Energy Themed Laboratory Experiments in Mechanical Engineering

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Abstract

The global focus on upgrading electrical energy generation facilities from fossil fuel to green energy sources can help reduce the emission of harmful pollutants into the atmosphere and conserve natural resources. Focusing on this topic, Clemson University has established an innovation campus in Charleston, SC that focuses on the design and implementation of power systems using renewable energy sources. A curriculum for the senior mechanical engineering laboratory (ME 4440) was developed for the purpose of educating students through energy themed experiments. The salient feature of this curriculum is integration of practical training, consisting of both hands-on operation and computer simulation. A series of five energy themed experiments have been developed to place an emphasis on: design of experiments, sensor selection, real time data acquisition, mathematical modeling, data analysis, and technical writing. These experimental investigations include horizontal and vertical axis wind machines, vibration modal analysis of mechanical structures, multibody modeling of drivetrains, and solar power generation with light tracking, and have been scaled to fit inside a classroom setting. The learning objectives, system descriptions, and list of materials are presented to offer insight into the curriculum elements. The introduction of these laboratories will enable the Department of Mechanical Engineering to meet the challenges of educating students for evolving opportunities in the renewable energy industry.

Keywords

Wind Power, Solar Energy, Vibration Analysis, Testing, Computer Modeling

Introduction

Renewable energy is the fastest-growing energy source in the United States[1]. To accelerate the development of renewable technologies, Clemson University established an innovation campus in Charleston, South Carolina that focuses on wind and solar power systems. This campus has an emphasis on education, research, and innovation through the Zucker Family Graduate Education Center and the Dominion Energy Innovation Center, which features an advanced wind-turbine drivetrain and electric grid testing facility. The 7.5 MW and 15 MW test rigs can accommodate geared and direct-drive wind turbine nacelles plus large turbine gearboxes and generators for hardware-in-the-loop wind power research. Figure 1 illustrates the 15 MW wind turbine test platform. The 15 MW electrical grid simulator supports both wind turbine generator and electrical machine investigations including ride-through fault testing.

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Figure 1. Clemson 15MW wind turbine test platform

As part of the Education Center's mission, a senior year academic program has been implemented for undergraduate students in the Departments of Mechanical Engineering (ME), Electrical & Computer Engineering (EE), and Computer Science (CS). These seniors will spend their final two semesters on the Charleston campus studying with Clemson faculty, researchers, and graduate students plus receive access to the specialized energy equipment in collaboration with facility engineers, technicians, and industry partners. They will complete their course work and laboratory activities in the Education Center and then explore world class energy-themed test facilities in the Innovation Center.

In the senior ME laboratory, a series of experiments have been created that place an emphasis on energy through hands-on experimental and simulation investigations. The ME students will have an opportunity to explore wind turbine computer simulations, vibrational analysis methods applied to mechanical components, solar cell arrays to generate electric power, vertical axis wind turbine to generate electric power, and analyze large mechanical gear boxes. All laboratory experiments were designed with a high degree of real-world applicability and are reflective of hardware models that represent and/or can be applied to full-scale systems. Finally, these experiments are designed to accommodate a two-credit hour course with regular assessment[2].

Undergraduate laboratory experiments

The five senior ME laboratory experiments developed especially for the Clemson University Charleston Innovation Campus are presented. A background statement, description of the experimental configuration, and list of learning objectives is provided for each system.

<u>Savonius Wind Turbine</u>

There are two primary designs of wind turbines, a Horizontal Axis Wind Turbine (HAWT) and a Vertical Axis Wind Turbine (VAWT). A Savonius style wind turbine is a VAWT that is commonly used for applications when affordability and reliability are valued over efficiency[3]. Applications include water pumps, anemometers, and power generation on deep sea buoys[4].

In this laboratory experiment, students will incorporate their knowledge of fluid mechanics, physics, machine design, and computational analysis to investigate wind energy and electro-mechanical conversion principles. The students will consider the specific mechanical and

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electrical power losses throughout the Savonius turbine system. Through the investigation process, students will garner experience with the underlying physics that describe a VAWT operation as well as the models that characterize the systems performance. It will be the responsibility of the student teams to identify the major causes of error in the model, where their assumptions break down, and how they might be adjusted to improve accuracy. Finally, students will investigate the viability of wind energy in South Carolina, discussing the value of investing in wind energy for both personal and commercial uses.

The experimental setup consists of a turbine, blower tower, and data collection system which is illustrated in Figure 2. The turbine frame is constructed of T-slot aluminum extrusions. This frame is used to support the rotor, shafts, and permanent magnet generator (PMG), and the supporting structures (i.e. bearings, fixtures). Each bucket that makes up the two-stage rotor assembly is constructed of aluminum alloy, with a 90-degree offset between the top and bottom bucket pairs. The rotor is centered on a 25 mm steel shaft, which runs from the top of the frame through a jaw coupler before entering the PMG. The turbine shaft is connected to the generator through a chain and sprocket with a 1:1 ratio with an efficiency of approximately 50%.The learning objectives for this module are: (i) understand the operation of the wind turbine and blower tower system, (ii) apply fluid mechanics and aerodynamic principles to wind energy analysis, (iii)compare theoretical to experimental power curves and the assumptions and their role/impact,(iv) identify sources of inefficiencies in a turbine design and opportunities for improvement, (v) investigate economic viability of wind power through system scaling to real-world application.

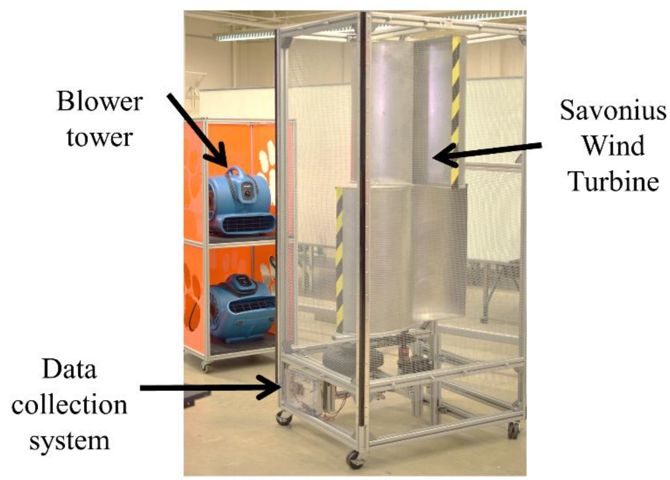

Figure 2. Savonius wind turbine test platform

<u>Solar Panel with Light Tracking</u>

Solar energy is one of the most common and accessible type of renewable resources. The quantum particles within the sun’s electromagnetic radiation are called photons. The photons contain energy which can be harnessed using photovoltaic cells. A photovoltaic cell consists of a p-n junction in a silicon wafer which are used to construct a solar panel[5]. Typically, the output of a single photovoltaic cell is less than 1 Watt[6], therefore, multiple photovoltaic cells are combined to create a solar cell array. The respective generated current from the solar cell (panel) is direct current (DC), but if alternating current (AC) is desirable, a DC to AC inverter is used.

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The solar panel's energy generation depends upon the solar irradiance and the angle of incidence. Hence, the objective of this laboratory is to develop a program/script that will detect the best angular orientation and move the solar panel for maximum power generation. A tracking mechanism is designed using four Light Dependent Resistors (LDRs), and a feedback control loop to adjust the orientation of the solar panel with respect to the position of a 30-Watt LED light with a luminosity of 3000 lumens. An Arduino Uno is used with the LDRs to detect the direction of the light. The control tracking system rotates the solar panel between -/+90° with respect to maximum light intensity. The power generation is assessed by measuring the voltage across a load via the Arduino Uno. Figure 3 illustrates the solar power system which consists of an 80-Watt solar panel, mounted on a frame, and rotated using a stepper motor coupled with 47:1 gear box. The movement of the solar panel is controlled by the Arduino Uno and motor shield.

To simulate the movement of the sun, students will position a light source at various incident angular positions. As the position of the light source is altered, the LDR sensor voltages increase and decrease with respect to the location of the light source. The controller compares the voltages, and sends the signals to the motor driver, so that the stepper motor rotates accordingly. The learning objectives for this module are: (i) understand the structure and working principle of a photovoltaic cell. ,(ii) study the effect of angle of incidence on the power generated by the solar panel, (iii) acquire the generated power output and solar panel position (tracking versus non-tracking), (iv) create a feedback loop for a tracking system using Arduino and Simulink programming, (v) size a system for a residential home and determine cost benefit of light-tracking solar panels.

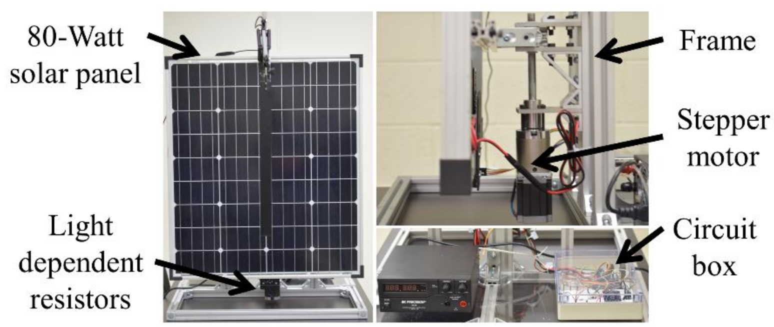

Figure 3. Solar panel bench top experiment with stepper motor and light tracker

<u>Fundamentals of Vibration Analysis</u>

Structural vibration testing and analysis is performed by many industries, including aerospace, auto-making, manufacturing, power generation, consumer electronics and defense to suspend unwanted vibrations and improve product quality[7]. Students will be required to perform a vibration analysis of a high-speed rotating shaft guard. In preparation for this involved structural analysis, students will familiarize themselves with the necessary fundamental concepts of vibration analysis of a weighted-tip cantilever beam.

Impulse-force hammers are widely used in vibration testing to produce short-duration (i.e. impulse) forces and to measure the force produced. First, students will theoretically predict the first three natural frequencies of the cantilever beam using Euler-Bernoulli beam theory.

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Experimental data from the impact hammer and accelerometer will allow the students to determine the natural frequencies of the beam and compare the measured results to their theoretical calculations. The students will then determine the Frequency Response Function (FRF) and perform a modal analysis. The FRF measurement, which is the ratio of the response to a measured input force, removes the force spectrum from the data and describes the inherent structural response between the measured points[8]. Students will explore real world applications by analyzing accelerometer data from the high-speed shaft guard.

The experimental setup consists of a 5052 Aluminum beam (304.8 mm x 25.4 mm x 3.18 mm) instrumented with a ceramic shear IPC® accelerometer. The accelerometer is routed through a signal conditioner and then routed to National Instruments data acquisition hardware, as shown in Figure 4. The accelerometer is attached to the free end of the beam and a signal is produced and analyzed via LabVIEW. Students are expected to experiment with the data collection rate as reported in Hz and determine how they may reduce the signal to noise ratio. The learning objectives for this module are: (i) implement and perform a frequency vibration analysis of a cantilever beam structure, (ii) perform impulse testing with multiple impulse-hammer tips and plot the amplitude spectrum, (iii) compare the theoretical vibrational modes to the measured vibrational modes, (iv) apply Fast Fourier Transforms (FFTs) and modal analysis to calculate the natural frequency, (v) explain analysis techniques and their use for vibration isolation in rotating machinery.

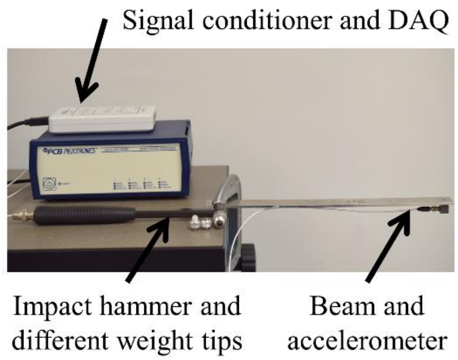

Figure 4. Vibration analysis with accelerometers and impact hammer on beam

Computational Modeling and Simulation of Horizontal Axis Wind Turbine

In this laboratory experiment, a HAWT is examined by mathematical modeling. Students shall employ laboratory data from an existing simulated experiment to compute the appropriate power curves, DC motor modelling and the respective sizing of components. This will be accomplished through a feedback loop control model for a simple HAWT system. The key components of a horizontal wind turbine are depicted in Figure 5.

Students shall be required to develop a Matlab/Simulink® model to evaluate the turbine blade rotor system containing a simple gearbox, flywheel, and generator drivetrain. Basic component models are provided to the student and they are required to integrate the component models into one system. Various dynamic response characteristics will be explored, and the students will be required to way the economic viability of component sizes to overall system performance. The

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learning objectives for this module are: (i) identify the major components and controls of a wind turbine (ii) familiarize themselves with input wind speed profile response, (iii) describe wind energy conversion theory and rotor dynamics, (iv) develop and run wind turbine drive train dynamic simulation using Simulink, (v) attenuate wind speed variations by optimizing design.

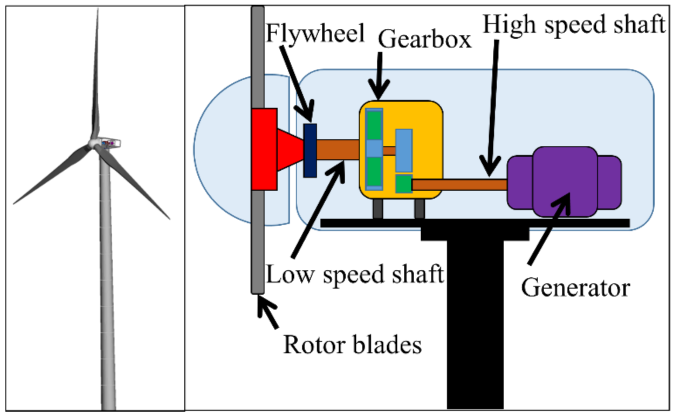

Figure 5. Schematic of a wind turbine

Multi-Body Modeling of Drivetrains

During normal operation of a HAWT, the drivetrain components experience axial, lateral, and vertical forces as well as tilt or yaw moments due to the wind incident on the blades. Understanding these forces within the drivetrain and how they affect operation is imperative to improving wind turbine reliability. In this laboratory module, a multibody model of a 5 MW wind turbine developed using Matlab/Simulink/SIMPACK® will be utilized to run simulations and analyze responses. Students shall use the pre-existing multibody model to study the influence of varying parameters such as stiffness and geometry of specific components. Students will also examine the influence of varying component fidelities on the responses.

The model consists of the flexible tower and blades, and the internal drivetrain components including the main frame, the gearbox, the high-speed coupling and the generator. The model accepts wind profile as input. This profile is generated using pre-defined parameters such as average speed, direction, and turbulence intensity. The model allows for defining sensors to measure additional outputs including mechanical loads, torque, speed, and the resulting reaction forces and/or misalignments (displacement responses) at locations along mounted locations. The learning objectives for this module are: (i) identify different components of a wind turbine drivetrain, (ii) simulate different wind loading cases and analyze turbine responses, (iii) perform load path analysis and understand integrated system loads versus component loads, (iv) correlate model fidelity to response characteristics.

Conclusion

The undergraduate laboratory experience in the ME program at Clemson University is a cornerstone for integrating classroom theory with practical applications. Although fundamental concepts can be accessed through textbooks and on-line resources, the hands-on-aspects of

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engineering laboratories are more difficult to gather outside of an academic setting. Although videos may be available, they in themselves cannot replace the in-person knowledge gained through experimental investigations. Universities should be committed to laboratory discovery through a thoughtful sequence of science and engineering laboratory for BSME students.

In this paper, a series of five experiments have been presented focused on the theme of renewable energy for a senior level laboratory. The computer simulations investigated the performance of horizontal axis wind turbines and gearbox vibrations in wind turbine drivetrains. The experimental studies included modal analysis of a mechanical structure, Savonius wind turbine operation, and power generation from a solar panel with light tracking. Together these assignments offer students a foundation in green energy power systems while reinforcing the learning objectives established by the faculty to help prepare them for a successful engineering career.

References

1. Y. Krozer, "Valorisation of energy services: Essay on the value addition due to renewable energy," *Energy. Sustain. Soc.*, vol. 9, no. 1, 2019.
2. A. Miller, B.W. Imrie, and K. Cox, *Student assessment in higher education : A handbook for assessing performance*. London: Krogan Page, 1998.
3. J. Asselin, C. Bostick, T. Knippenberg, J. Schweisinger, and H. Wilson, "Improving the efficiency of a Savonius wind turbine learning module experiment for distance learning courses" *ASEE Zone 2 Conference*, San Juan, PR, 2017.
4. G. M. Masters, *Renewable and efficient electric power systems*. Hoboken, NJ: Wiley & Sons, 2004.
5. R. P. Smith, A. A. C. Hwang, T. Beetz, and E. Helgren, "Introduction to semiconductor processing: fabrication and characterization of p-n junction silicon solar cells" *Am. J. Phys.*, vol. 86, no. 10, pp. 740–746, 2018.
6. S. A. Kalogirou, "Photovoltaic Systems," *Sol. Energy Eng.*, vol. 81, pp. 481–540, 2014.
7. Crystal Instruments "Basics of Structural Vibration Testing and Analysis," CI Product Note, no. 006, 2016. [Online]. Available: https://www.crystalinstruments.com/basics-of-structural-vibration-testing-and-analysis#top. [Accessed Oct. 18, 2019].
8. O. Døssing, *Structural Testing, Part 2: Modal Analysis and Simulation*, Naerum, Denmark: Bruel & Kjaer, 1988.

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