FINAL TECHNICAL REPORT:
Midwest Consortium for Wind Turbine Reliability and Optimization

Purdue University
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Final Technical Report

Purdue University

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ABSTRACT

This report provides an overview of the efforts aimed to establish a student focused laboratory apparatus that will enhance Purdue's ability to recruit and train students in topics related to the dynamics, operations and economics of wind turbines. The project also aims to facilitate outreach to students at Purdue and in grades K-12 in the State of Indiana by sharing wind turbine operational data. For this project, a portable wind turbine test apparatus was developed and fabricated utilizing an AirX 400W wind energy converter. This turbine and test apparatus was outfitted with an array of sensors used to monitor wind speed, turbine rotor speed, power output and the tower structural dynamics. A major portion of this project included the development of a data logging program used to display real-time sensor data and the recording and creation of output files for data post-processing. The apparatus was tested in an open field to subject the turbine to typical operating conditions and the data acquisition system was adjusted to obtain desired functionality to facilitate use for student projects in existing courses offered at Purdue University and Indiana University. Data collected using the data logging program is analyzed and presented to demonstrate the usefulness of the test apparatus related to wind turbine dynamics and operations.

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Developing indigenous energy technologies safeguards energy freedom, creates jobs, and provides opportunities for academic learning/training programs. Investing in wind technologies ensures green energy, a cleaner environment, and business opportunities in the emerging global markets for the wind energy technology. Extensive research and trained manpower is needed to improve the efficiency and reduce the maintenance and production cost of wind turbines. To achieve these goals, a hands-on education apparatus is needed to provide testing facility of real projects and to reinforce theoretical learning with experimental observation.

The first objective of this project was to design and fabricate a small scale portable wind turbine for research purposes. The turbine was built and equipped with data acquisition instruments and tested to record and analyze wind data. Software codes were developed for data acquisition, processing and post-processing. The source code is also provided to facilitate future research and further data will be made available online for use of students and K-12 teachers.

An educational apparatus was used to observe the wind turbine's dynamic response. It was able to record wind speed and nacelle accelerations. The power curve for the test turbine was plotted and compared with the manufacturer supplied data. The forced frequency response spectrum was also analyzed to observe the frequencies of interest. This educational apparatus could be used to analyze wind turbine response under various operating and loading conditions.

The second objective of the project was to incorporate the educational apparatus into existing courses offered at institution of higher learning. The objective is under way and in the fall of 2012 this educational apparatus will be used in wind energy related courses offered at Purdue.

2. BACKGROUND AND NEED

Rising concerns about decreasing fossil fuel reserves and about future energy security have driven much research in recent years on the harvesting of sustainable energy sources and, in particular, wind energy has become the most successfully commercialized source. Additionally, new wind projects installed in the U.S. during 2008 represented an investment of $17 billion and created 35,000 jobs despite the current economic downturn. In light of this rapid growth, utility turbines in modern wind farms have lower power output and operational uptime than design forecasts, leading to suboptimal economics of wind power [Kus09]. It has also been shown, that with increasing annual turbine power output there is a correlation with a decrease of individual turbine reliability as illustrated in Figure 2 -1 [Ech08]. That is to say, this plot indicates that doubling of the rated power from 500 kW or less, indicated by the blue bars, to more than 1000 kW (mega Watt scale turbines), indicated by the yellow bars, has also doubled the annual rate of reliability incidents. Additionally, the rated power of most utility-scale wind turbines fall into this category. This failure rate is partly the result of new designs for larger turbines due to the high demand for wind energy. Turbines at a rated power less than 500 kW have existed for 20 years or more and have experienced multiple design iterations to mature the technology. Furthermore, the components which are most prone to failure are those which constitute a larger portion of the turbines cost as the size and power output has increased. Figure 2 -2 shows that an increase in rated output (i.e. rotor diameter) from 0.75 MW to 3 MW results in the cost of blades and drive train components (gearbox, generator, etc.) increasing from 45% to nearly 60% of the total cost of the system.

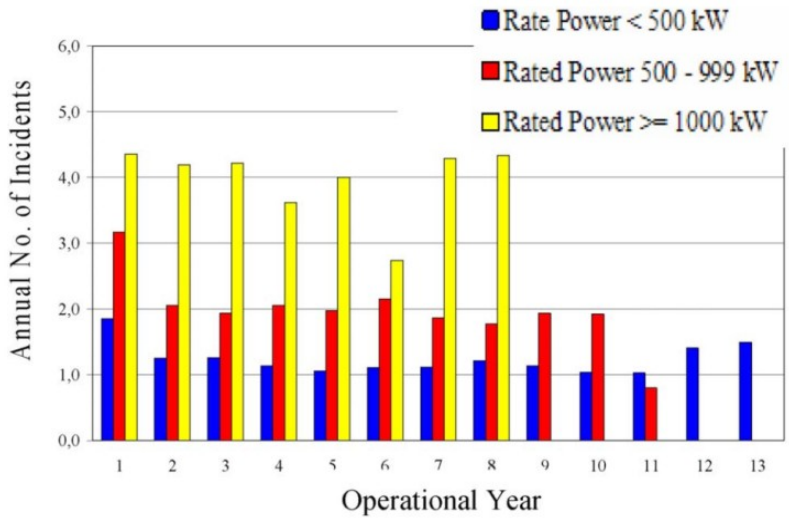

Figure 2-1: Number of reliability incidents per wind turbine per operational year, categorized by the rated power[Ech08].

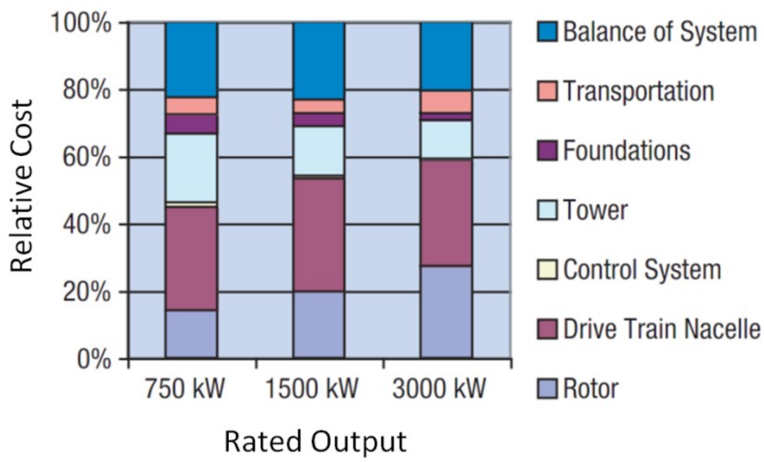

Figure 2-2: The relationship between major component costs and turbine output[Ene05].

It is crucial for the long term of success of wind turbines as a viable and competitive source of energy to establish inquiry-based education tools consisting of hands-on projects that require students to integrate their theoretical understanding with experimental observations. A small scale wind turbine test apparatus will enable students to observe the key principles of wind turbines and will also take advantage of student interest in wind energy by supporting outreach to students and cultivating future contributors to the economic success of wind turbines.

3. OBJECTIVES

The overall objective of this project is to create U.S. jobs and education/training programs that continue to fuel the job growth in the green economy. To facilitate this objective, first, a student-focused laboratory apparatus that will enable educational institutions in the State of Indiana, including Purdue University and Indiana University, to recruit and train students in cross-disciplinary topics related to the science, engineering, economics, and policy of wind energy needed to be established. The apparatus was made to be portable and posses' instrumentation with which students can demonstrate the key operational principles of wind turbines. Experiments conducted using this apparatus will form the basis of student projects in existing courses offered by Purdue University (Wind Energy and Wind Turbines, Experimental Structural Mechanics) and Indiana University (Principles of Wind Energy, Wind Power Meteorology). In the future, data from the wind turbine will be published online so that it can be accessed by students and the community of K-12 teachers. The portable wind turbine will also be deployed in the future the enable outreach at events such as the Indiana State Fair to recruit students and educate the general public.

The following outcomes were expected after conducting this project: a portable field laboratory apparatus properly instrumented for characterizing the performance of the wind turbine and wind state dynamic behavior; a graduate student thesis report that describes the design and performance characterization of the laboratory apparatus as well as educational materials for use in courses: and student reports that describe course projects and the learning outcomes that the apparatus has helped realize.

4. APPROACH

4.1 Construction of the Test Apparatus

A wind turbine apparatus was first designed and fabricated as seen in Figure 4 -3. The apparatus is constructed of 2 inch steel box tubing with 1/4 inch wall thickness. The overall footprint is 4x4 feet which includes cross members that connect opposite side pieces and span the center of the frame in both directions. Fastened to the top of the frame is a 3/8 inch steel plate. The plate provides a large mounting area for various parts, sensors, hardware, and miscellaneous instrumentation. The test cart features 8 inch dual wheel pneumatic casters providing the mobility necessary to actualize the goal of making the apparatus a mobile educational tool. At the center of the cart is a pivoting frame that holds a telescoping aluminum tower. The pivoting frame locks into the steel plate mounted to the box tubing frame. The telescoping tower is made of three sections that lock by turning of a cam system inside the respective tower sections. The overall height of the tower and cart combines for a wind turbine hub height of 21ft. An AirX 400W wind turbine is mounted on the tower.

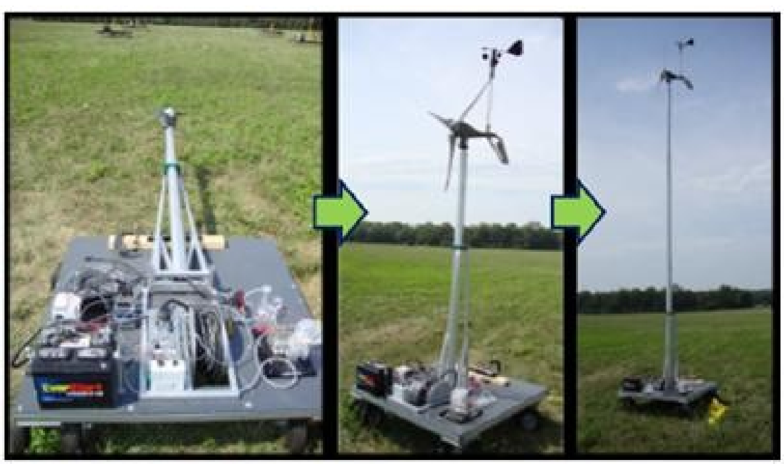

Figure 4-3: Setup of the wind cart from its portable state (left) to its operational state (right).

The apparatus is equipped with data acquisition instrumentation that monitors the apparatus's environment and its response to several inputs. The instrumentation includes a tachometer, an anemometer and an accelerometer as well as a voltmeter and ammeter. A data logging program was developed using LabVIEW. The program includes functionality that facilitates the display of real-time data and the recording and creation of output files that can be used for post processing. Finally, the apparatus was tested in an open field and adjusted to obtain desired functionality. Testing was conducted on consecutive days between 10am and 2pm. During testing, the nacelle was positioned approximately 21 feet above the ground. The location and local orientation of the sensor is shown in Figure 4 -4. Operational data was collected, post-processed and substantiated using data published by the manufacturers.

Figure 4-4: Wind turbine nacelle with coordinate system shown. The coordinate system is fixed to the tower and does not rotate with the nacelle.

4.2 Sensors and Data Acquisition Instrumentation

The equipment list consisting of all data acquisition instrumentation installed on the wind turbine apparatus is as follows:

- Silicon Designs, Inc. Model 2460 Triaxial Analog Accelerometer
- NI 9203 16-Bit Analog Input Module
- NI 9234 24-Bit Software-Selectable IEPE and AC/DC Analog Input Module
- NI cDAQ-9174 Chassis

- Nova Lynx 200-WS-23 Current Loop Wind Sensor
- Eagle Tree Systems USB Car Data Recorder
- Eagle Tree Systems Electrical Expander
- Eagle Tree Systems Optical RPM Sensor

A sensor map illustrating the associations between the various data acquisition devices can be seen in Figure 4 -5.

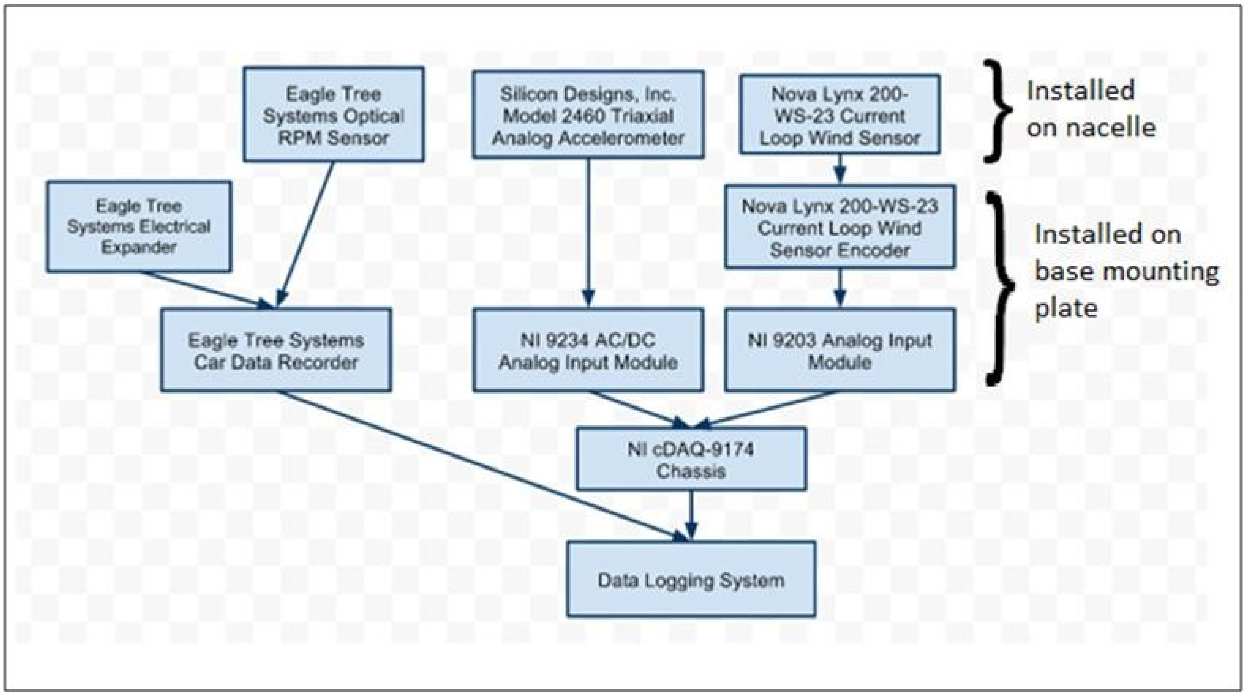

Figure 4-5: Sensor map for the wind turbine apparatus.

4.3 Data Acquisition Software

The data acquisition software was created using LabVIEW. A fully compiled version of the application as well as all files necessary for it to run and the instructions for the proper installation and use of the program can be found in the WindTurbineTrainerDAQ directory.

The source code for the application can be found within the FinalProgam directory. The following is a list of all Virtual Instruments (VIs) found in the FinalProgram directory:

VIs:

1. FinalProgram_v5.3STABLE – the main VI for the DAQ application

Sub VIs:

1. FP_Sub_aquiredataCDR – handles the acquisition of data from the car data recorder hardware
2. FP_Sub_aquiredataDAQ – handles the acquisition of data from the NI cDAQ 1974 Chassis
3. FP_Sub_CoherentTimeScales – makes sure the timescales for all the graphs are aligned
4. FP_Sub_DetermineTimeStamp – calculates and tracks relative time
5. FP_Sub_Empty_file_path_check – checks for empty file path fields
6. FP_Sub_Extract_CDR_Data – extracts data from the CDR live file to an array
7. FP_Sub_Extract_Numeric_from_CDRarray – extracts specific data from the array of CDR values from the previous function
8. FP_Sub_FileOutput_Improved – handles the creation of the storing of acquired data to a text file

4.4 Post-Processing Functions Used In Data Analysis

The MATLAB functions used for post-processing to obtain the data documented in this report can be found within the PostProcessingFunctions directory.

- plot_fdom_accel %% given acceleration data and dt, this function plots a forced response frequency spectra
- plot_accelws %% given imported unprocessed raw data from the WindTurbineTrainerDAQ application, this function plots triaxial acceleration and a moving average wind speed vs. time

- plot_powerdata %% given imported unprocessed raw data from the WindTurbineTrainerDAQ application, this function plots a power curve and the published power curve for the AirX wind turbine on the same axis
- fdomain %% computes the complex Fourier coefficients from vector x and the corresponding frequencies (one-sided)
- moving %% computes moving averages of order m

1. RESULTS

The apparatus and the data acquisition software for it were successfully realized over the span of the project. The apparatus consists of power generation and storage instrumentation, wind speed sensors for monitoring the wind state at multiple heights, dynamic sensors on the wind turbine nacelle for monitoring the response of the turbine and a portable base with a telescoping tower to allow for transport and repositioning of the nacelle. The data acquired by the apparatus can be post-processed to produce graphs and representations that are essential to characterizing the performance of the AirX 400W wind turbine — power curves, wind speed, rotor RPM as well as time and frequency domain acceleration plots. The sample results discussed below were obtained during a testing session that lasted 12.5 minutes though which time the wind speed varied from 0 to 25.6 mph and the peak power observed was 170 Watts at a wind speed of 20.71 mph. Throughout the duration of the test session, the wind speed fluctuated significantly as seen in the bottom figure of Figure 5 -6.

4.5 Dynamic Response to the Wind State

The wind speed across the turbine disk was measured during testing and a curve fit was derived using a moving average filter with an order of 105 points. Unprocessed time domain acceleration was also plotted. (See Figure 5 -6). The plot will enable students to observe the wind turbine's dynamic response to the wind state.

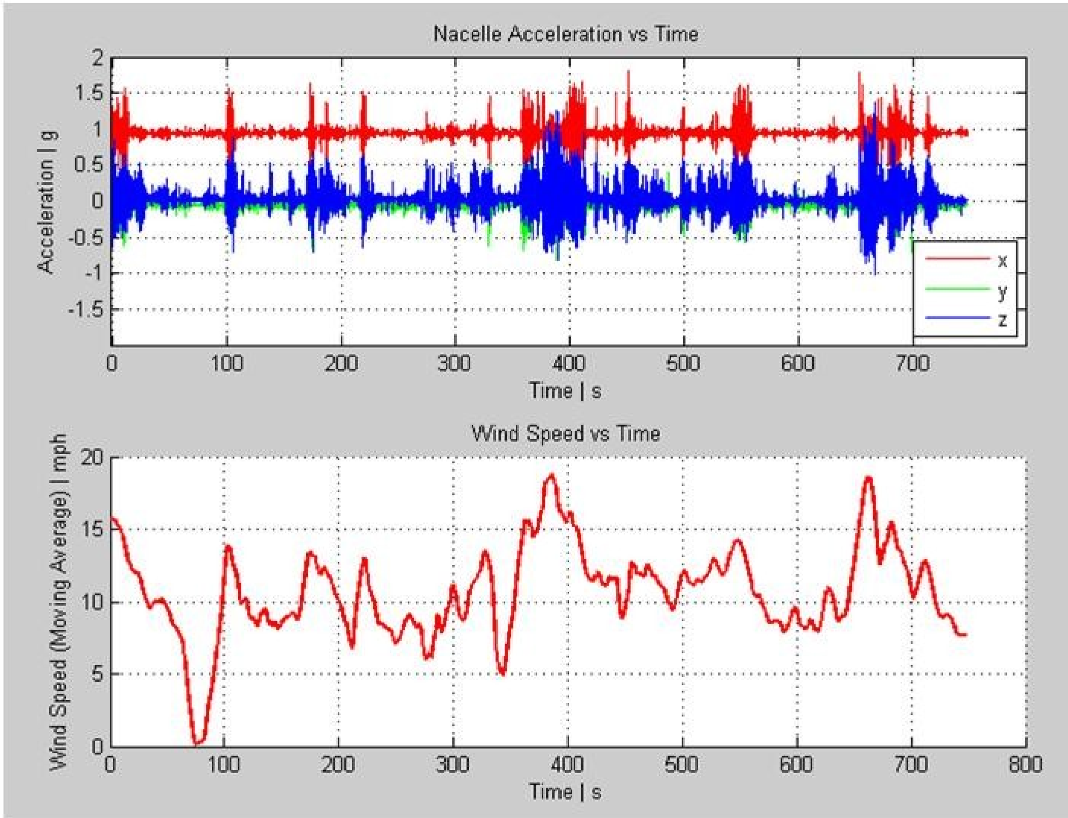

Figure 5-6: Dynamic response due to wind state.

4.6 Power Performance

Following the post-processing of the acquired field data, a scatter graph was plotted and then a normalized power curve was derived using a third order polynomial regression fit. The published power curve for the AirX 400W turbine was plotted on the same axes. (See Figure 5 -7). The power curve will play an essential role in the performance analysis of the wind turbine's power conversion process.

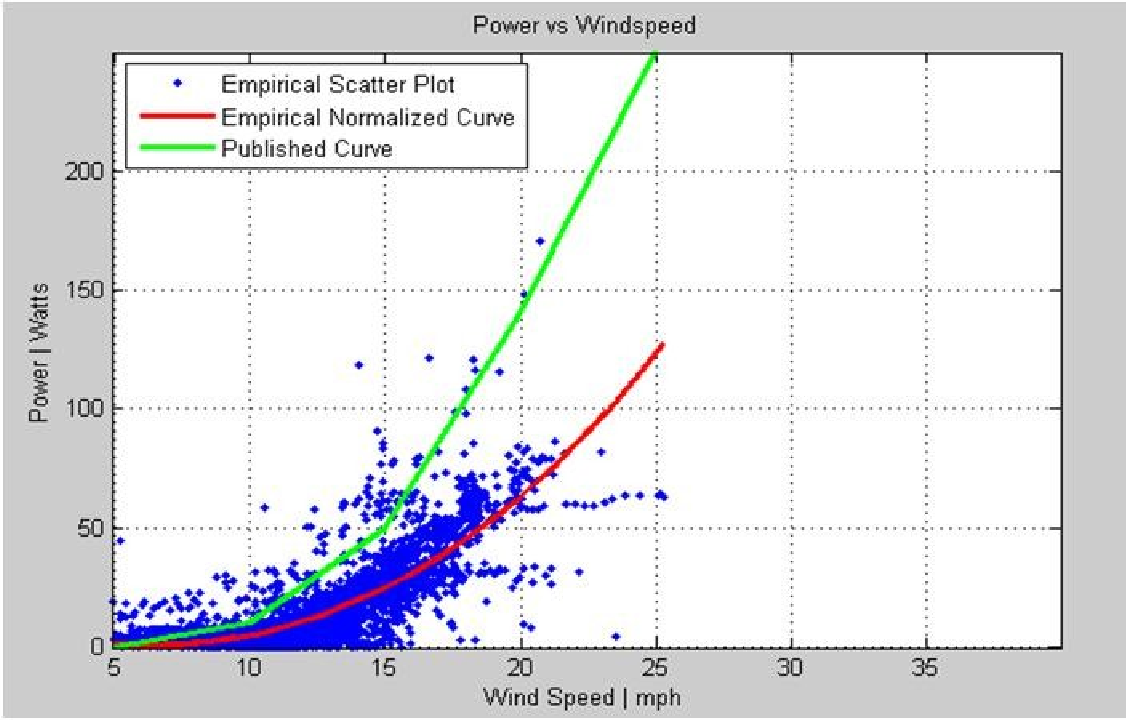

Figure 5-7: Wind turbine power performance.

4.7 Forced Response Frequency Spectra

Acceleration data acquired during testing was used to derive and plot a graph of magnitude of DC acceleration vs. frequency (See Figure 5 -8). Upon further processing and refinement, the plot will enable students to discern which frequencies motivate high levels of excitation or resonant behavior that may be detrimental to the wind turbine.

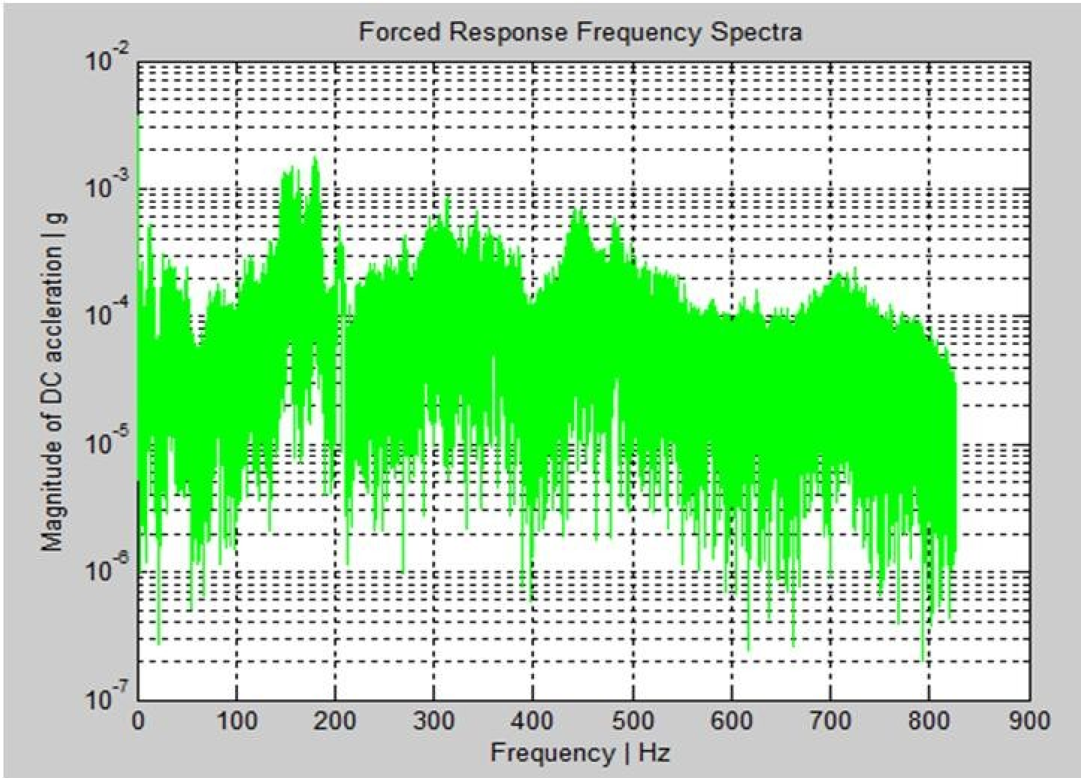

Figure 5-8: Forced frequency response spectra measured at the turbine tower.

4.8 Analysis of Results

Based on field testing and analysis of the sample results discussed below, the wind turbine apparatus fulfils its purpose as an educational tool that enables students to observe phenomena encompassing the wind state, turbine dynamics and the power conversion process. However, inconsistent and rapidly fluctuating outdoor wind conditions resulted in several batches of inconclusive data. The use of this apparatus in a controlled environment, such as a wind tunnel, is advisable.

4.8.1 Power Performance

It was only possible to plot a partial power curve (shown in Figure 5 -7) for the wind turbine due to the rarity and inconsistency of wind speeds above 15 mph during testing. The shape of the empirical power curve in Figure 5 -7 resembles that of the published curve; however, there is a notable deviation from the published curve at higher wind speeds. It should be noted that there are several data points that coincide with the published curve. It is plausible that this deviation is due to the non-optimum and inconsistent wind conditions experienced during testing. Another possible cause for these results is that the nacelle was positioned 21 feet above the ground while the manufacturers recommends 25 feet as the minimum height above open ground for an effective performance. More testing in optimum conditions is required to characterize the power performance of the wind turbine apparatus completely.

4.8.2 Dynamic Response to the Wind State

Heightened levels of excitation in the all directions are observed to coincide with the wind speed peaks in Figure 5 -6. Troughs coincide with a reduced acceleration response. The observation is justified as wind loading and turbine rotor dynamics are the excitation sources that cause the accelerations graphed in Figure 5 -6. It appears that only wind speeds above 10mph sufficiently excite the tower. The increased motion of the tower at higher wind speeds was visible during field testing.

4.8.3 Forced Response Frequency Spectra

It is difficult to identify any strong peaks in the forced response data due to the multi-frequency content of the acceleration data. The excitation source is a combination of wind loading and turbine rotor dynamics. Both these sources are generally broadband excitation sources explaining the results seen in Figure 5 -8. Better results could be obtained by testing the tower at various steady-state rotor speeds. Underlying oscillations can be extracted from the data by cyclic averaging resulting in clearer frequency peaks. Additionally, modal testing of the tower could be performed to identify the damped natural frequencies and modes of vibration. The forcing functions that typically act on a wind turbine are generally dominated by low frequency components; a typical wind spectrum is shown in Figure 5 -9, adapted from Burton 2001. The power spectral density of the wind can provide information on the character of fluctuations in real power output as well as utilize it as the input to operational modal analysis.

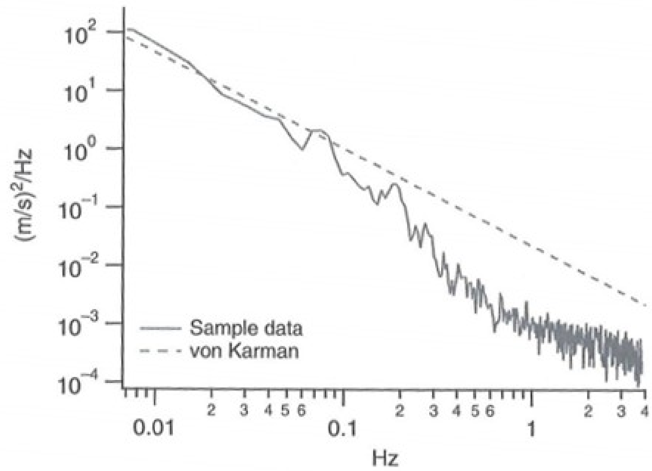

Figure 5-9: A typical wind data power spectral density function [burton].

5. SUMMARY AND CONCLUSIONS

A student focused laboratory wind turbine apparatus that will enhance Purdue's ability to recruit and train students in topics related to the dynamics, operation and economics of wind turbines was successfully established. A working procedure for use of the test apparatus was created for future testing in student projects. Data collected from the test apparatus was analyzed to demonstrate the applicability of the apparatus in courses related to wind turbine dynamics and operating principles.

The proposed plan is to utilize the apparatus in several courses such as ME 274, Dynamics and the Wind Energy course offered in fall 2012. There are also plans to include the test apparatus for student projects in the Mechanical Engineering Technology (MET) Machine Diagnostics course. Additionally, the test apparatus is being considered for use in a Computer Science course with an emphasis on embedded systems. However, a Summer Undergraduate Research Fellowship (SURF) Poster presentation (July 2011) was used to highlight the project goals and current results of the test apparatus, promoting awareness of the project and educational wind energy efforts at Purdue University.

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APPENDICES

Appendix A: Wind Turbine Operating Instructions

I. Overview

These instructions detail the proper and safe setup and operation of the wind turbine trainer cart test apparatus. The trainer cart was developed to introduce wind turbine dynamics and principles through a hands-on learning approach. The trainer cart features an AirX 400 Watt wind turbine manufactured by South West Windpower. The turbine is instrumented with an anemometer, optical tachometer and ammeter to assess the turbine's performance. Additionally, the tower is equipped with an accelerometer to monitor and characterize the structural dynamics due to various wind loads and operating modes of the turbine. The trainer cart is mobile, allowing for easy positioning into an open area for operation. The tower is made of three sections that are extended and interlocked. The tower can then be erected and secured to the frame. This procedure is detailed in the steps below.

II. Cart Placement

The cart must always be positioned in a flat open area with no obstructions. The recommended area is approximately 30x30ft. This provides sufficient space to extend the tower. The cart is equipped with pneumatic casters at each corner. Always ensure the caster tires are fully inflated to the proper pressure as specified on the tire. Never move the cart when the tower is fully extended. Only move the cart when the tower is lowered. To move the cart, push on the frame. Never push on the tower to move the cart.

III. Extending the Tower

Two people are required for this task. One person must unroll the spool of wire as the tower is extended by the second person. It is important to have one person unspool the wire as the tower sections are extended to avoid excessive strain on the power and sensor cables.

Once the tower is extended each section must be locked. This is done by turning the tower sections one at a time. First the middle tower section is rotated clockwise until the tower section locks into the base tower section. This can be tested by attempting to push the tower into its un-telescoped position (without turning the tower section). Next, repeat the process for the top tower section.

IV. Power Connections

Plug the wind turbine power cable (black) and sensor cable (gray) into the breakout box outlets. The outlets are marked on the box. Each cable only fits one way into the outlet.

With the cables connected, flip the Turbine switch to "off" position. The Turbine switch can be turned to the "on" position after the tower is erected. See next section. This switch must be used as a shutoff switch when lowering the turbine and can be used as an emergency shutoff.

V. Erecting the Tower

Three people are required to erect the tower; two people to safely lift and hold the tower in the upright position and one person to fasten bolts at the base of the tower to the cart. There are four bolts used to attach the tower to the cart. Two blots are used as pivot and remain loose when the tower is lowered. They are never to be removed. Two more bolts are opposite the pivot point and are removed to tower the tower. When the tower is in the upright position the bolts must be inserted into the tower support frame and tightened down with the corresponding nut. The pivot bolts can then be tightened. After the tower is secure the Turbine switch can be flipped to the "on" position and the data acquisition system (DAQ) can be initialized. See the following section for details on proper connections and use of the DAQ system.

Appendix B: Data Acquisition Instructions

I. Overview

The wind turbine apparatus collects data through various installed sensors. The sensors collect and transmit data to the computer via two devices connected to the computer via USB. However, for the *WindTurbineTrainerDAQ* application to obtain rpm and output power readings, another application *(DataRecorder)* must be installed and running in the background. Instructions for the proper installation and use of the software related to the wind turbine apparatus are as follows.

II. Installation Instructions

II.1. Connecting the Hardware

1. Connect both USB cables to USB ports on the computer to be used

II.2. DataRecorder Application

1. Run the *EagleTreeDataRecorder* setup and follow the on-screen instructions.
2. Run the program for the first time, when asked about the type of models you are using with the recorder, select “Model Cars, Trucks or other ground based Models”
3. When prompted to enter a model name, enter a model name of your choice and click Next
4. Chose “I don’t wish to calibrate my servos with the Recorder at this time” and click Next
5. In the RPM Setup for Car panel: select “I am using the optical RPM Sensor” and enter “2.0” as the number of light-colored optical strips. Ignore all settings in the *speed calculation settings* section. Click Ok to proceed
6. On the Choose the Parameters You Want the Onboard Recorder to Log: Make sure only “RPM Sensor A”, “Electric Motor Voltage (Standard Electric Expander)” and “Electric Motor Current (Standard Electric Expander)” are selected. Click Ok to continue

7. On the Instrument Panel Setup: you can choose to display the values you are recording, however this is unnecessary. If you do want these values displayed, only “Electric Motor Ammeter”, “Electric Motor Voltmeter”, “Motor RPM Gauge”, “Electric motor amps”, “voltage numeric display” and “motor RPM” will display meaningful data. Click Ok to continue

8. When asked to connect the Seagull Dashboard, click cancel

9. In order for the *WindTurbineTrainerDAQ* application to retrieve information from the DataRecorder application some changes will need to be made to its registry configuration. Close the EagleTree Data Recorder application

10. Run regedit.exe from Start->Run, and navigate to the following Key: HKEY_CURRENT_USER/Software/Eagle Tree Systems/CDR Application/Settings

11. Once there, using "Edit->New->DWORD Value", add a new REG_DWORD value, LiveModeLiveFile, and set it to 1. It should appear in the same section as several other parameters.

12. Start the Data Recorder application and then click LiveMode

13. When LiveMode is clicked for the first time, the LiveMode Settings panel will appear. Make sure “Click here to record the Live Mode data to a disk file” and “Save these settings” are checked. Then click Ok

14. LiveMode will start running and it can be stopped and started using the LiveMode button.

15. Installation and configuration of the Data Recorder application is now complete

II.3. DAQmx Drivers

1. Insert the DAQmx Driver CD

2. If the setup does not automatically run, go to access the CD’s content through My Computer and run Setup.exe

3. After the installation is complete, you will be prompted to restart the computer. Make sure to restart the computer before proceeding to step III

III. Operational Instructions

1. Ensure that all hardware is connected correctly
2. Run the *DataRecorder* application
3. Run the *WindTurbineTrainerDAQ* application
4. Click the *Live Mode* button on the *DataRecorder* application to activate the data recorder *
5. On the *WindTurbineTrainerDAQ* application, fill in the *File path to LiveRecorderFile.log* field (This file path is usually *C:\Users\<insert username here>\AppData\Local\VirtualStore\LiveRecorderFile.log)***
6. Click the *OK* button once the correct file path has been set
7. If you do not wish to record data skip steps 7-9. If you wish to record data, first create a blank text file using a text editor such as *Notepad*
8. Set the file path for the *File Path to Save Recorded Data to* field to the blank text file created in step 7 ***
9. Use the *Start/Stop* button to start and stop recording to the specified file ****
10. Click the *Abort Execution* (Red Circle) button on the top of the interface to stop the program. The program can be started up again by clicking the *Run* (Arrow) button

* Note: Do not leave LiveMode running for more than 15 to 20 minutes continiously as the LiveRecorderFile can become large. This may lead to the over use of system resources or even crash the WindTurbineTrainerDAQ application. Start and stop LiveMode every 15 minutes to prevent this. Also note that when you stop live mode, you will be asked if you want to Save changes to LiveMode. Click No.

** If the file path is not this, you will need to search for LiveRecorderFile.log, and then set the file path to it.

*** Note: If a non-blank file is specified, the data will simply be appended to this file

****Note: The timer begins once the OK button is pressed (Refer to step 6) so the recorded time may not start at 0 seconds

IV. Using the recorded data

- Data recorded by this program is tab delimited and the text file created can be imported into both Excel and MATLAB
- The column headings are as follows:

  Time (seconds), Wind Speed, Blade Speed, Voltage, Current, Power, Accelerometer 1 x,y,z and Accelerometer 2 x,y,z