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BYOE: Comparison of Vertical- and Horizontal-axis Wind Turbines

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Wind turbine technology provides an opportunity to measure a number of experimental quantities, including wind speed, electrical power generated, and rotational speed over various electrical loads. An experiment using scale model wind turbines in a wind tunnel was developed for a junior level course in Measurements and Analysis at Northeastern University. The goal of the course is to learn to design and execute engineering experiments and analyze the data. The experiment was conducted in a small scale wind tunnel that had been designed and built by senior undergraduate design students. Teams of 3-4 students were given either a three bladed horizontal axis wind turbine or a Savonius vertical axis wind turbine. The three-bladed turbine was taken from a commercially available kit and modified using custom 3D printed parts. The Savonius wind turbine was completely designed and 3D printed in house. In each lab section, each group tested one of the turbines, then shared the data with the other groups. Students were expected to develop an experimental plan to determine what data needed to be gathered and a LabView™ VI for data acquisition. During testing the tunnel fan speed was increased incrementally. At each fan speed increment the group varied electrical load on the generator while measuring wind speed, voltage, current, and rotational speed. Wind speed downstream of the wind turbine was measured using a Pitot tube and a differential pressure transducer. Wind speed upstream of the wind turbine was measured using a hotwire anemometer. The power generated by the wind turbine and the temperature of the air were measured using a Vernier™ Energy Sensor and Temperature Probe, connected to a Vernier™ SensorDAQ. The rotational speed of the turbine was measured using a non-contact optical tachometer and an oscilloscope. At the end of the experiment, students had enough data to compare vertical and horizontal axis wind turbines in terms of power generated, power coefficients, and tip speed ratio. Students were able to examine the relationship between load on the generator and turbine behavior. During the analysis portion of the lab report, students were also asked to compare the behavior, uncertainty, and accuracy of the various sensors. In a post lab survey 74% students rated the first iteration of this lab as more interesting than the previous wind tunnel lab, which had measured drag on a model car. Students demonstrated increased proficiency in calculating instrument uncertainty and increased understanding of wind tunnel concepts between the pre-lab homework and the post-lab report. Some frustration was noted due to unexpected wind measurements from the Pitot tube. Future terms will concentrate on minor improvements to the instrumentation and connection of the wind turbines to the wind tunnel.

Educational Goals

Measurements and Analysis with Thermal Science Applications is a junior level laboratory course at Northeastern University. This course teaches design of experiments and measurement science with a particular emphasis on thermofluids. In a typical semester this course has approximately 130 students. The course consists of three lecture sections and one 2-hour lab session per week. The lectures introduce course concepts including design of experiments, data analysis, and other measurements concepts. Lab experiments are done in groups of 3-4 students, and each experiment is designed to be completed in one session. LabView is taught in the first lab session, and students are required to install LabView on at least one personal laptop per group. The VI is developed by the students prior to coming to lab, with the understanding that troubleshooting may need to be done in the lab section. Each group also is issued a SensorDAQ USB data acquisition device, which allows them to test their VI outside of class. Prior to the lab session students also do a pre-lab assignment that is due the week before lab, to be returned in lecture before the lab section.

One of the seven experiments in this course introduces students to wind tunnel testing, wind speed measurement, and different types of wind turbines.

The primary goals of this experiment are:

1. To learn how to measure wind speed using Pitot tubes and anemometers.
2. To measure rotational velocity using non-contact methods
3. To compare vertical and horizontal axis wind turbines in terms of power produced as a function of wind speed and load on the generator.
4. To demonstrate key wind turbine concepts such as extracted power from wind, power coefficient, and tip speed ratio.

Equipment Used

The equipment required for this experiment was chosen to work as much as possible with the Vernier SensorDAQ data acquisition system[1]. One of the educational goals of the course is to develop proficiency in the LabView data acquisition software, with which the SensorDAQ is designed to integrate. The wind tunnel used was designed by a capstone design team (Figure 1), however any wind tunnel could be used.[2]

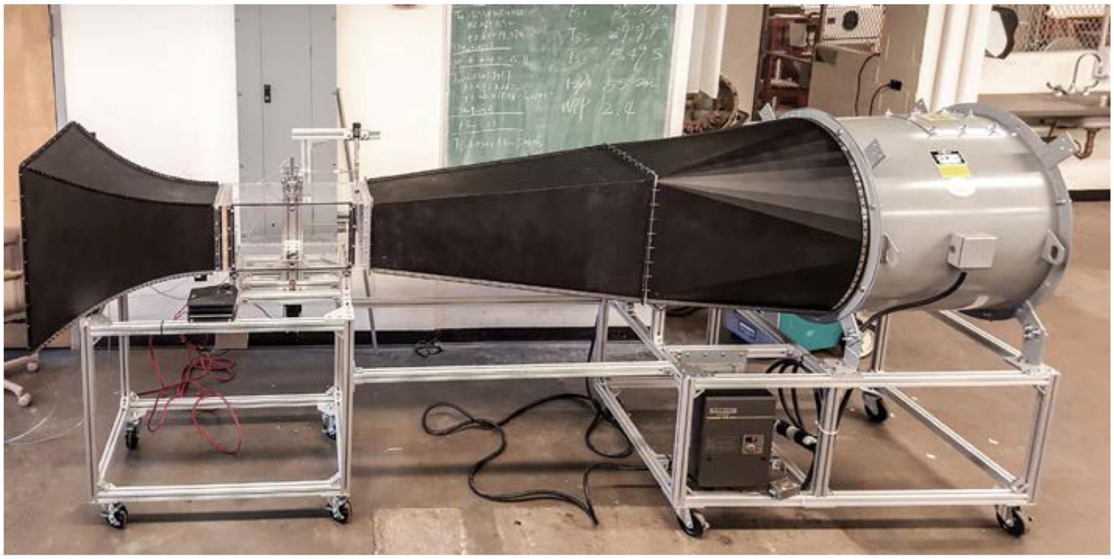

Figure 1: Student designed small scale wind turbine

The specific instruments used for the experiment were as follows:

- Pitot-static tube
- Dwyer Differential Pressure Transducer, 0-1” WC range[3]
- General Model CHD20DLl Hot Wire Anemometer[4]
- Monarch Instruments Remote Optical Sensor[5]
- Oscilloscope
- Vernier K-Thermocouple[6]
- Vernier Variable Load[7]
- Vernier Energy Sensor[8]

Two model wind turbines were used – a three bladed horizontal axis wind turbine and a Savonius vertical axis turbine. The horizontal axis wind turbine was a modified KidWind^{TM} MINI Turbine Kit[9], as shown in Figure 2. The blades and generator were attached to a custom 3D printed mast and base which was designed to fit in the available wind tunnel.

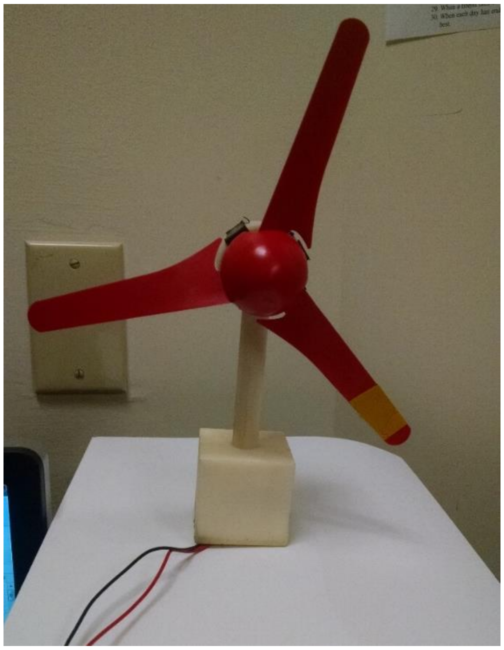

Figure 2: Horizontal axis wind turbine with custom 3D printed base

The Savonius turbine was designed and 3D printed by the authors and is shown in Figure 3. Both turbines had timing marks added in the form of reflective tape to facilitate rotational velocity measurements. All 3D printed parts were fabricated from ABS plastic. The generators used were the same as from the KidWind^{TM} kits.

Figure 3: Savonius vertical axis wind turbine

Experimental Procedure

A pre-lab homework assignment was required for all students. This assignment required them to develop a data table and determine the number of data points that they would need to perform the required analysis. Additional problems focused on researching the expected behavior of vertical and horizontal axis turbines[10], calculating the expected uncertainty in the instruments, and performing sample calculations on tip speed ratio and other wind turbine concepts.

Prior to lab, each group was required to develop a LabView VI that could record data from the differential pressure transducer attached to the Pitot tube, the energy sensor, and the thermocouple. The lab section was divided into two groups for the experiment, with one group measuring the horizontal axis turbine and the other measuring the vertical axis turbine. Each group came for half of the lab session, requiring one hour to do each turbine. The groups then shared data so that everyone could compare both types of turbines. This also permitted the experiment to be finished in one lab session.

Each group measured the dimensions of their assigned wind turbine prior to installing it in the wind tunnel. The turbine was screwed in place at the base, to prevent it from moving during testing. The Pitot tube was previously installed in the wind tunnel to measure the downstream wind speed. The hot wire anemometer probe was inserted upstream of the wind tunnel through a hole in the wind tunnel. The generator wires were connected to the variable load resistor, which was connected to the energy sensor. The optical tachometer was positioned on the outside of the tunnel and connected to the oscilloscope.

Starting at a low wind speed, the students increased the speed slowly until the turbine began to turn. The fan speed was recorded and the variable load resistor was set at a high resistance value chosen by the students. Pressure, anemometer wind speed, temperature, rotational frequency, voltage and current were recorded at each of several resistor values. This procedure was repeated for a number of fan speeds with all data recorded at each interval. At the end of the lab session, both groups exchanged data on the two types of turbines.

Required Analysis

Lab reports were written in small groups of four students. Students were required to tabulate all experimental data. They were required to calculate tip speed ratio, theoretical and extracted wind power, Reynolds number, and the coefficient of performance for each of the wind turbines at each wind speed. Several plots were required, including tip speed ratio vs. coefficient of performance (Figure 4), wind speed vs. power generated (Figure 5), power generated vs. resistance, and rpm vs. resistance. For each plot students needed to compare the behavior of the two different turbines and discuss how they matched expected behavior based on pre-lab research. Additionally, students were required to compare the design stage uncertainty, accuracy, and precision of each instrument. Wind conditions were also analyzed to determine if the wind was laminar or turbulent at any given point, and to relate that to wind turbine behavior.

Ultimately, the students were asked to determine which type of wind turbine generated the most power in each set of conditions.

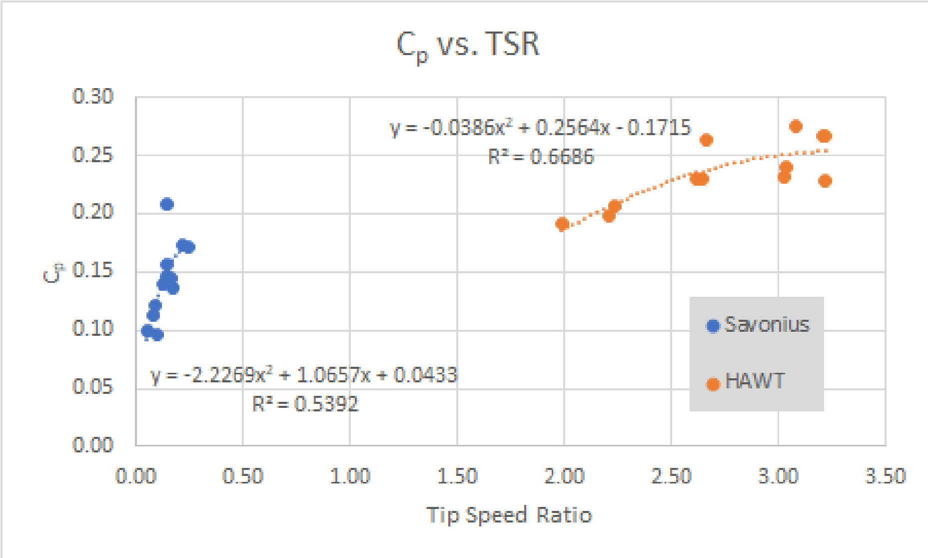

Figure 4: Example of student generated data for Coefficient of Performance vs. Tip Speed Ratio

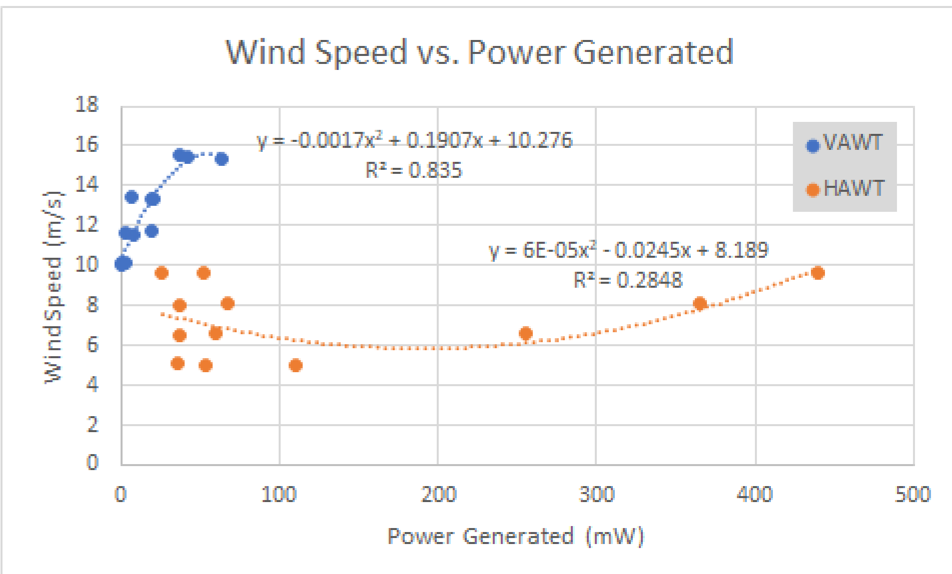

Figure 5: Example of student generated data for Wind Speed vs. Power Generated

Benefits of Approach

Students were surveyed at the end of the experiment to determine their attitudes toward the lab experience. The survey responses for the first offering of this experiment are shown in Table 1. Although there were a number of issues with the first attempt, notably a failure in the optical sensor, the students still responded positively to the experiment. There was some level of frustration expressed, as 53% of the students agreed or strongly agreed that the lab was frustrating or confusing. However, students also found the lab to be interesting and engaging, and believed they could apply this information to future problems.

Table 1: Lab Survey Responses from Fall 2016

Survey Question	% Strongly Agree/Agree	Neutral	%Strongly Disagree/Disagree
The lab helped me learn	67	21	12
The lab was interesting and engaging	74	10	16
The lab was frustrating and confusing	53	14	34
The lab was supported by lecture	87	12	1
I can apply this information to other problems	70	27	4

A few changes were made after the initial offering of the experiment. Originally, the rotational speed was going to be measured using a stroboscopic tachometer and a timing mark. This proved to be problematic, as the students had trouble judging when the timing mark on the turbine appeared stationary and thus the remote optical sensor was chosen instead. It was also crucial that the Pitot tube be positioned properly in the tunnel. Initially, the Pitot tube was only measuring the overall wind tunnel speed, which did not permit calculation of the coefficient of performance. This was changed to have two wind speed readings, with the Pitot tube upstream and the anemometer downstream of the turbine. Finally, the initial connection of the wind turbine to the wind tunnel was not ideal, and caused the wind turbine to twist and shift out of place during testing. This connection was subsequently redesigned using Velcro for future offerings. In general, this lab was of high interest to many of the students, particularly those interested in energy systems, and gave them experience in using a variety of different sensors.

Conclusions

This experiment was designed to allow students to compare vertical and horizontal wind turbines. Model wind turbines were 3D printed and the power generated by the different types of turbines were measured under different wind and resistive load conditions. Students also gained experience measuring wind speed with both Pitot tubes and hot wire anemometers, as well as non-contact methods of measuring rotational frequency. Although there were some initial difficulties students reacted positively to the experiment and found it to be a valuable and engaging educational experience.

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