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Improving Vertical Axis Wind Turbine (VAWT) Performance

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1. Background on VAWTs

According to the Minnesota Department of Commerce, “wind is an increasingly significant source of energy in Minnesota” [1]. The majority of growth in wind energy has been accomplished with horizontal axis wind turbines (HAWTs), typically in large arrays or “wind farms” that produce utility scale amounts of power. However, small-scale systems have also seen large growth, 35% in 2012, with particular attractiveness for rural and agricultural areas [2]. The National Renewable Energy Laboratory (NREL) suggests that greater use of small wind turbines in the built environment can positively affect the public perception of wind energy [3].

An alternative to the HAWT design is the vertical axis wind turbine (VAWT). A VAWT spins around a vertical axis with the wind moving perpendicular to the axis. Blades can take different forms (Figure 1) and are based on lift or drag principles. VAWTs are not as prevalent as HAWTs and can suffer from lower efficiencies and height limitations. However, VAWTs offer several advantageous aspects, particularly in terms of small-scale electricity production.

VAWTs offer potential advantages in the effective use of land area compared to HAWTs. The footprint of HAWT increases proportionally with an increase in swept area. Moreover, when installed in groups HAWTs must be placed several diameters apart to avoid aerodynamic interference. Conversely, the swept area of a VAWT can be increased vertically without affecting the footprint [4,5,6]. Studies have also suggested that constructive aerodynamic interference can increase the output of groups of VAWTs (Figure 2) [4,7].

VAWTs can accept wind from any direction so their orientation does not need to be adjusted. Combined with ground mounted generators, their mechanical systems are simpler [8]. With lower rotational speeds they tend to be quieter than HAWTs [5]. Some researchers also point to a reduction in animal (bird and bat) mortalities with VAWTs [9]. However, these same aspects also result in lower overall efficiencies than HAWTs and an increase in fatigue loads for VAWTs.

Due to the dominance of HAWTs relatively little research has been conducted into improving VAWT performance. An improved understanding of the aerodynamic flow fields around VAWTs and the resulting impact of them on performance is needed. This is especially important for consumers and small businesses that are considering building or installing VAWTs. This project targets two key limitations that exist. First, most numerical methods for studying placement and flow fields involve the use of complicated and costly computational fluid dynamics (CFD) software. Second, wind resource maps typically represent values at 30 m or higher. Small scale VAWT installations are typically at a lower elevation where the influence of ground effects can dominate.

2. Project Description

The creation and validation of an accessible VAWT flow field model and the generation of a wind resource map tailored for small-scale VAWTs has the potential to improve VAWT

Figure 1: VAWT concept by Windtech, Roseville MN (left) and VAWT model sold by Minnesota Wind Technology, St. Paul MN (right). Photos are from company websites.

Figure 2: Caltech Field Laboratory for Optimized Wind Energy demonstrating an array of VAWTS (http://www.gizmag.com/optimizing-wind-turbine-placement/19217/).

efficiencies and remove barriers to some small-scale wind installations. To fulfill the goals and objectives of this project a combination of numerical and experimental approaches will be necessary.

The Leaky Rankine Body (LRB) approach represents VAWTs with “a two-dimensional potential flow model consisting of a uniform flow, a potential source, and a potential sink”. Each VAWT is specified in the approach by the source strength, the sink strength, and the downstream spacing [10]. While the method has been shown to closely represent the performance of individual and arrays of VAWTs, it is a first approximation and over predicts losses. However, as a two-dimensional model it is much simpler to solve numerically which makes it more accessible to the general public. By using the principle of superposition simple solutions can be combined into more complex scenarios with a minimum of effort. This allows arrays of VAWTs and surrounding structures to be modeled with reduced difficulty and computational time.

This multi-year project was funded through a sub-grant from the Xcel Energy Renewable Development Fund. The project is operating with three main goals.

1. Create a numerical tool that can aid in VAWT placement to improve their performance and efficiency.
2. Produce strategies that improve the performance and efficiency for the VAWT placement with regard to their surroundings, other VAWTs, and potentially HAWTs.
3. Determine areas of high potential for the installation of VAWTs in Minnesota.

3. Student Involvement in the Project

Minnesota State University, Mankato is a regional comprehensive university. Research within the engineering programs tends to be very applied in nature. While a Master of Science in Engineering degree is offered, there are no doctoral programs in engineering and the number of graduate students is small. This implies a heavy reliance on undergraduate research assistants. Advising and supervision of these students has been split between three principal investigators from Mechanical Engineering, Civil Engineering, and Mathematics.

Several different components of student work on the project will now be highlighted.

3.1. Boundary Layer Wind Tunnel Design

A traditional wind tunnel produces a uniform velocity flow field. However, to conduct scale model studies of a wind turbine a boundary layer wind tunnel is required. These generate a growing boundary layer that simulates air flow over the surface of the Earth. Boundary layer wind tunnels can cost many thousands to over a million dollars and they typically take up large amounts of space. Therefore, the alternative of designing and constructing a new tunnel was first explored.

The initial design requirements were that the tunnel be 1) portable so it can be used for multiple projects or courses, 2) storable when not in use, and 3) relatively inexpensive. Working dimensions were estimated at 1 m x 1 m with a test section length of at least 10-15 m. Designing the shape and flow straightening sections of the wind tunnel was considered crucial to achieving the desired flow fields. While a data acquisition method such as laser Doppler velocimetry (LDV) is typically used to measure velocity fields it does complicate the portable nature with issues of safety and calibration. Therefore, a slightly more intrusive seven-hole probe method was to be explored [11]. Combined with a three-dimensional traversing system this method would be able to measure multi-component velocities around scale models.

Due to delays in the funding mechanism and a campus conflict of interest review, the official start of the grant was delayed for several months. This task was undertaken before the project funding arrived by structuring it as a mechanical engineering senior design project with a team of four students.

The team worked on the project for two semesters. The results determined that a fully portable wind tunnel would not be possible due to weight and storage size restrictions. Given existing laboratory sizes and cost restraints, the size of the design was also adjusted. The final design was 10.3 m long with the widest section being 1.6 m. The test section was 0.6 m by 0.6 m. The selected fan had an 8.24 kW power requirement for test velocities from 5.56 m/s to 19.44 m/s. The test section was composed of plywood, except for one viewing panel of Plexiglas. The contraction and diffuser were designed as fiberglass. The data acquisition system was not fully designed, although some components were suggested.

As part of the design effort the team was able to tour the University of Minnesota St. Anthony Falls Laboratory. It was determined that the boundary layer wind tunnel at the lab had better characteristics than their final design (e.g. test section size) and that it was available for use with minimal cost. Because of this it was decided not to construct the designed tunnel and to reallocate the funds to other experimental approaches.

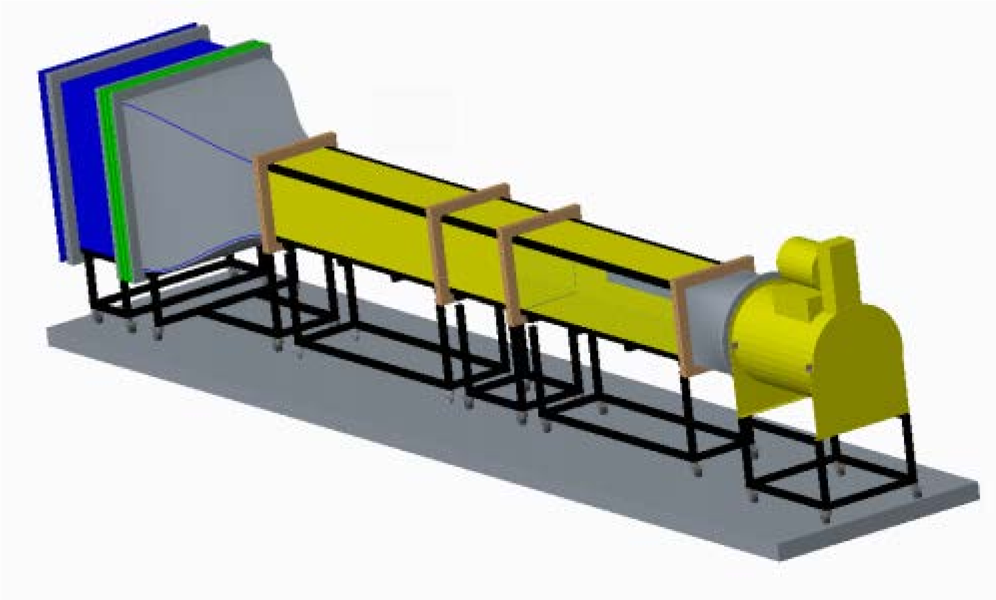

Figure 3: Solid model representation of the student boundary layer wind tunnel design.

3.2 Potential Flow Numerical Modeling

The purpose of the project is to employ the LRB method in an open source format or integrated with readily available software (i.e. compiled MATLAB or Microsoft Excel). Initial validation of the LRB code will be done by comparison with published results, simulations conducted with a large scale CFD package (i.e. ANSYS Fluent), and experimental results from the laboratory setting. Final validation will be achieved by comparing results to experimental measurements taken at existing VAWT installations within Minnesota.

A graduate student in mechanical engineering has taken on development of the potential flow simulation as a thesis project. Using MATLAB and the principle of superposition, he is creating a program that will allow rectangles (buildings), circles (trees), and source-sink pairs (VAWTs) to be combined.

3.3 Navier-Stokes Numerical Modeling

Extensive parametric modeling using a Navier-Stokes CFD package is not expected, however, the Fluent package is being used to help develop experimental models and to verify the LRB simulations. A graduate student with a background in aeronautical engineering has been hired to conduct this modeling.

For accurate representation of the flows, a turbulence model has to be employed. In addition, the motion of the VAWT blades themselves greatly complicates the simulation. Initial simulations quickly determined there were memory and runtime limitations. The resulting model being used is two-dimensional (i.e. a horizontal plane) with a dynamic mesh. Two versions of the model have been explored. The first sets the VAWT blades turning at a constant speed. The second, preferred model, incorporates the inertia of the blades and starts the simulation from a condition of zero rotational motion.

The current model (Figure 4) incorporates over 1 million cells and requires over one day (24 hours) of runtime to simulate one second of motion. Access to the Minnesota Supercomputing Institute has been obtained to determine the runtime on their systems. Specifications have also been developed for a new computer to be purchased which would hopefully speed up results.

3.4 Experimental Measurements in the Lab

VAWTs employ numerous blade shapes. While the LRB method has been explored for some designs it will be necessary to tailor the parameters for specific VAWT shapes and three dimensional wakes [6]. Scale models mounted in a low speed wind tunnel and a water channel will be used to collect the required experimental data. While the wind tunnel is not the boundary layer variety it can be used to perform basic model validations. On the other hand, due to the length of the water channel it will be able to develop a suitable boundary layer for testing.

To produce the scale models 3D printing is being used. Several undergraduate students have researched existing VAWT models and have explored printing them in both PLA and ABS materials. For prototyping they have been exploring a range of printer options including MakerBot, Cube, and AirWolf. The nature of the research has required these students to pay

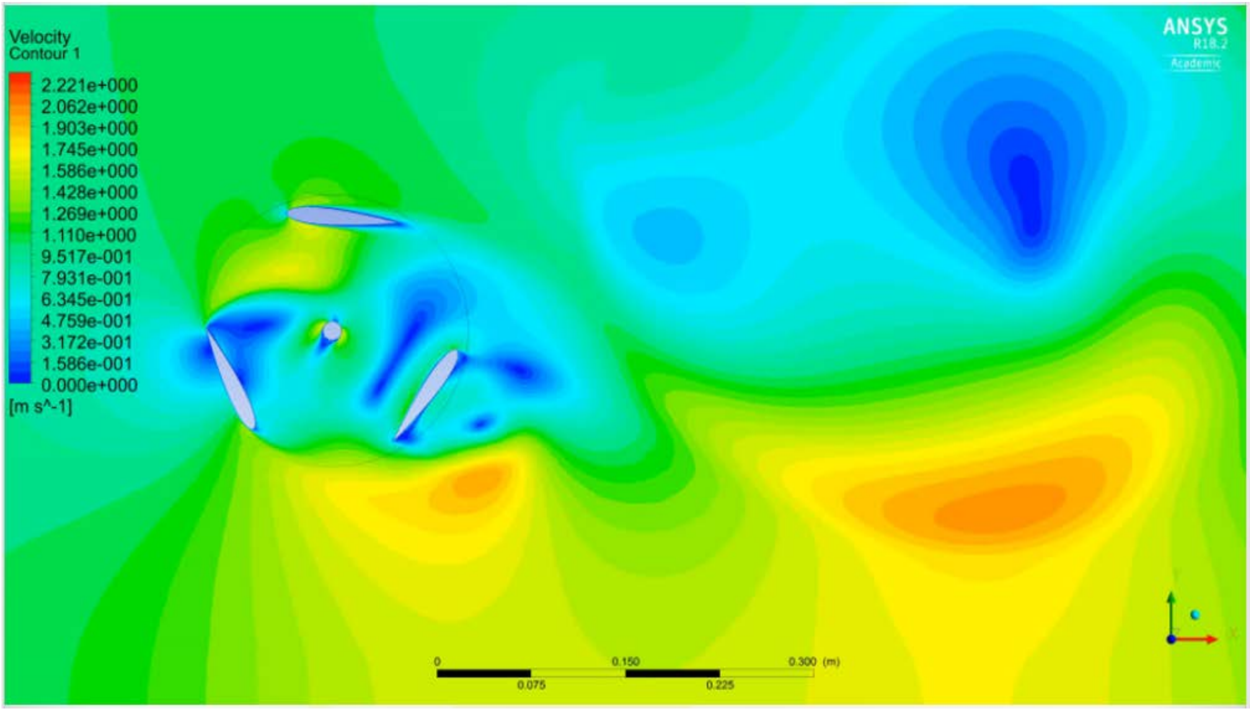

Figure 4: CFD simulation with Fluent showing velocity field around a three bladed VAWT.

close attention to tolerancing as well as surface finishing options to ensure proper roughness of the final parts.

Specialized mounting hardware has been designed (Figure 5). The magnetically attached mount was designed by an undergraduate researcher. It will allow the positioning of the model to be adjusted and allow a rotating shaft to extend through the top surface of the tunnel or channel. This shaft can be attached to a torque sensor to measure VAWT performance. Alternatively, it could be connected to a small electric motor which will simulate inertial resistance against the blades.

3.5 Experimental Measurements in the Field

Experimental data will also be gathered outside of the lab. Measurements of wind profiles at potential sites will be needed for the final verification stage of the LRB software. Collecting data from sites with existing VAWTs will allow a comparison between numerical performance estimates and scale model measurements.

Anemometer towers that measure wind velocity at several vertical increments have been designed and constructed for this stage (Figure 6). Each tower has a steel welded base with adjustable poles for various heights up to 16 feet. Masts hold the sensors at different vertical heights. The top sensor is from Davis Instruments and measures both wind velocity and direction. Below it are two Inspeed pulse anemometers. Each tower is equipped with a National

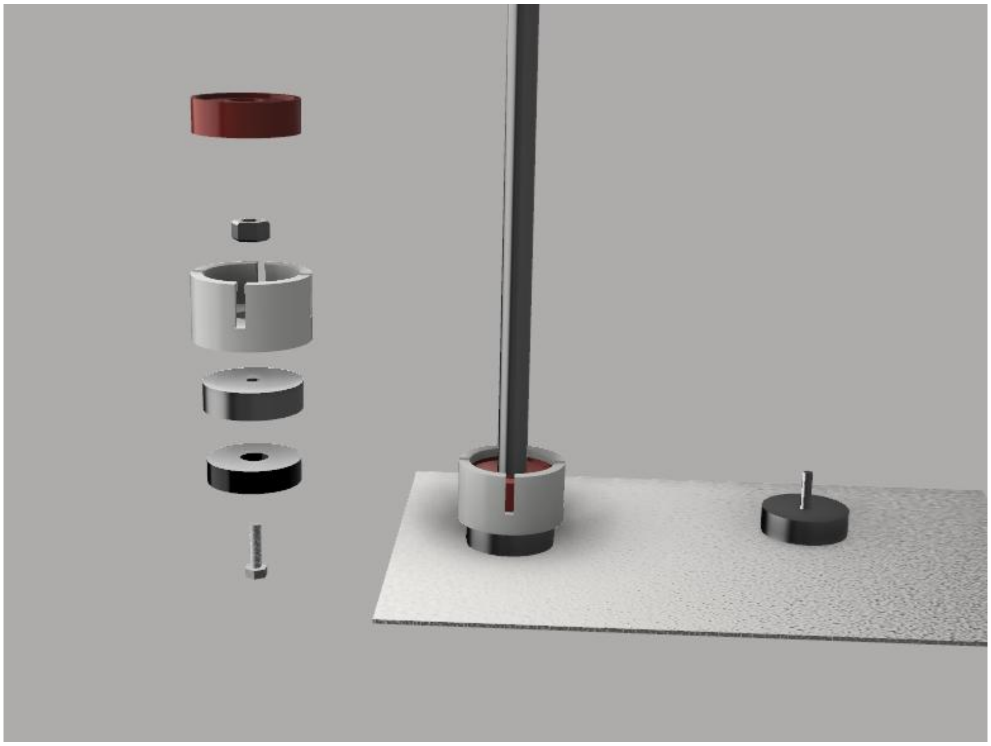

Figure 5: CAD representation of mounting hardware for scale models in wind tunnel and water channel.

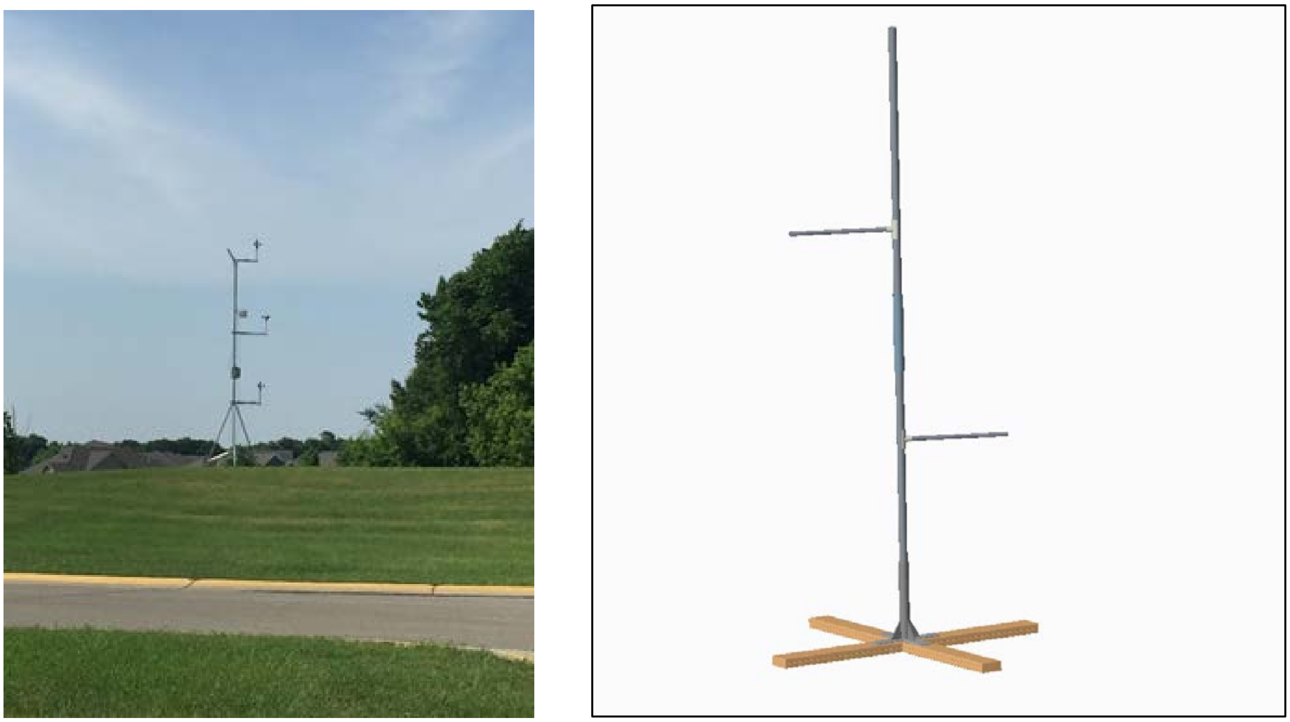

Figure 6: Anemometer tower (undergoing testing on left, design drawing on right).

Instruments myRIO unit programmed in LabVIEW. The unit collects all data and saves it to a flash drive or remote laptop. By placing several of these towers around an existing VAWT a rough approximation of the flow field will be determined [12].

The towers have been tested outside for basic operation. Minor glitches in recording and synchronization of data were discovered. The myRIO programming and data reduction is being adjusted to account for this. Currently the towers are undergoing calibration studies in the laboratory to confirm that all sensors are recording accurate values.

4. Feedback from Students

As a learning experience this project has already provided many opportunities for our students. However, there is always room to improve the impact and efficiency of the process. Students who have worked on the project during the last year were asked to complete a simple survey (note: this did not include the students who participated during their senior design course). Eight students completed the survey. This does not provide a statistically valid sample but it does provide basic quantitative data. The demographics of students were:

- The students self-reported as one sophomore, three juniors, two seniors, and two graduate students.
- The average GPA for the group was 3.2 with a high value of 3.68 and a low of 2.7.
- The average number of months on the project was 7.4.
- The average hours worked per week on the project was 14. However, these values seem highly suspect as there were some students reporting 30 or more.

At the beginning of the project students were given an overview of basic experimental procedures and literature search processes. They were shown the article databases available through the library and experimental equipment in the labs. Student feedback of this experience is seen in Figure 7 and was largely positive. Students were then asked to identify the skills that they had developed as part of their research experience (Figure 8). Next, students were asked if the experience had affected their beliefs about several items (Table 1). A majority of the students found the experience increased their desire to be an engineer. Half of the students also commented the experience increased their belief in being successful as an engineer.

Students were given the opportunity to comment on some of the most rewarding or positive aspects of working on the project. The majority of responses related to greater experience or knowledge with the specific aspect of the project they were working on (e.g. computational fluid dynamics). However, several students also commented on the experience of working on a large project and learning about a topic important to society (i.e. renewable energy).

Responses as to the most detrimental or negative aspect of the project were largely similar. Managing time between research, classes, and outside internships was seen to be a challenge. Suggestions for improving the experience included allowing students to make more mini-presentations and more directed mentorship. These ideas will be considered as the project moves forward.

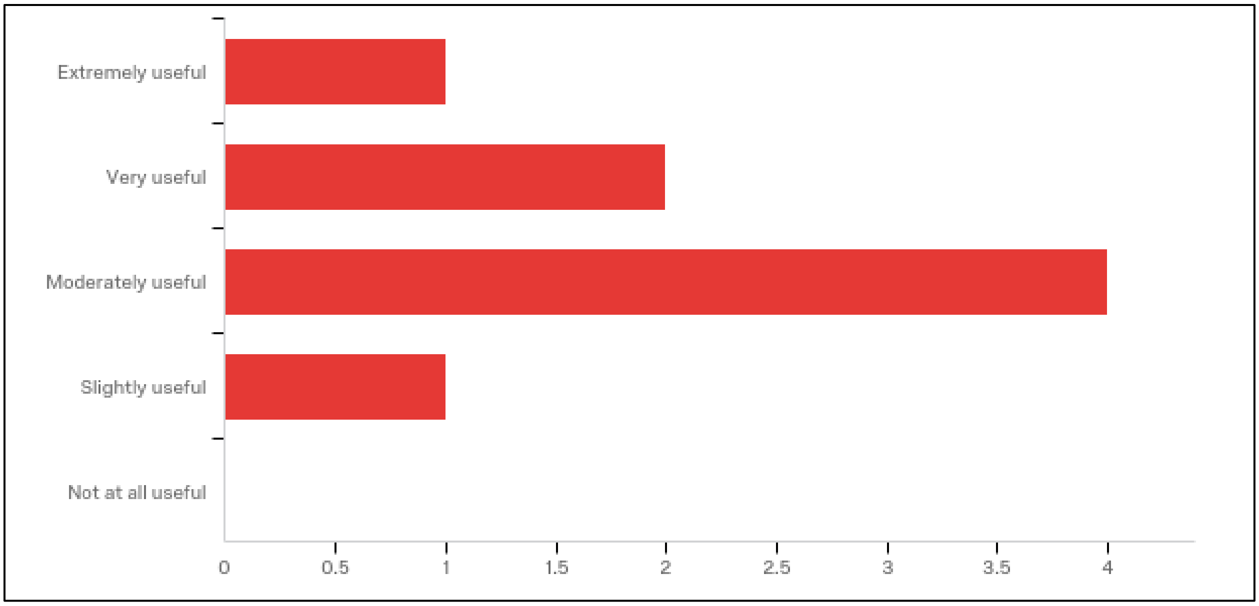

Figure 7: Student response to “How useful was the training you received?”.

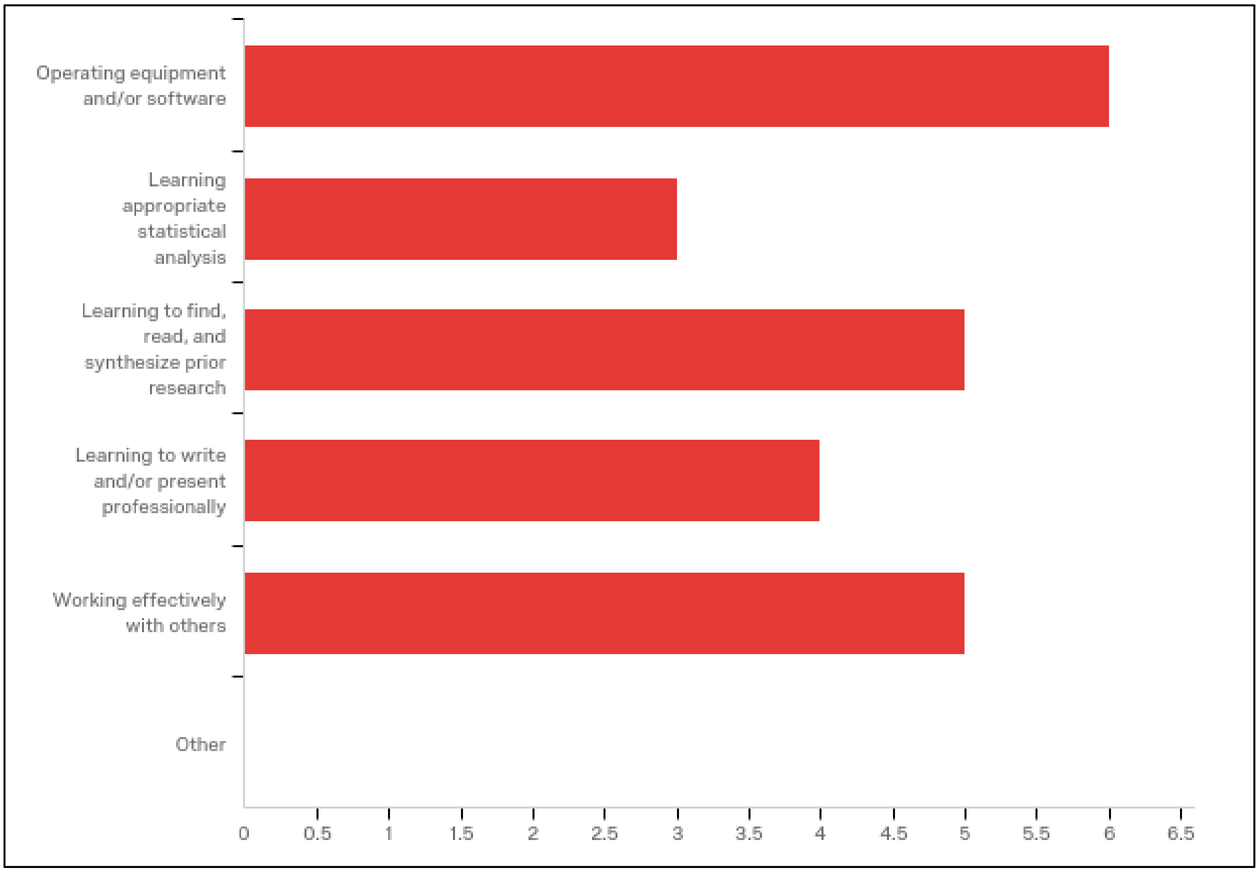

Figure 8: Student response to “What skills have you learned or improved during the research?”

Table 1: Student response to “Rate how your research experience has impacted our opinions of the following items.”

	Decreased	No change	Increased
Desire to be an engineer	0	2	6
Belief you can succeed in the engineering program	0	3	4
Desire to pursue a graduate degree	1	5	2

5. Future Work

This project will continue for another year. There are several technical aspects that will need to be completed during that time. The majority of the experimental testing in the laboratory and the field will be scheduled for Summer 2018. During the next academic year, research will shift to an analysis of regional wind resources and identification of the highest potential for VAWTs. Work will continue on the LRB model and it is hoped that by Fall 2018 tasks will shift to designing a user interface for the functioning simulation.

One of the greatest challenges with the future work will be trained undergraduate and graduate assistants. As the current students graduate or take on full time industry internships it leaves openings within the research team. Recruiting and training the next group of students will need to be a priority. Feedback and suggestions from the current group will guide this process.

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