaphragm as the blade rotates. The resulting difference in measured and actual surface pressure, due to the centrifugal force is purely a function of span-wise location of the port, and is given by,

$$P_{cent} = 0.5\rho\left(\frac{V_{tip} r_{\mathrm{sec}}}{R}\right)^2$$

2. Hydrostatic correction: As the blade rotates, the position of the transducer varies in the vertical direction, thus resulting in varying hydrostatic pressure acting on the transducer diaphragm during the course of rotation ($\approx$ 10 Pa/m at the test site). For a differential pressure transducer, it can be shown that the resulting pressure changes will be negligible. However, since both the reference and measurement side of the transducer are attached to tubing, a phase shift will be introduced that depends on the geometry of the tubing and the ambient conditions. The equation for the resulting pressure change due to the hydrostatic effect is then given by,

$$\Delta P_{HS} = -\rho g r \cos(\theta - \phi_{pr}) - (-\rho g r \cos(\theta - \phi_{ref}))$$

   Where, θ is the azimuthal angle and ϕ represents the phase lag on the pressure side and reference side of the transducer, as indicated by the sub-scripts pr and ref, respectively. The phase lags are modeled using the methodology discussed for tubing effect corrections later in this section.

3. Reference pressure correction: For the setup currently used in the CRADA turbine, the reference ports of the transducers are not open to the atmosphere but a closed basket (with small leak) in the hub. Thus, in order to reference the measurements to the free stream static pressure, the measured pressures must be offset appropriately. This offset can be calculated using the measured stagnation pressure and the free stream velocity. Mathematically, this offset is determined by using

$$P_{Offset} = P_{\infty} - P_{basket} = P_{stag,measured} - Q_{met}$$

4. Pressure correction for the tubing effect: In addition to what was discussed above, in the current setup the pressure measurements are conducted remotely, where the sensors are not flushed with the surface, but are connected to the surface ports through long pressure tubing of varying geometry. In such cases, the tubing affects the pressure measurements in a manner similar to a low pass filter by attenuating the amplitude and introducing a phase shift as compared to the original signal.[3] In order to reconstruct the original signal, a transfer function is created based on the tubing geometry used for the measurements and the local conditions at the time of measurements. This method was validated using wind tunnel tests and the results (an example of which is shown in figure 6) showed that the original signal can be reconstructed with a high degree of accuracy.

C. Current Results

The ultimate objective of this measurement campaign is to use the acquired data for improvement of multiple processes that are essential for an efficient rotor design. Currently, preliminary data analysis is being conducted that will lead to the development of a database with a much wider utility. This section briefly describes the results of these preliminary analysis.

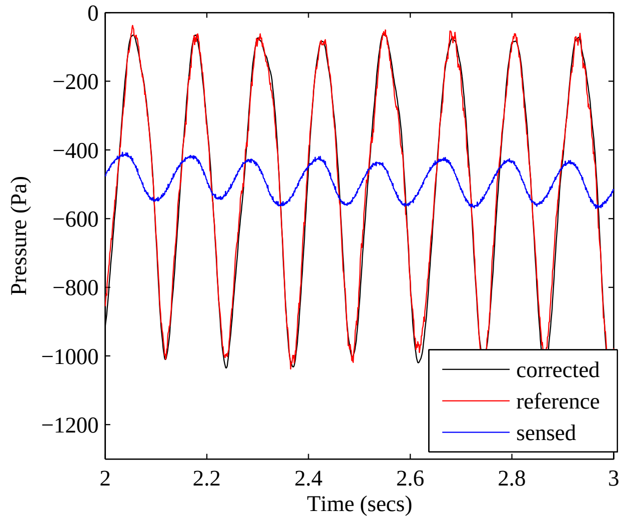

Figure 6. Results from validation tests for the tubing correction on an airfoil pitching at 8 Hz. The Sensed signal is measured by the remote sensor, the reference signal is from a flush mounted transducer for validation and the corrected pressure is the corrected sensed signal.

1. Inflow angle and velocity: 5-hole pitot probes

In order to correctly identify the comparison points for the experimental and computational data, it is essential to determine the correct inflow angle and velocity at which the data is acquired. The 5-hole pitot probes that are mounted on the leading edge of the blade are one of the most direct and reliable method to instantaneously determine the inflow angles and velocities the turbine blades are subjected to as they go undergo rotation. Such direct measurements essentially eliminate the need to account (in post-processing) for turbulence, yaw and shear in the flow, that can dynamically alter the angle of attack the blade experiences. To provide an example of the type of data acquired and post-processing, figure 7 is presented. The acquired pressures P1-6 are shown in the two figures in first column and the variables obtained after post-processing (local inflow and slip angles and local velocity) are shown in the figures in second column. Clearly, the importance of having such data cannot be underestimated, as it produces parameters that must be used for accurate comparison of data with CFD results. In future the tools used for processing the 5-hole probe data will include upwash corrections for improved accuracy. The data will then be used to extract additional parameters, such as shear and turbulence in the rotor plane.

2. Surface Pressure Measurements

As one of the main objective of the aerodynamic testing is to develop a database for comparison with CFD results, the raw data is post-processed after acquisition using methods described previously and compared with the CFD results. As an example, the pressure distributions (after applying the corrections mentioned previously) for the nine stations at $V_\infty \approx 10m/s$ are shown in figure 8. The gaps in the measured data are due to a filtering of channels showing bad data due to freeze, plug, etc.. As the figure shows, the experimental and CFD data are in better agreement at the outboard stations than at the inboard stations. This is due to inability of CFD tools to capture the pressure distribution accurately over thick airfoils. This is a perfect example that shows applications that can benefit from the data being collected in this campaign. On the outboard stations CFD does a very good job predicting the pressure distribution.

The results shown in figure 8 also show the importance of the corrections that are being used in this work. To emphasis the need of correction additional data at $V_\infty \approx 20m/s$ is shown in the figure 9. For this case, the CFD tools do an extremely well job of predicting the pressure distribution at outboard stations. The mismatch at inboard stations can be attributed to points that were discussed earlier. Nonetheless, the good agreement at outboard stations is a result of corrections and would not have been otherwise possible.

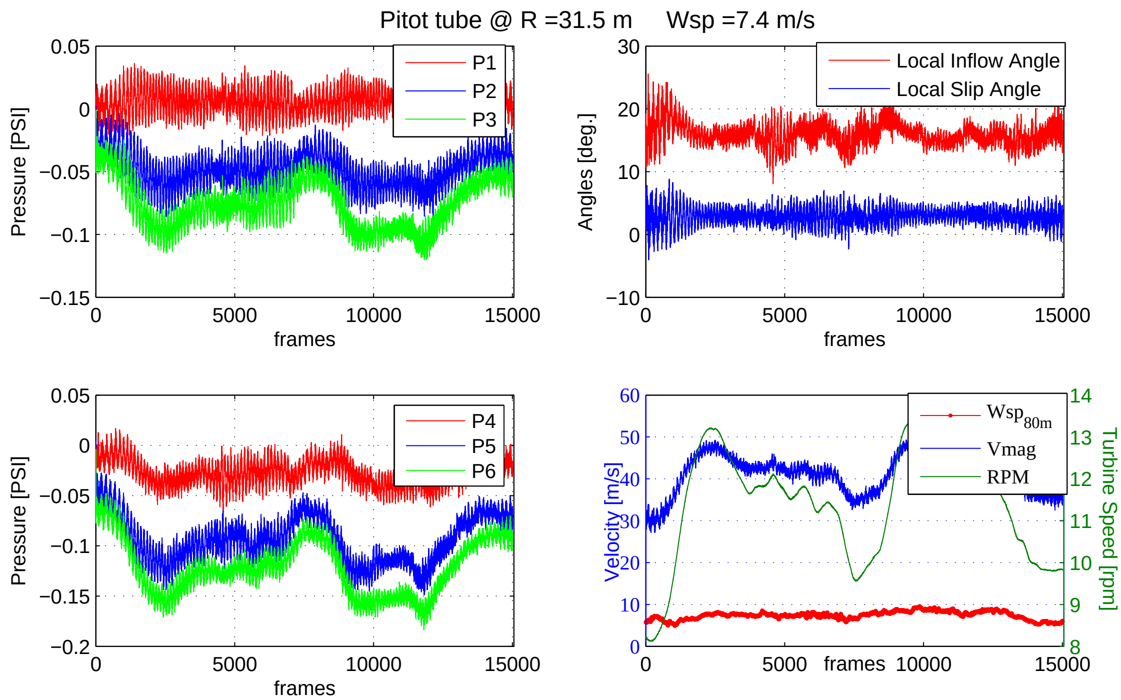

Figure 7. An example to demonstrate the data acquired and analyzed from five-hole pitot probes.

D. Collaboration with Academia

Besides the collaboration with government labs, such as NREL, Siemens Wind Power A/S is also dedicated to creating long lasting relation with academia and train future engineers to meet industry needs. To further this goal, currently two interns, from Technical University of Denmark are involved in development of post-processing tools and will be using the resulting data as part of their graduate thesis work. The students are currently involved in developing tools for implementing the corrections, aerodynamic characterization, and the inflow characterization using the data from 5-hole pitot probes, surface pressures, met mast and the on-site Lidar.

VIII. Conclusions

A Siemens SWT-2.3-101 turbine was installed as part of a Combined Research And Development Agreement (CRADA) between National Renewable Energy Lab and Siemens. The turbine was installed on NREL site in Boulder, CO, which is known to provide extreme wind conditions with strong shear, high turbulence intensity, severe wind ramps and gust events. The tests that have been completed or are planned in near future include inflow characterization, aerodynamic performance characterization, loads performance, noise emissions etc. As part of this ongoing research effort, tools have been developed to account for distortions that are inherent to the nature of experiments. The quantitative results obtained so far (such as those from noise emission tests and aerodynamic tests) have proven beneficial and have helped in identifying some of the areas in which improvements can be made. Final results from such a broad range of tests on the turbine will allow to produce high quality data that can be used to validate, improve and produce a wide range of in-house tools that are used as part of turbine design cycle.

IX. Future Work

With majority of the systems required for the studies outlined in this paper in place, future efforts will concentrate on data acquisition and analysis for a wide range of wind velocities. Finally, as part of this

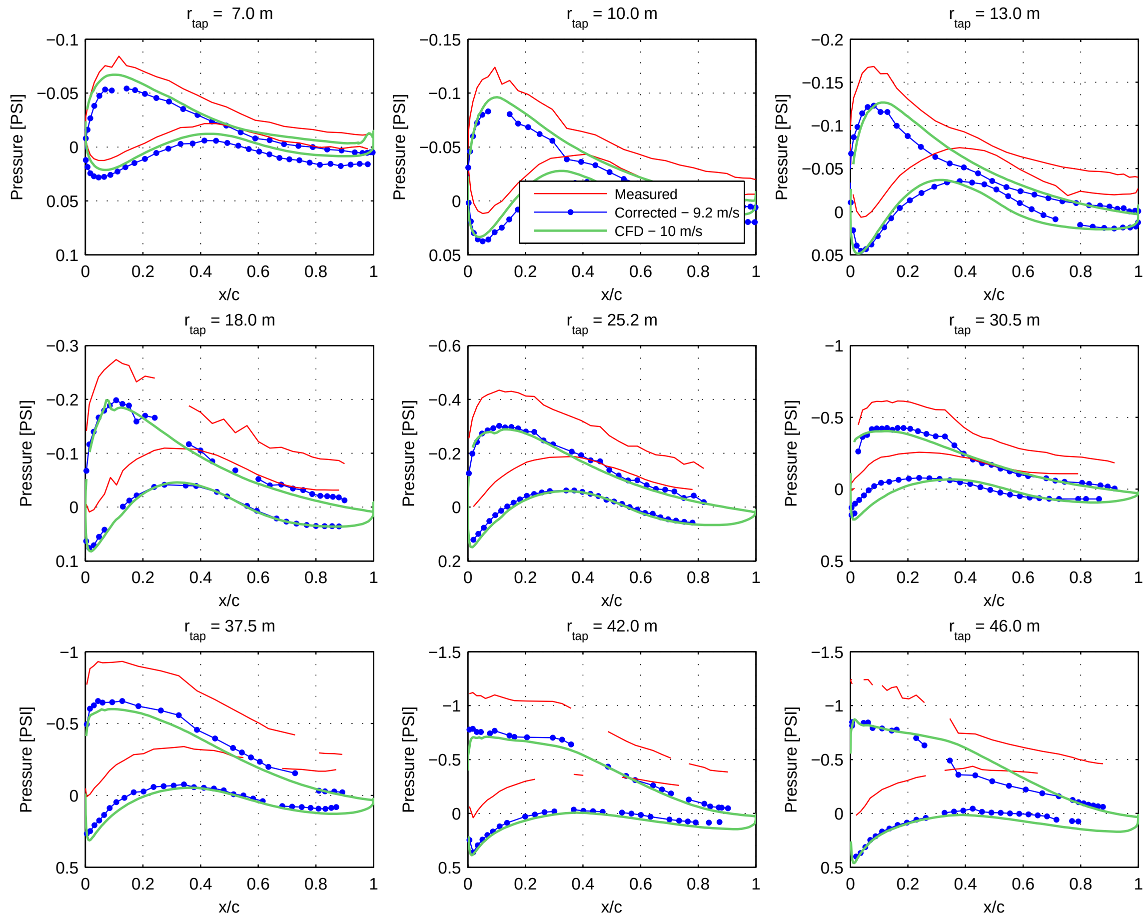

Figure 8. Comparison of a sample measurement that has been corrected with the CFD results at $V_\infty \approx 10m/s$.

research campaign, the efforts will concentrate on producing high fidelity models utilizing the collected data and integrating these models into the turbine design cycle. Some of the future work was alluded to in the previous discussion. Other studies that are to be completed in future include,

- Inflow Characterization: Future efforts in this category will concentrate on corrections that are required to produce useful data from the five-hole pitot probes, such as up-wash correction. The resulting data will be used for variety of process validation, for example the process used for the site specific power curve corrections.

- Aerodynamic Performance Characterization: The future analysis will focus on comparison between derived measurement, wind tunnel polar curves and those obtained from CFD. Additionally, the data will be used to assess the performance of 3D correction models and validation of CFD models. Such comparison will reveal the robustness of in-house tools, which can be improved if required.

- Loads Performance: Future efforts in this category will emphasize on analysis of loads data that is being acquired. Additionally, advanced tests will be conducted to produce loads data with parked rotor.

- Noise Emission: Future acoustic work will focus on systematically evaluating different design parameters for aero-acoustic noise mitigation devices in an attempt to more greatly reduce the overall level of noise being emitted from the rotor. This work will also look at the affect these noise mitigation devices have on spectral content and noise source location, hopefully revealing a better way of reducing noise without sacrificing energy production.

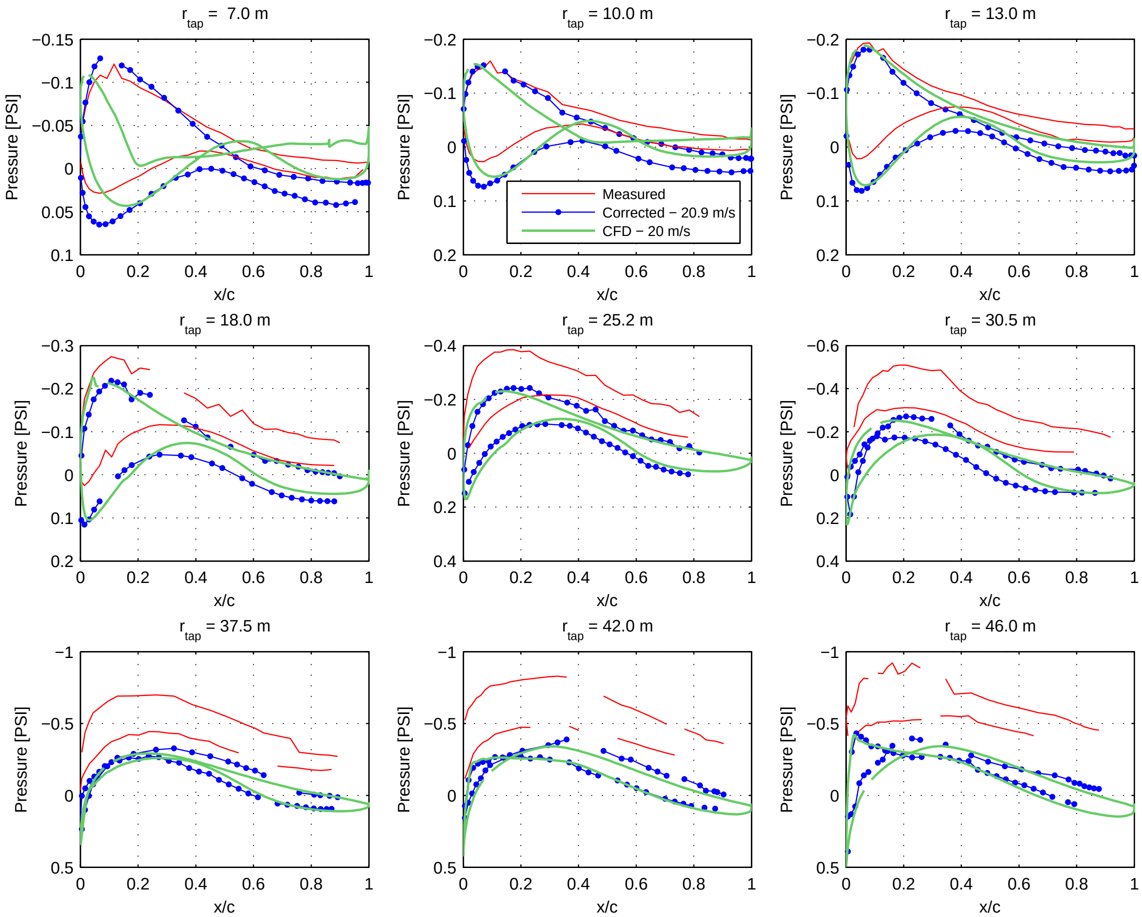

Figure 9. Comparison of a sample measurement that has been corrected with the CFD results at $V_\infty \approx 20m/s$.

Finally, all the data will be stored in a database serving as a unique validation data set for improving wind turbine design codes and essentially resulting in even more cost-effective wind turbines in the near future.

Acknowledgements

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