Vertical Axis Wind Turbine Evaluation and Design

A Major Qualifying Project Report Submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the Degree of Bachelor of Science.

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Abstract

      This project studied the potential for installing roof-mounted vertical axis wind turbine (VAWT) systems on house roofs. The project designed several types of VAWT blades with the goal of maximizing the efficiency of a shrouded turbine. The project also used a wind simulation software program, WASP, to analyze existing wind data measured on the roofs of various WPI buildings. Scale-model tests were performed in the WPI closed-circuit wind tunnel. An RPM meter and a 12 volt step generator were used to measure turbine rotation speeds and power output at different wind speeds. The project also studied roof mounting systems for turbines that are meant to dissipate vibrations to the roof structure. Turbine vibrations were measured during the wind tunnel tests and in impact tests on a scale-model house. Recommendations were made for future designs of roof-mounted VAWTs.

Capstone Design Experience ABET requirement

To fulfill the requirements for a Major Qualifying Project (MQP), this project must meet the requirements for a capstone design experience. The Accreditation Board for Engineering and Technology (ABET) defines the capstone design experience as an "experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political." (Cryer, 2011)

The design components for this project include the following attributes which satisfy the ABET requirements for capstone design:

Environmental: Environmental concerns have been an important issue in the engineering field. Projects have been taking consideration of environmental impacts as a result of their products. Wind turbines are a form of renewable energy that will help the environment by not producing emissions while creating electricity. As an end result less fossil fuel would be required in order to provide electricity for a house.

Sustainability: The project outcome will produce a commodity that will be able to help the environment and make society more self-sustainable. This is accomplished by making society more independent from using fossil fuels. This has been a very big topic as of recent and many different movements happening in America and around the world are focused on using our renewable energy, such as wind. This project is helping the succession of this idea and broadening the capability of turbines to reduce carbon footprints.

Manufacturability and Economic: With a simpler design of these turbines and easier assembly, it will make it possible for local hardware stores to sell these products. Along with simpler

design this will also decrease manufacturing cost and make it more economical for families to buy.

Health and Safety: This project considers health and safety concerns by addressing roof mounting systems. The hope is to design a mounting system that will not cause structural damage to residential roofs. A mount that is able to diminish vibrations before entering roof trusses will help protect trusses longevity and decrease chance of failure.

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Authorship

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Suggestions	Drew Digeser, Chris Dunn	Drew Digeser, Chris Dunn

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1.0   Introduction

With populations increasing exponentially and our natural resources being strained by increases in demand, it is more important than ever to invest in renewable energy. Our consumption of fossil fuels as energy has been traced to be a leading cause in environmental issues. The byproduct of fossil fuel consumption is carbon dioxide, which has been named to be a primary constituent leading to Global Warming. The amount of carbon dioxide that someone or something produces is known as its "carbon footprint." The media has been focusing on this issue and many green movements have started to try and reduce our "carbon footprint." (Green Student U, 2008)

There are only a few types of energy that do not produce carbon dioxide. These are nuclear power and renewable energy sources such as wind, solar and hydro power. Renewable energy sources are the cleanest from of these sources, because there is no waste formed as byproducts of these sources. Nuclear energy produces nuclear waste which could take up to but not limited to 100 years until it can be disposed of properly. Wind turbines have been used throughout the world to generate electricity from off shore wind farms to residential smaller scale wind turbines. (California Energy Commission, 2012)

Figure 1.1 Examples of different HAWT systems

There are two main types of wind turbines. The two general categories for wind turbines include vertical axis or horizontal axis wind turbines. The turbines are classified upon how the shaft of the generator is mounted. The horizontal axis wind turbine HAWT was invented before the vertical axis wind turbine (VAWT), which led to its popularity and wide use. Figure 1.2 shows a diagram of these two types of systems.
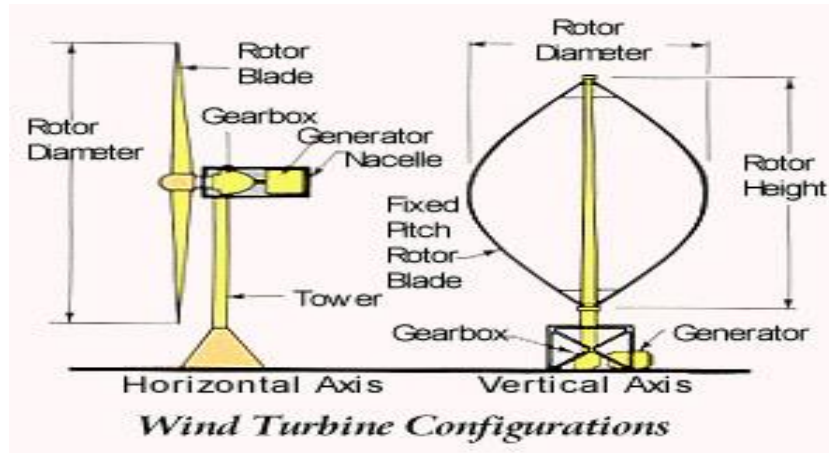
Figure 1.2 HAWT VS. VAWT Design

This project is an extension of previous work at WPI in MQP projects that focused upon VAWTs. The research in this project was intended to improve VAWT efficiency and maximize the energy generation from the wind's available power. This was done by considering alternate turbine designs adding a shroud around the wind turbine. The project researched blade designs that performed the best with a 90° enclosure. The enclosure is a shroud that surrounds the turbine and allows wind to enter the area at a 90° angle. The enclosure was expected to increase the turbine's revolutions as compared to a turbine without an enclosure. The project also entailed research into reducing the amount of vibration experienced by a roof caused by wind turbines. This was approached by variations of vibration dampening systems on the roof mounting system. To see how effective a VAWT system would be in Worcester, specifically WPI facilities, a software program called WAsP was used with wind speed data collected over the past couple of years. WPI has a few anemometers located on top of Daniels and East Hall as well as the campus center. With these data, the WASP software was used to create plots showing the wind patterns experienced on top of the dormitories.

2 Background

As world population and standards of living increase there is an ever growing demand for energy. This increase in energy creates significant demand for energy created by fossil fuels, which the world has a limited amount of and carbon emissions can lead to global warming. The fears of diminishing natural resources and concern of significant climate change as a result of the burning of fossil fuels has created great worldwide interest in clean renewable energy that can meet the electrical demands of the world. One common strategy is to use wind turbines that generate electricity from wind.

2.1 Wind Intro

Wind is generated from solar energy unevenly heating the earth. This uneven heating creates pressure changes in the atmosphere, generating wind. This wind can then be harnessed by a wind turbine. As the wind pushes the blades of a turbine, a generator attached to the axis of the shaft and when spun creates electricity that can be sent to the grid and used in households for electricity. (windies.gov, 2012)

Wind turbines are a clean way to generate power, yet there are many significant problems with them as well. One problem is that they are extremely expensive to design and install, and in order to generate enough energy for communities and cities require space for wind farms. Another issue is that they have to be created in locations where there is enough wind energy to generate enough electricity to justify the cost of the machine. (windies.gov, 2012)

2.1.1 Power Density

Geography can greatly effect wind speed, and in effect the power from the wind. Knowing this information prior to setting up a wind turbine is imperative. Calculating the average power from wind is a simple equation:

$$P = \frac{1}{2}\rho V^3 A$$

<div style="text-align: right">Equation 1</div>

Equation 1 indicates the importance of wind speed in power generation because power generation increases proportionally as wind increases to the third power. Knowing the power density will allow wind turbines to be placed in efficient locations for generating electricity. Figure 2.1 shows a scale for power density using equation 1. Wind class one and two contain relatively low amounts of power and have been tested to not be efficient for wind energy generation. Class three does not have sufficient power for large scale energy generation, yet it does potentially have value in personal wind turbine generation. Classes 4-6 have enough energy to be efficient in large scale wind turbine generation intended to power communities and cities.

	Wind Speed Classification Specs			
Wind Class	50 METERS		150 METERS	
	Power Density (W/m^2)	Wind Speed m/s (mph)	Power Density (W/m^2)	Wind Speed m/s (mph)
1	0-200	0 – 6.0 (0-13.4)	0-320	0 – 7.0 (0-15.7)
2	200-300	6.0-6.8 (13.4-15.2)	320-480	7.0-7.9 (15.7-17.7)
3	300-400	6.8-7.5 (15.2-16.8)	480-640	7.9-8.8 (17.7-19.6)
4	400-500	7.5-8.1 (16.8-18.1)	640-800	8.8-9.5 (19.6-21.1)
5	500-600	8.1-8.6 (18.1-19.3)	800-960	9.5-10.1 (21,1-22.6)
6	600-800	8.6-9.5 (19.3-21.3)	960-1280	10.1-11.1 (22.6-24.9)

Figure 2.1 Wind Speed Table

Figure 2.2 shows were these wind classes occur regularly in the United States.

Nationwide these efficient locations can be utilized to find where wind speeds are the

highest. By reading the information from the figures 2.1 and 2.2, one can attempt to place turbines were the wind is generally the most consistent and powerful for the generation of electricity. As Figure 2.2 indicates the Western part of the United States overall have the best winds for energy generation.
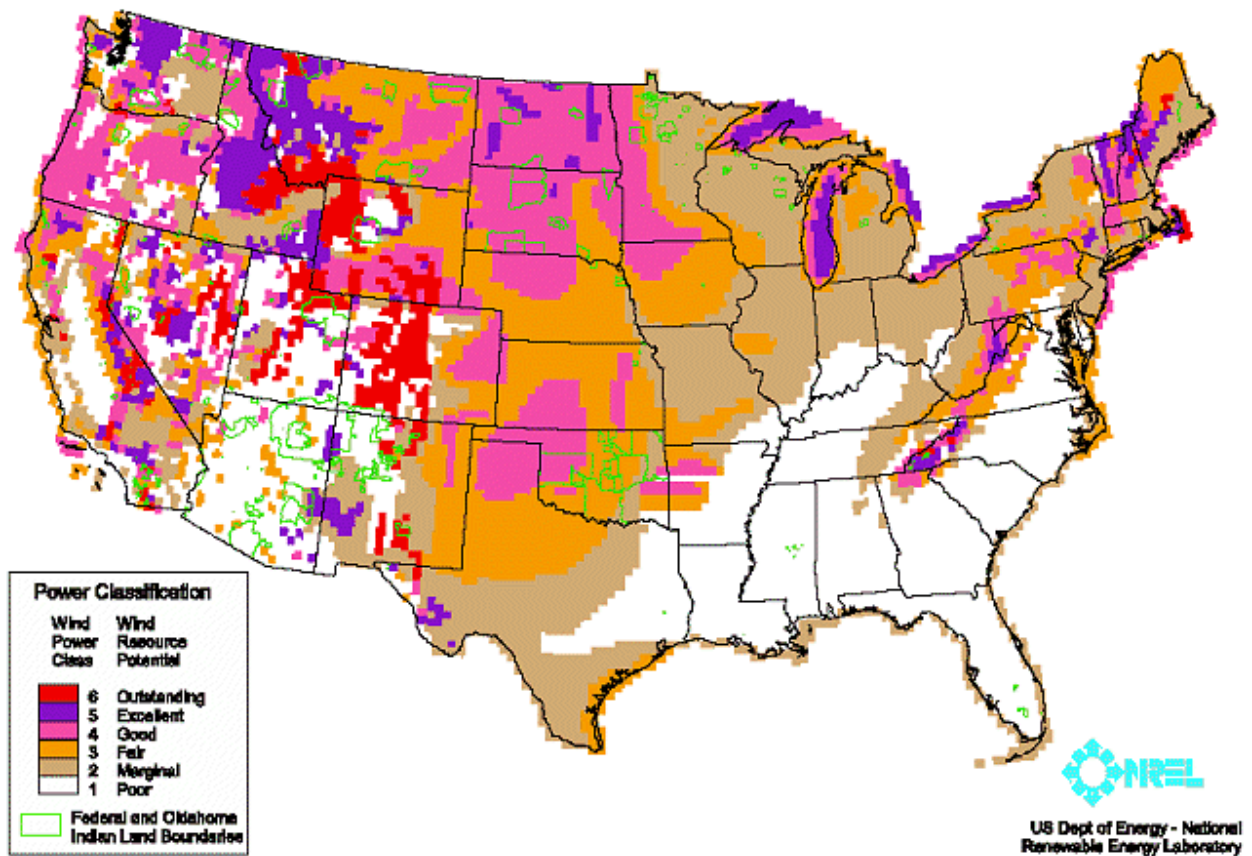
Figure 13. Wind Resource Potential

Figure 2.2 Wind Classifications in America

2.1.2 Wind Speed

Another important factor is the height of the turbine rotor. One of the major reasons wind turbine costs are so high is because the higher altitude the turbine is located, the higher the velocity of the wind, which in turn increases the power output from the generator. Equation 2 is the power model which estimates the effect that height has on wind.

$$V(z) = V(z_{ref}) \left[\frac{z}{z_{ref}} \right]^{\alpha}$$ **Equation 2**

$V(z_{ref)\ is}$ the reference point that can be looked up in a chart, z is the height above the ground, and alpha is the power law exponent in which is affected by the surface geometry of the land and needs to be researched. Figure 2.3 contains equation 2 against height to show how wind velocities exponentially affect power output.
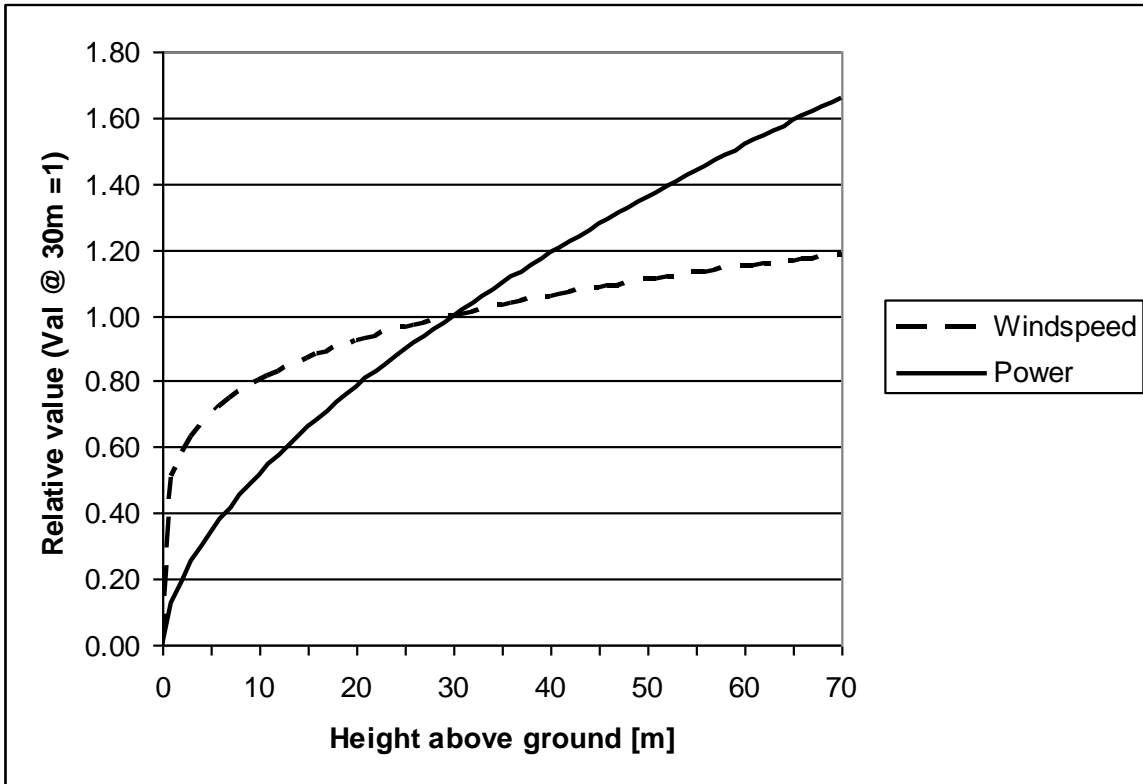
Figure 2.3 Correlation of height with wind speed and power

As figure 2.3 indicates, below 30m in the air the wind velocity increases at a faster rate than the corresponding power density. However, once an altitude of 30m is reached, the power density increases at a faster rate than wind velocities increases. This demonstrates that the higher a wind turbine is, the more energy can be obtained from the turbine.

2.1.3 Power Coefficient

The power coefficient is the percentage of power received by the wind turbine through the swept area of the turbine blades. Equation depicts how to calculate the coefficient of power.

$$C_P = 4\frac{V_t^2}{V_u^2}\left[1 - \frac{V_t}{V_u}\right]$$

In equation 3, V_u is the velocity of the wind as it approaches the wind turbine and V_t is the velocity of the wind as it passes through the swept area of the wind turbine blades. The maximum theoretically possible coefficient of power is called the Betz limit which is 0.593. Most current turbines today have a power coefficient between 0.3 and 0.4.

2.1.4 Tip Speed Ratio

Equation 4 defines the tip speed ratio is the ratio of the tip speed of the blade divided by the wind speed. The equation for tip speed ratio is described below:

$$\lambda = \frac{\Omega R}{V_u}$$

In equation 4, λ is the tip speed ratio, Omega is the rotor rotational speed in radians per second, R is the rotor radius in meters and V_u is the wind speed.

2.2 Wind Turbine Classification

The two major classifications of wind turbines are horizontal and vertical axis wind turbines, (HAWT and VAWT). The horizontal axis wind turbines are the most common and have blades rotate on an axis parallel to the ground.

2.2.1 HAWT
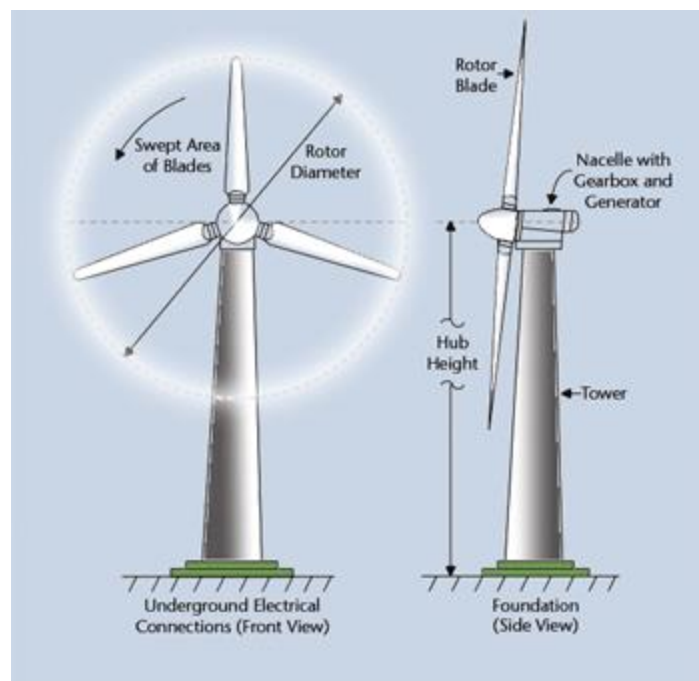
Drawing of the rotor and blades of a wind turbine, courtesy of ESN

Figure 2.4 HAWT configuration

Figure 2.4 shows a typical Horizontal axis wind turbines. The horizontal axis axil is attached by bearings at the top of the tower were the blades are also attached to the axel.

The axil is enclosed in a nacelle. The nacelle is where the gearbox and generator are located. Horizontal axis wind turbines utilize airfoil design to generate the spinning of the blades. The concept of the wind foil of a HAWT blade is that the wind travels over the top of the blade rather than under it, creating less pressure on top of the blade generating lift and creating rotational movement. Figure 2.5 depicts this information.
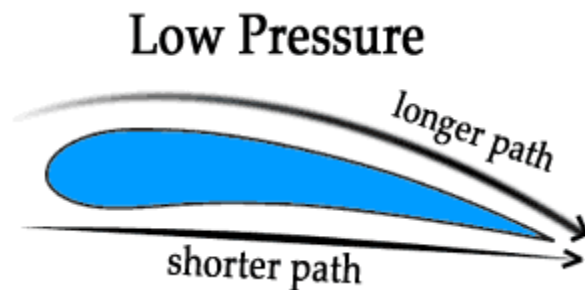

Figure 2.5 Air Foil

2.2.2 VAWT

The other major classification for wind turbines are vertical axis wind turbines. These turbines spin on a vertical axis. Figure 2.6 is an example of a Darrieus vertical axis wind turbine. This turbine is an example of a commercially used vertical axis turbine. One of the major problems with vertical axis wind turbines is that an initial force is required to start the turbine's spinning. Another issue is that they are difficult to be designed for high altitudes. The blades on a vertical axis wind turbine can utilize an airfoil design like the VAWT; however a VAWT can also use blades that directly face the wind, as shown in figure 2.7

Figure 2.6 Darrieus VAWT

Figure 2.7 Three flat bladed VAWT

2.3 The Effects of Shrouds on Vertical Axis Wind Turbines (VAWT)

A previous Major Qualifying Project (MQP) report by Julie Eagle (Eagle, 2012) addressed VAWT design, entitled *Enclosed Vertical Axis Wind Turbines*, shows preliminary research on how a protective shroud affects vertical axis wind turbines placed within it. The research confirms that a three bladed turbine design with air foil blades outperform and is more efficient at lower speeds then the equivalent flat blade design. This information is depicted in Figure 2.8.
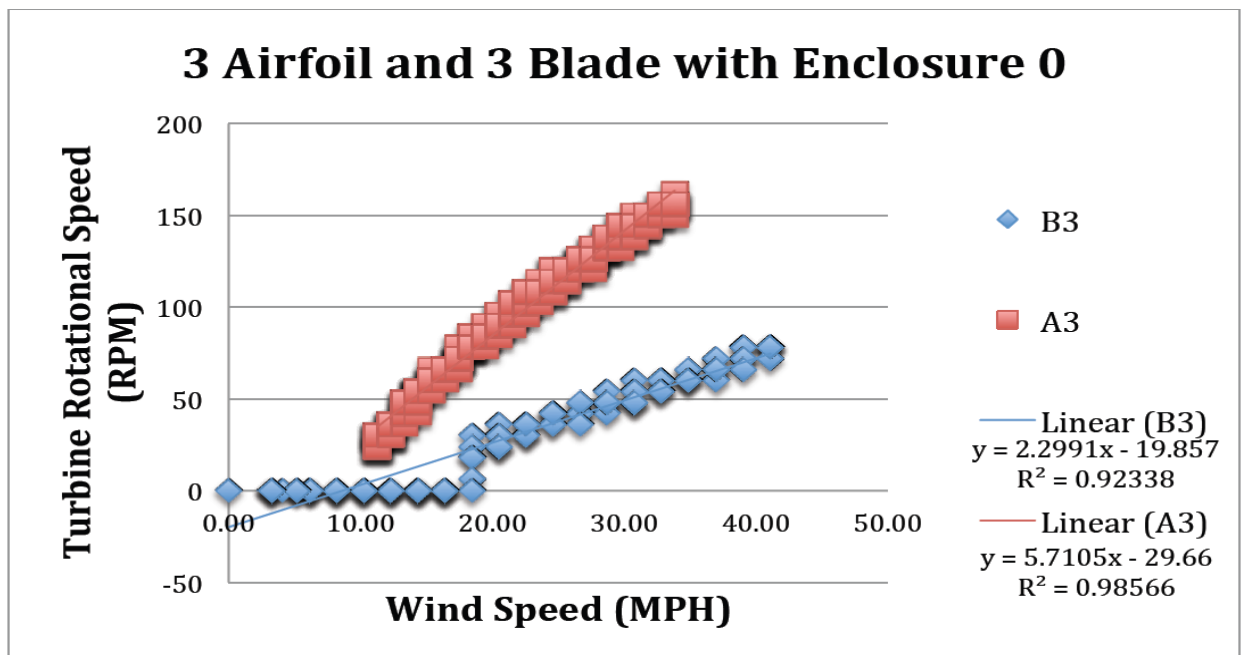

Figure 2.8 Comparison flat blades vs. air foil design (without enclosure)

The results from figure 2.8 demonstrate poor potential for home rooftop wind turbine potential because the airfoil design (labeled as A3) has a cut in speed of 10 miles per hour. The flat bladed design (labeled as B3) takes even higher wind speeds to initiate

spinning with a cut in wind speed of 20 miles per hour. The reason these results are poor for a rooftop wind turbine is because in Massachusetts the estimated wind speed that will approach a rooftop wind turbine is 6.24 miles per hour indicating that neither of these designs can be expected to generate significant amounts of energy throughout the year. The results also do not indicate their real performance because there was no load put on the turbine system, such as a generator. The wind speeds indicated to spin the turbine are much lower than actual wind speeds required to rotate a turbine with generator.

Further testing from the same project (Eagle, 2012) compares the previous test with the same turbines, but with a protective shroud and a funnel that accelerates wind speed. These results are depicted in figure 2.9. The x-axis represents the wind speed that is produced by the wind tunnel and not the accelerated wind speed occurring within the enclosure.

3 Airfoil and 3 Blade with Enclosure 1

Turbine Rotational Speed (RPM) vs. Wind Speed (MPH)

B3

A3

Linear (B3)
$y = 53.976x - 209.64$
$R^2 = 0.98256$
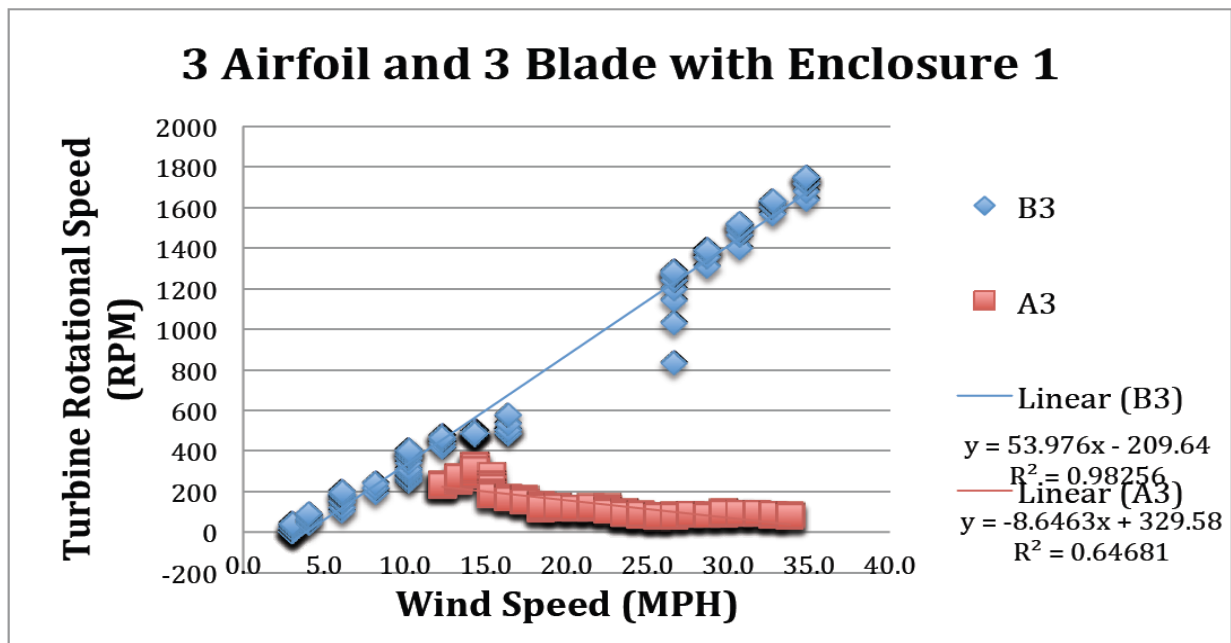Linear (A3)
$y = -8.6463x + 329.58$
$R^2 = 0.64681$

Figure 2.9 Comparison flat blades VAWT vs. air foil design (Enclosure 210°)

The results in figures 2.8 and 2.9, from Julie Eagles report, primarily indicate that funneling wind into an enclosure increases the rotation rate of the turbines significantly. This leads to a promising potential for vertical axis rooftop wind turbines. An unexpected result from this test is that the flat bladed design (B3) performed better than the airfoil design (A3) in this test. This is very surprising because without the funnel and shroud the airfoil design performed better than the flat bladed design.

Similarly during the test shown in figure 2.8, the airfoil design had a cut in speed around 10 miles per hour in the test depicted in figure 2.9. However, the design peaked at about 15 miles per hour and had a decrease in its rotation rate as speed increased thereafter. This still leaves these VAWTs at below performance levels for the wind speed expected on roof tops in the Worcester area. The flat bladed design performed better than expected and outperformed the airfoil design in this test. The decrease in speed was at about 2.5 miles per hour which is below the expected wind speed the product would encounter. The results are also encouraging because at 6.24 miles per hour the flat bladed design had a similar rotation rate to the airfoil designs without a shroud at over 35 miles per hour. Again, this is without a load attached so we can expect when attaching a load that the rotation rate will decrease as a resistance is applied.

2.3.1 Shrouded Wind Turbines

Currently there is not much research about how a shroud will affect a vertical axis wind turbine. Still, the funneled shroud concept has been used since the 1920's for horizontal axis wind turbines. While there is supporting facts that a funneled shroud does increase airspeed to the turbine, it does also increase the size, weight, and cost of the

project. These negative factors deter large wind turbines from having a funnel, as well as the fact that none have been commercially used that can compete with a modern 3 bladed horizontal axis wind turbine. However, current research shows a promising future for shrouded horizontal axis wind turbines with some currently being tested with claims of a 2-5 times increase in power generation in comparison to similarly sized non shrouded horizontal axis wind turbines.

2.4 Savonius VAWT

The Savonius VAWT design was created by Finnish inventor S.J. Savonius in the 1920's. The design utilizes an open overlapping two half cup designs that is very beneficial to wind turbine design. Some of the most appealing benefits of the Savonius design are it simple and cheap to construct, it has low noise and angular velocity when in use, and it can accept wind from any direction and can withstand extreme weather conditions without significant damage. In addition there are multiple variations to the design that change the performance of the turbine depending on blade configuration. According to Dept. of Mechanical Engineering at IIT, a split Savonius has a coefficient of power of 0 .35 compared with the simple two half cup design with a coefficient of Power of 0 .15. (Saha, 2008)

Some of the disadvantages of the Savonius design are that the turbine is not a very stable design. Large scale models of a Savonius are not applicable because the design is not sturdy enough to handle the heavier weight of the turbine blades for large sizes. Some additional facts that should be considered when using a Savonius design are that they are

most effective at lower speeds rather than high speeds and they can operate in turbulent winds.

2.5 Home Turbines

Home wind turbines are a relatively new field that companies are looking to examine. Currently home turbines that can be mounted on the roof of a house are too expensive and do not generate enough electricity to break even over the machines expected lifetime. What many companies are currently researching is a way to reduce the price of personal wind turbines to make it marketable to the average citizen who is on the grid and is not willing to lose money on a wind turbine just to benefit the environment.

An example of a home wind turbine is the Bergey 1KW system that has an initial cost of about $6,000 and a 20 year lifespan. An independent study concluded that this system will on average generate 100KW hours a month. At this rate the citizen using the system is essentially paying 26 cents a KW over the course of the 20 years of the system which is more expensive than just purchasing electricity from the grid. The average household uses about 11,500 KWh a month (eia.gov, 2012), so this system would only generate 1/12th of the average household system. Even Bergeys 10 KW system with wind speeds at 10mph only generates about 30,000 KWh a year at a much higher initial cost.

Figure 2.11 Bergey 1 KW System

There are personal wind turbines that can be attached to a tower in a yard that are cost effective, but they require land space and permits. In many towns and urban communities land space and permits are not an option. (Popular Mechanics, 2009)Placing wind turbines on roofs is the solution to most permit and space issues. However, like the Bergey described above, they are not cost efficient and have other issues, this is why only 1% of personal wind turbines have been mounted on roofs. Some of the non-cost related issues of turbines mounted on roofs are vibrations leading to structural damage of the roof and noise that bothers occupants in the house. Solving these issues is the future goal for personal home wind turbine designs.

2.6 Background to WASP

WASP is a PC-program for the vertical and horizontal calculation of wind climate statistics. It contains different models to describe the wind flow over different areas and terrains.

Analysis of raw data was mainly used in this project. This option enables an analysis of any time-series of wind measurements to provide a statistical summary of the observed, site-specific wind climate. This part is implemented in separate software tools: the Observed Wind Climate (OWC) Wizard and the WAsP Climate Analyst. This part of the program was a vital part for our research on wind patterns around our campus sites.

This program is mainly for predicting wind climates, wind resources, and power productions from wind turbines and wind farms. The predictions are based on wind data measured at meteorological stations in the same region. The program includes a complex terrain flow model, a roughness change model, a model for sheltering obstacles, and a wake model. The software package further contains a Climate Analyst for creating the wind-climatological inputs, a Map Editor for creating and editing the topographical inputs, and a Turbine Editor for creating the wind turbine inputs to WAsP. The fundamentals of WAsP and the wind atlas methodology are described in the European Wind Atlas. WAsP is developed and distributed by the Department of Wind Energy at the Technical University of Denmark, Denmark as shown in figure 2.12.
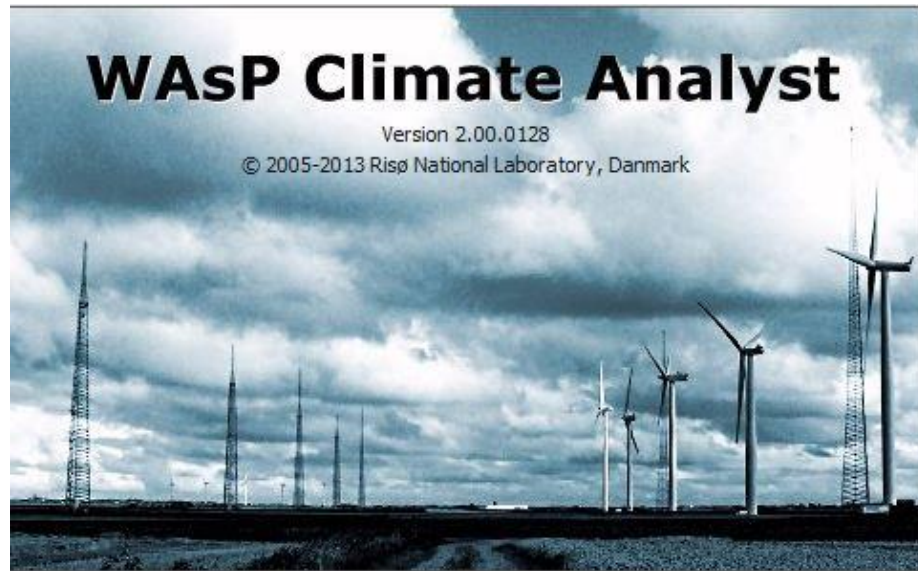
Figure 2.12 WAsP Climate Analyst

2.7 Mounting system

The most common method for a mounting structure for wind turbines is a monopole design. This consists of some sort of base, usually concrete, with a steel structured pole that extends to the owners desired height. As the progression of turbines has grown there has been desire for roof mounted systems. These roof mounted systems have not had the amount of research as the traditional monopole design. As the growth of roof mounted turbines rises there is an urge to design out the flaws that has been shadowing previous roof mounted systems.

2.8 Noise and Vibrations

Wind turbines can create a constant humming noise that is considered an annoyance as well as produce vibrations that over time can ruin the integrity of a roof. This has hindered the popularity of consumers wanting to have wind turbines mounted to their roof. This has limited wind turbines to be mounted on poles next to houses but many city ordnance laws prohibit this in residential areas. As a wind turbine is spinning and producing electricity it creates a constant vibration. This constant vibration can damage the shingles around the base as well as damage the trusses around the area where they are mounted. These vibrations are very difficult to prevent, so it is important to have a mounting system that will disperse the vibrations before reaching the actual structure of the house. Many roofing companies do not put a warrantee on the roof if there is a wind turbine due to the result of the vibrations. . This will dissuade a consumer away from having a wind turbine mounted on the roof. Another issue that dissuades a consumer from using wind turbines is the constant humming noise produced when a turbine is generating electricity. A VAWT as opposed to a horizontal axis turbine does not produce as much noise as the traditional turbines due to design differences of the turbines as well as the path of motion of the blade. Another reason that VAWT are more for residential areas is their ability to operate at peak efficiency with turbulence that is produced by roof contours. When wind is traveling over roof peaks and different slopes of roofs they produce a turbulent wind pattern that actually disrupts horizontal axis turbines from producing electricity. This turbulent wind pattern caused by roof peaks does not disrupt the functioning of VAWTs, as well as produce as loud of noise compared to HAWT systems.

The rise in popularity of roof mounted VAWTs is opening research into a way to eliminate harmful vibrations from turbines that cause roof damage. This project goes into solving and improving the flaws of roof mounting systems as well as improvements to the overall design of the VAWT blade design in methodical steps that can be seen in the next chapter.

3. Methodology

The goal of this project was to design a vertical axis wind turbine (VAWT) that could generate power under relatively low wind velocities. To accomplish this goal, the objectives were to (1) analyze how different geometry of the wind turbines within various enclosures affect wind turbine power output (2) test how the vibrations caused from the rotations of the wind turbine affect the structural integrity of various aspects housing structures, and (3) compare the operation of VAWTs that are directly placed in the wind with VAWTs that placed within an enclosure.

To meet these objectives, the tasks were to:

-Complete background research on wind turbine data

-Design turbine blade designs for testing

- Design model roof structure

-Create experimental set up

-Manufacture parts and build model house

-Develop future design recommendations

3.1 Background Research

Background research included reviewing a previous project, *Enclosed Vertical Axis Wind Turbines*, by Julie Eagle, which provided a foundation for the current project. Using that information, we then studied new areas in order to complete our research.

3.1.2 Old Projects

Analyzing previous research allowed us to determine that the use of a funneled shroud allowed the vertical axis wind turbine had higher potential to generate more energy than a vertical axis wind turbine without a shroud. The tests also demonstrated that airfoil designs potentially do not perform as well as flat bladed designs perform in the enclosure.

The reports indicate that flat bladed designs perform poorly in non-enclosed situations but they have increased performance in enclosures. The report test results state that the flat bladed designs enclosed in 90° shroud perform better than airfoil designs in the 90° enclosure and they also outperform the airfoil design without a shroud.

3.1.3 Additional Research

Research started with basic aerodynamic principles and different blade designs that have potential to work effectively in an enclosure. Research showed that aerodynamically efficient blades have great potential to work for a vertical axis wind turbine. (Ponta, Otero, 2007) In addition a split Savonius design, which is shown in figure 3.1, is able to operate at peak efficiency with turbulent wind, which meets one of the criteria for roof mounted turbines.
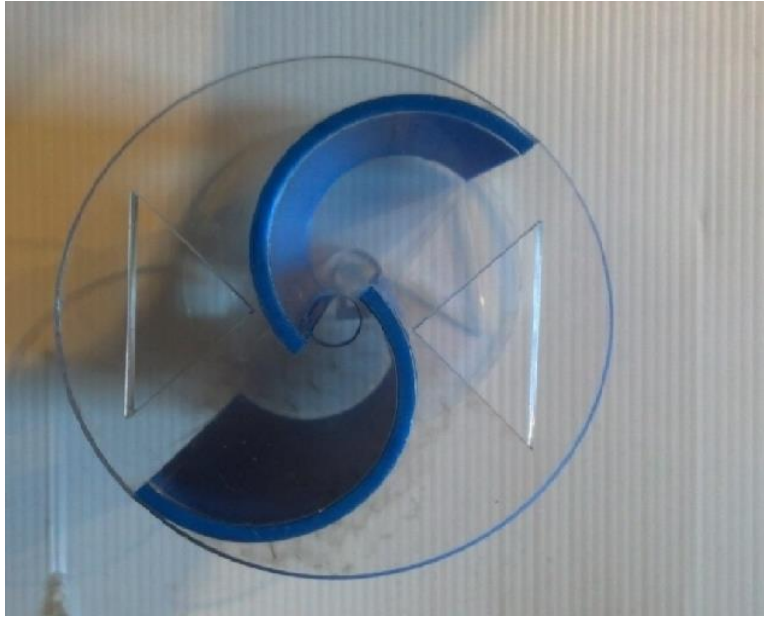
Figure 3.1 Split Savonius top view

3.2 Design turbine blade designs to test

After compiling background research we analyzed the information and decided upon two chosen turbine blade designs that could be tested to demonstrate improved results. The two designs were an adjustable angle S1223 airfoil design and a split Savonius airfoil design.

3.2.1 Adjustable angle S1223 airfoil design

Previous projects used the S1223 airfoil design because it is a low speed airfoil design. However, as stated in the background it did not perform well in the enclosures. Possible solutions could be to use different angles of attack for the blades.

To begin the design process we kept the some of the parameters of the old design, such as turbine height, blade size, and diameter of the VAWT. An additional design parameter was to allow each blade to rotate 360° and provide them with a capability to be locked at any desired angle. The airfoil design was also comprised of three blades because research indicates 3 blades for wind turbines with airfoils is ideal for limiting vibrations and increasing efficiency.

To account for the 360° of rotation, with one degree of freedom, the design had two pins that locked in with holes in the top and bottom disk which hold the turbine together. The pin on the bottom of the airfoil design is a threaded bolt that allows the airfoil to be locked in place with a hex nut. The pin on the top of the airfoil is attached to a turning device that holds the blade to the top disk. The turning device also has a compass rose on it that aligns with a compass rose on the top piece allowing for easy angle measurements while adjusting the blade angle.
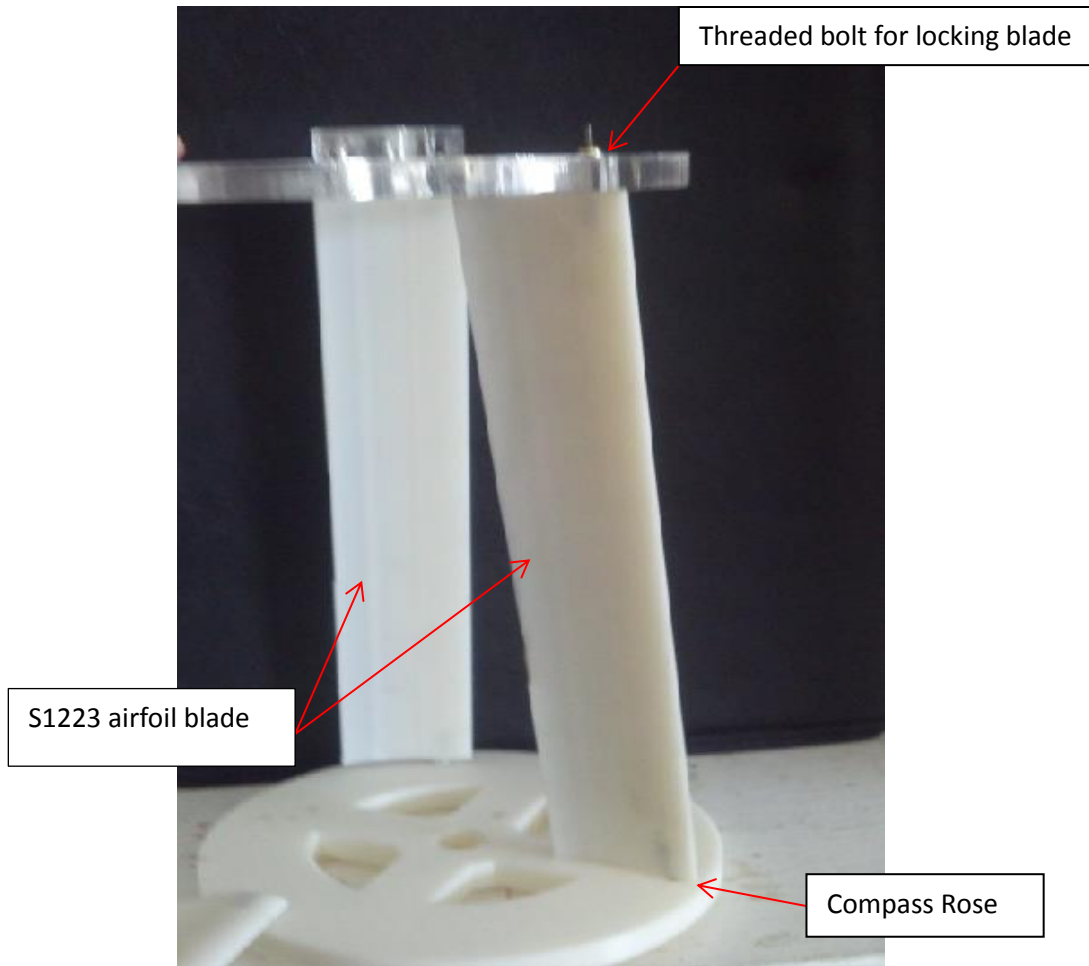
Figure 3.2 Airfoil s1223 diagram

3.2.2 Design of split Savonius turbine

Prior to designing the split Savonius wind turbine, we created parameters in order to allow testing to be assessed in comparison to testing in previous projects. These parameters assured that the turbine blades were of same height, and the total radii of the blades are the same as the flat bladed designs from the reports.

After examining different wind turbines we decided that a simple split Savonius design would fit best for our application. The split Savonius we designed had a zero offset;

indicating that where the overlapped cusps meet the distance in the y-axis is zero. This can be seen in Figure 3,3 where the red line indicates the zero offset. In addition the overlapping cusps had an offset of 1.5 inches in order to surpass the 0.5 inch rod, located in the center of the blades, without creating interference and allow for wind to pass past the rod.
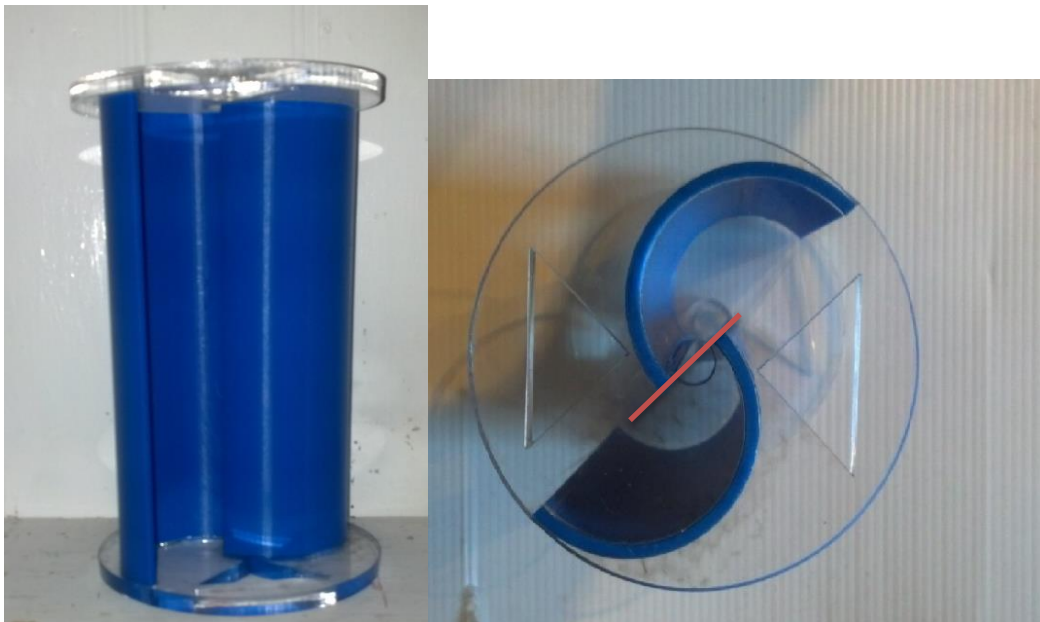

Figure 3.3 Split Savonius front and top view

This design, while simple, will give the best indication of whether the split Savonius design is promising for future research with enclosed wind turbines.

Figure 3.4: Split Savonius in enclosure 4 (90°)

3.3 Scale Model roof structure

To accurately test vibrations a roof would experience from a turbine, we constructed a scale model roof structure. We had to design a blueprint for the structure, construct the scale model house and perform various vibrations testing on the structure.

Testing included sending pulses through the vertical shaft attached to the roof and having four accelerometers placed on the structure to detect any acceleration.

3.3.1 Designing Scale Model Roof

To test vibrations associated with wind turbines, we felt the best way would be to actually replicate the vibrations experienced from a turbine onto a structure. We created a plan to build a scale model of a house. There are many possible design alternatives for roof trusses. A goal for defining a truss was to have the most popular design that would be able to provide realistic results. We finally came to the conclusion that a double cantilever truss would satisfy our requirements. A double cantilever truss is shown in Figure 3.5. (roof-truss, 2006)
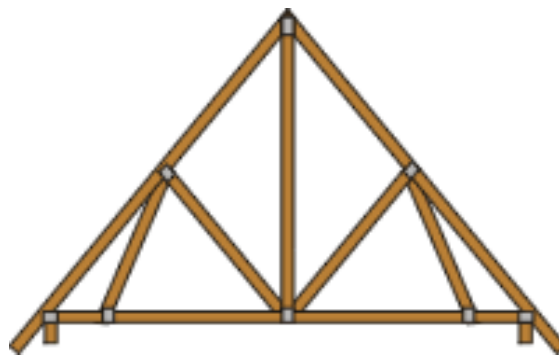

Figure 3.5 Double Cantilever Truss

The house was built as a 6:1 scale model with the structure measuring 4 feet by 3 feet at the base. The scale model house is in accordance with Massachusetts building code, with the spacing of wall studs and roof trusses, to ensure reliable testing.

3.3.2 Create experimental set up

After designing the components and structures desired for testing power output for wind turbine designs and the structures desired to be tested, we created the experimental set-ups required to test the prototypes and structures.

3.4 Wind turbine set-up

The test set up was in Higgins Laboratory Room 016 Wind Tunnel. When the turbine is set up in the wind tunnel it is located directly in the middle of the cross section of the tunnel. The turbine is attached to a stainless steel rod by using a set screw. At the top, the rod is pressure fitted into a step generator keeping the shaft stable. At the bottom the base is secured into the tunnel as well as being connected to an anemometer. An anemometer is a device that collects the turbines rotation rate in units of rpm. The generator is a 443540 Low RPM Permanent Magnet DC Generator and is attached to the wind tunnel as depicted in figure 3.6. The quarter inch shaft is attached to the generator with a press fit and a set screw to the shaft of the generator.

Figure 3.6 Securely Fastened Generator

The anemometer is measured through a Texas Instrument DAQ box. The generator voltage is measured through a Labview vi. and current is measured by hand with an ohmmeter. The generator's current is managed by a full wave bridge. The wave bridge is wired as depicted in Figure 3.7.

Figure 3.7 Wave Bridge with Wiring

The schematic in figure 3.8 (Diode bridge, 2012) shows how the wave bridge is
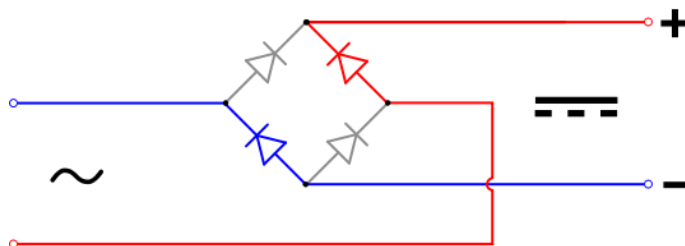
wired.

Figure 3.8: Wave Bridge Schematic

In addition to test the vibrations of the wind turbine we attached an accelerometer at the base of the turbine. The wiring from the accelerometer is attached to a DAQ box in order to record the data on a Labview virtual instruments or vi. The schematics of this can be seen in figure 3.8.

3.4.1 Generators

The generator used for the prototype is the 443540 Low RPM permanent magnet DC generator created by Wind Stream Power and is a 12 volt step generator. The generator has an internal resistance of 21ohms, yet it requires an additional load in order to produce power. Without an additional load no power can be generated. The additional load is a Wheatstone bridge called a wave bridge. This can be created with regular resistors. However, if the objective is to store energy rather than record it, the Wheatstone bridge must be made of single direction resistors to prevent the voltage from the battery from reversing direction back into the generator.

The current generator can only operate continuously with a current of 1.5 amperes and at a max of 1.5 minutes with a current of 3 amperes. To control the amperage the wave bridge described in the equation above must act as a load and control the amperage of the system.

3.4.2 Data Acquisition

In order to record all of the testing we created Labview vi.'s. The vi.'s recorded voltage from the generator, amplitude and period of the vibrations from the accelerometer on the turbine, and on the model house .These vi.'s are shown in Figure 3.9.
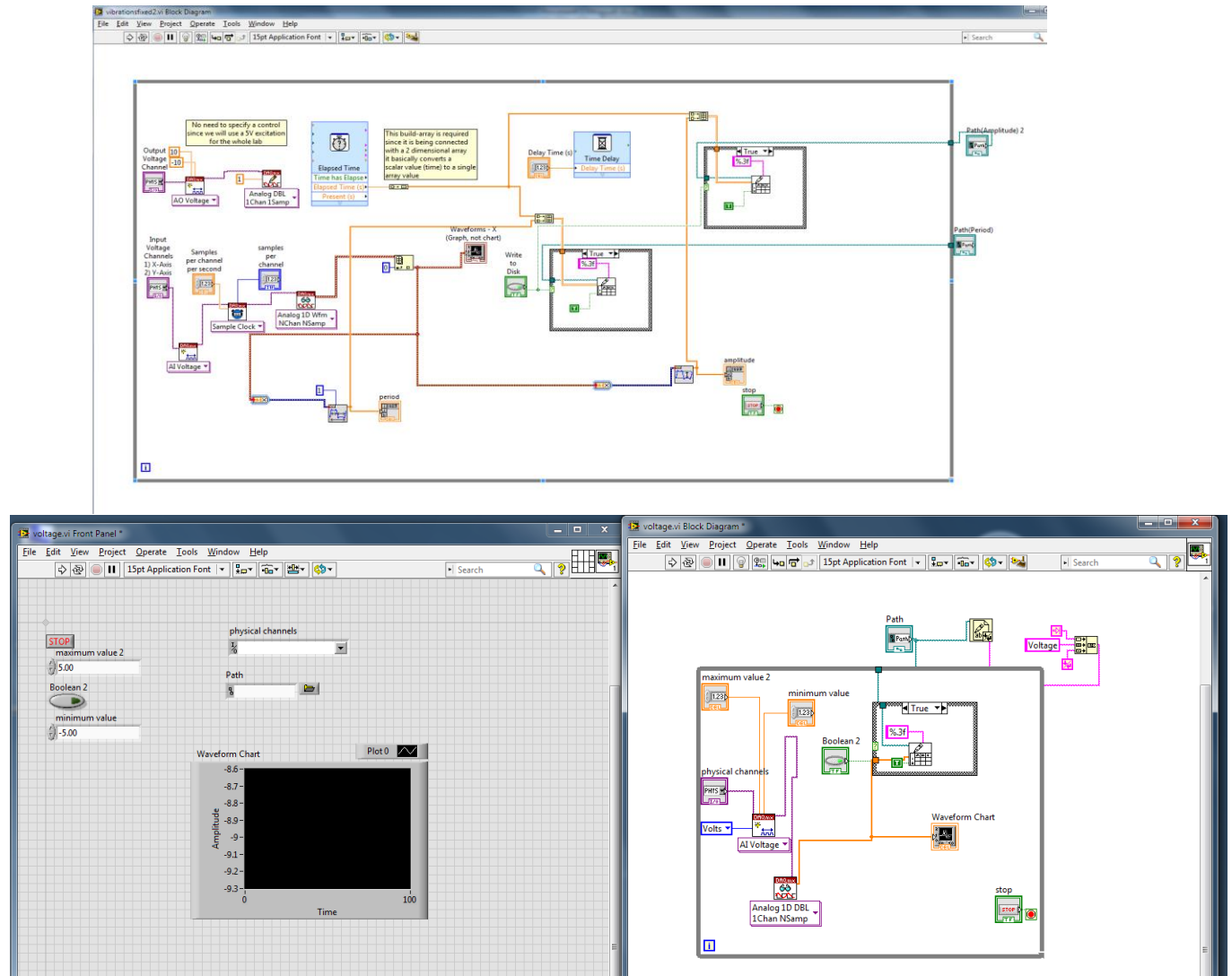

Figure 3.9 Labview vi

3.4.3 Power output from the generator

Power output tests included recording power from the split Savonius and the four flat bladed turbines. The first test is the split Savonius. We tested the turbine first without an enclosure and then with the 90° enclosure. We ran the wind tunnel at 22, 25, and 30 hertz.

Figure 3.10 Split Savonius Set up with 90° enclosure and 90° enclosure on right

The adjustable angle wind turbine followed similar testing procedures as the Savonius, although we started with the blades at a zero degree angle of attack and increased the angle of attack by 4 degree increments up to 28 degrees. Then, we analyzed the data and performed further testing with the most effective angle of attack. We also included an orientation with the blades inverted on the adjustable angle turbine, since a few studies suggest that this could potentially improve efficiency as well.

3.4.4 Perform vibrations testing on Turbine

In order to get an approximation of the rotational frequency of the turbine generation, we tested the Savonius without an enclosure at all running velocities, changing the frequency of the wind tunnel by 1 hertz intervals. We placed an accelerometer at the base of the turbine to detect the acceleration produced by the turbine. We then recorded the change in voltage in Labview vi, which gives us the change in acceleration. These data were then used to test how the vibrations affect the model house.

3.4.5 Perform vibration testing on the scale model house

In order to test for vibrations caused by the wind turbines, we devised an experiment that makes use of accelerometers to detect acceleration forces. From the recorded acceleration forces, we calculated the frequency of the acceleration. In order to detect how the house experiences vibrations, accelerometers were placed at different locations around the trusses on the roof. We then used a hammer to tap the house and the accelerometers detected the impact of the hit and recorded the acceleration data experienced throughout at the various spots on the roof. This was able to give us the houses natural frequency as well as the overall stability of the house.
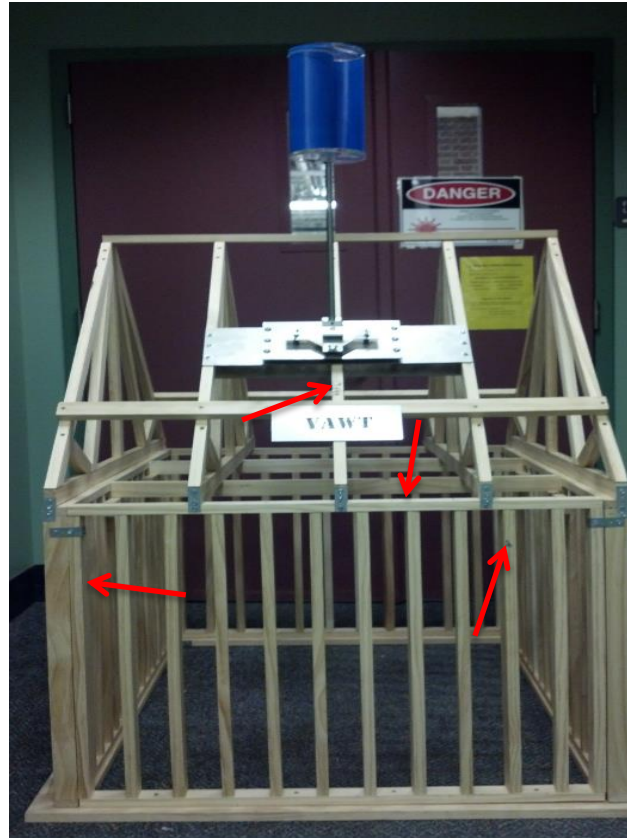
Figure 3.11: placement of the 4 spots for accelerometers

Next we placed the accelerometers around the base of the mounting system and at spots near the base of the roof. We designed a few different mounting systems with different vibration isolators and configurations. With the multiple configurations in place, we test each of them one by one. This was be done by putting together the desired configuration of the mounting system and tapping the top of the wind turbines support shaft and having the accelerometers pick up the vibration readings at the various locations chosen. By repeating this multiple times, with the different setups, we were able to see which one of the configurations was most efficient at eliminating vibrations from entering the house structure.

3.5 Manufacturing of turbine blades and rod.

The vertical shaft that held the turbine was manufactured out of quarter inch stainless steel with press fits designed to attach to the generator and the anemometer. It also had two set screws which kept the shaft connected to both instruments as well as a set screw in the middle to lock turbine in place.

The split Savonius blade was manufactured in the Stratysys Dimension FDM Rapid Prototyping 3d printer. The top and bottom pieces were cut out of 3/8th inch acrylic and then glued together.

The adjustable angle wind turbine was mostly manufactured in the 3-d printer. The metal rods used to lock the adjustable blade to the top and bottom pieces were glued together with epoxy.

3.5.1 Building of model house

The purpose of the model house was to replicate an actual structure for vibrational testing. Replication of the actual structural design of a house was a crucial component when constructing the model house. The model house was constructed from 1"x2" native pine studs. This is able to properly replicate studs used in residential buildings. The walls have 64 three-foot tall studs to hold up the roof that is comprised of five double cantilever trusses. These trusses are secured to the walls by metal brackets and two support wood beams that run through the center of the house. The base of the house is secured to a

square frame of 1"x4" native pine boards. This is able to give the structure a sturdier foundation that better replicates a true foundation. The house in midst of construction can be seen in figure 3.12.

Figure 3.12 Construction of model house

3.6 Testing

In order to determine the effectiveness of the products that were manufactured, we performed tests to evaluate them. We also tested the power output of the turbine blades and evaluated how the vibrations from the turbine affect the stress and strain on a housing structure.

3.6.1 Turbine testing

To test the effectiveness of the turbines, we tested each turbine: split Savonius and adjustable angle, without an enclosure and with a 90° enclosure. We ran each turbine in the wind tunnel for the maximum range, which was run at 22, 25, and 30 Hz. We recorded both power output and the rate of revolutions to compare the data with the adjustable angle wind turbine. We tested the turbine at various angles of attack, testing to determine the most efficient angle, with the same process as previously described.

3.6.2 Vibration testing

First, we placed multiple accelerometers around the base of the turbine to figure out the vibration frequency of the turbine while in the wind tunnel.

Second, after collecting series of data from this experiment, we examined the mounting system on top of the model roof. In order to detect how the house experiences vibrations, accelerometers were placed upon different parts of the trusses on the roof. We then used a hammer to send a pulse through the house. The accelerometers detected the impact of the hit and recorded the acceleration experienced at the various spots on the roof.

After recording data on the structure of the roof, next we place the accelerometers around the base of the mounting system and at spots near the base of the roof. We have designed a few different mounting systems with different vibration isolators and

configurations. With the multiple configurations in place, we one by one tested each of them out. This was done by putting together the desired configuration of the mounting system and tapping the top of the wind turbines shaft above the accelerometer that was placed on the shaft. The accelerometer was placed on the shaft as to record the acceleration of the initial pulse. The remaining accelerometers detected the acceleration readings at the various locations on the model house chosen. By repeating this multiple times with the different setups we will be able to see which one of the configurations was most efficient at eliminating vibrations from entering the house structure.
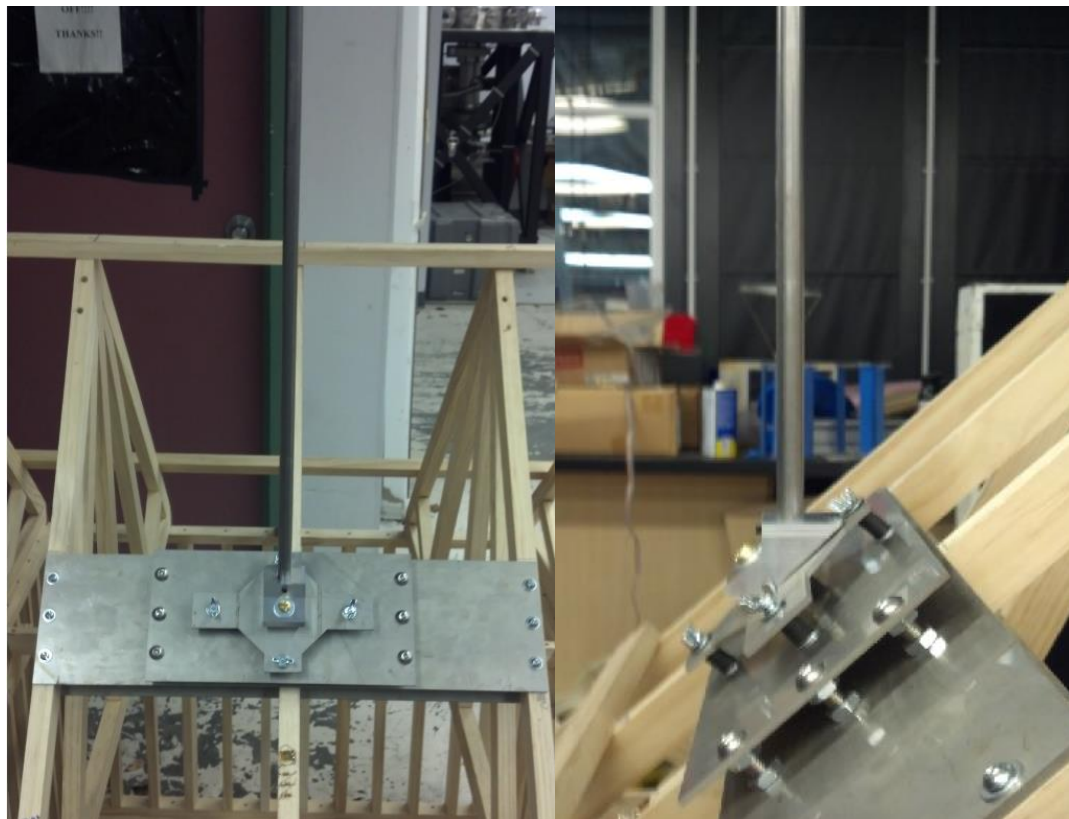
Figure 3.13 Mounting Configuration

3.7 Develop future design recommendations

Using the data received we made recommendations for future studies regarding the potential of commercial rooftop wind turbines. These recommendations will hopefully aid in the development of a technology that would allow green energy to reduce energy costs in the average household and better the environment. Future tests could help determine the feasibility of houses, neighborhoods, or cities powered by wind turbines and being able to run off of renewable energy.

4 Results

This section describes the results of our testing and shows how we compared our split Savonius design with the previous 4 flat bladed design and airfoil designs. The results also address the use of having funnels attached to shrouds, in hope of increasing power output. Lastly, the results will show the analysis of the vibration testing performed on the model house.

4.1 Turbine Data

The turbine data were taken at three different frequencies from the wind tunnel. These were at 22, 25, 30 Hz. The lack of data points and the need to resort to the use of high speeds for testing were a result of our large 12V generator. This made it impractical to accurately relate our power output results with realistic wind speeds that a turbine would expect to encounter. However, it did exhibit differences in each the performance for each set up, whether it was one of the various blade designs or enclosures.

4.1.1 Use of Funnels

The computer simulation indicates a lot about the funneled shroud design. First it reconfirms the theory that the funnel will increase wind speeds into the funnel as the color coded bars representing wind in the system above indicates.
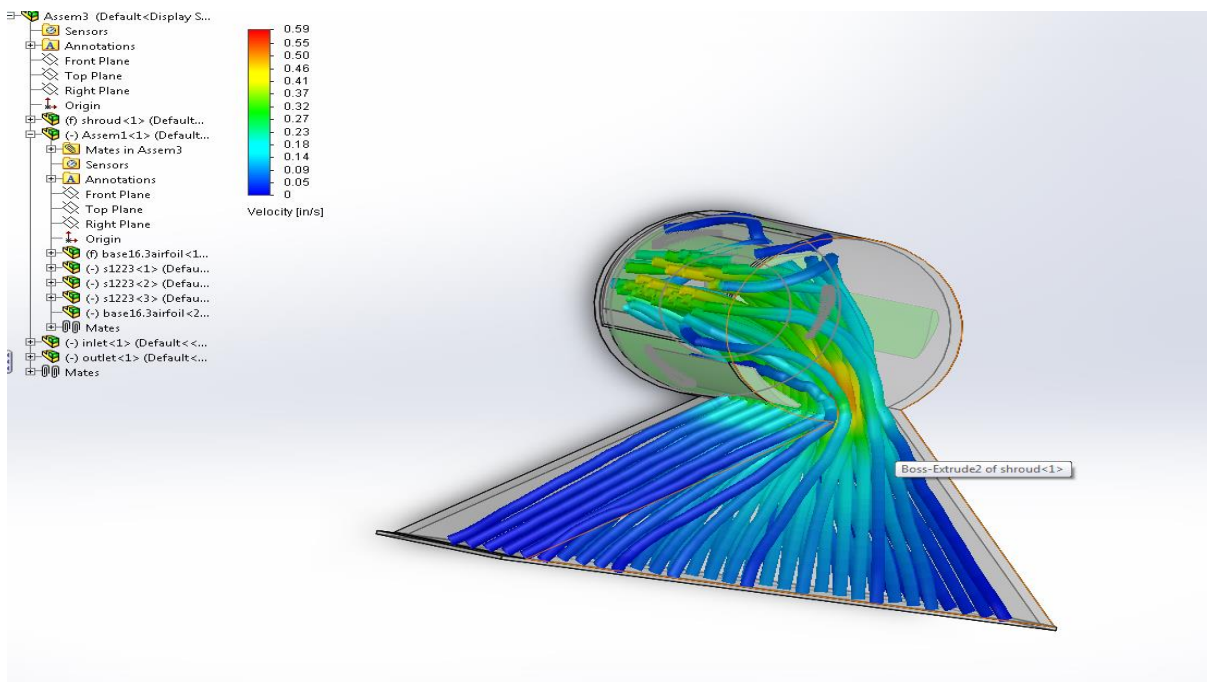
Figure 4.1 Solid Works depicting funnel and shroud air flow

Figure 4.1 also potentially shows why the airfoil design performed poorly in the shroud. As the wind funnels into a smaller area, it creates a higher pressure region as it enters the inlet of the shroud. The outlet of the shroud provides a lower pressure region so the wind dissipates towards the lower pressure region through the center of the shroud and thus not in the direction of the airfoils. This is important because airfoils only operate under certain angles of attack and once the blades are not in this angle the do not generate lift and only continue movement because of momentum rather than the wind moving the airfoil. While these results demonstrate that airfoils in a shroud are not effective, this may not be the case as more outlet positions need to be testes along with various angles of attack of the airfoil that need to be tested as well.

Our testing with various funnels attached to our enclosures was not successful and was not able to turn the generator, even when a load was not applied. The reason for this is because the wind accelerated around the funnel rather than flowing through the funnel. This is due to the fact that the funnel creates a higher pressure air system inside the funnel and the wind moved around it. Using funnels in this fashion proved to be an ineffective strategy.

4.1.2 Air Foil Design

The adjustable airfoil design we used was not able to spin the generator under load with or without the enclosure. Even though we tested at speeds 35 percent higher than all other airfoil tests, this design remained unsuccessful. This design proved to be an inefficient design for the vertical axis wind turbine.

4.1.3 Turbine Results

Final testing resulted in effective, informative results using the split Savonius with and without an enclosure. For comparison, we tested a flat four bladed design that had been used in a previous project by Julie Eagle.

Table 4.1 Average RPM data with various set ups

Wind Speed (Hz)	Split Savonius without Enclosure(rpm)	Split Savonius with Enclosure(rpm)	Four Flat Blade with Enclosure(rpm)
22	104.0	171.3	154.0
25	129.0	214.0	197.6
30	203.0	296.0	283.6

Table 4.1 shows the RPM data collected from the wind turbine tests. The table noticeably shows that the Split Savonius in the enclosure performs better than the other two turbine configurations. The enclosure with the split Savonius increased the rotation rate (in rpm's) by almost 36% compared to a split Savonius without the enclosure. Also, the split Savonius spun 7.3% faster on average in comparison to the 4 four flat bladed designs in the enclosure. These are both substantial numbers when considering the potential power increase for home energy generation.

Table 4.2 substantiates the previous data's accuracy were the voltage output of the generator was measured from which we were able to calculate power.

Table 4.2 Power and voltage output

Wind Tunnel Speed(Hz)	Split Savonius Without Enclosure		Split Savonius With 90° Enclosure		4-Blade Turbine With 90° Enclosure	
	Voltage (V)	Power(Watts)	Voltage (V)	Power(Watts)	Voltage 4 Blade (V)	Power(Watts) 4 Blade
22	.229	.021	.397	.065	.352	.051
25	.270	.030	.520	.113	.481	.096
30	.495	.102	.754	.237	.730	.222

Table 4.2 displays the voltage and calculated power output from the turbines. The data shows that the split Savonius in the enclosure performed better than all other turbines, confirming the accuracy of the rotation rate (rpm) test. The split Savonius without the enclosures resulted in an average voltage output that was about 40% less than the Split Savonius with the enclosure. The split Savonius in the 90° enclosure had an average voltage output that was 6.5% higher than the 4 bladed designs in the enclosure. However, this small percentage makes a much a larger difference in power output. The split Savonius in the enclosure had a 73% increase in power over the same design without an enclosure. Likewise, the split Savonius in the enclosure average power output was 11% more than the four bladed designs in the enclosure. The average voltage differential was significantly more at higher speeds indicating that even small changes in wind speed can increase power output radically.

4.2 Vibration Data

Figures 4.2 and 4.3 show vibration acceleration data that the vertical shaft experienced when hit by a force with hammer. Each one of the hits is represented at the location where the data spikes on the figures. These four areas are outlined in red boxes. Each of the four hits was taken from a different side of the rod. There is a very obvious difference in the frequency of the hits from the two different mounts. When the rubber vibration isolators are not placed on the mount, the frequency lasts nearly 23.2 times longer. When the vibration isolators are placed on the mount that supports the rod these frequencies experienced are dampened dramatically. This means that the upper portion of the mount that is not directly attached to the house does not experience the normal oscillation frequency that a static rod would experience. The acceleration of the force experienced is quickly returned back to the structures normal frequency. The next area of the structure where accelerometers were placed was the top (horizontal) of the wall studs and on 45° angle of roof trusses.
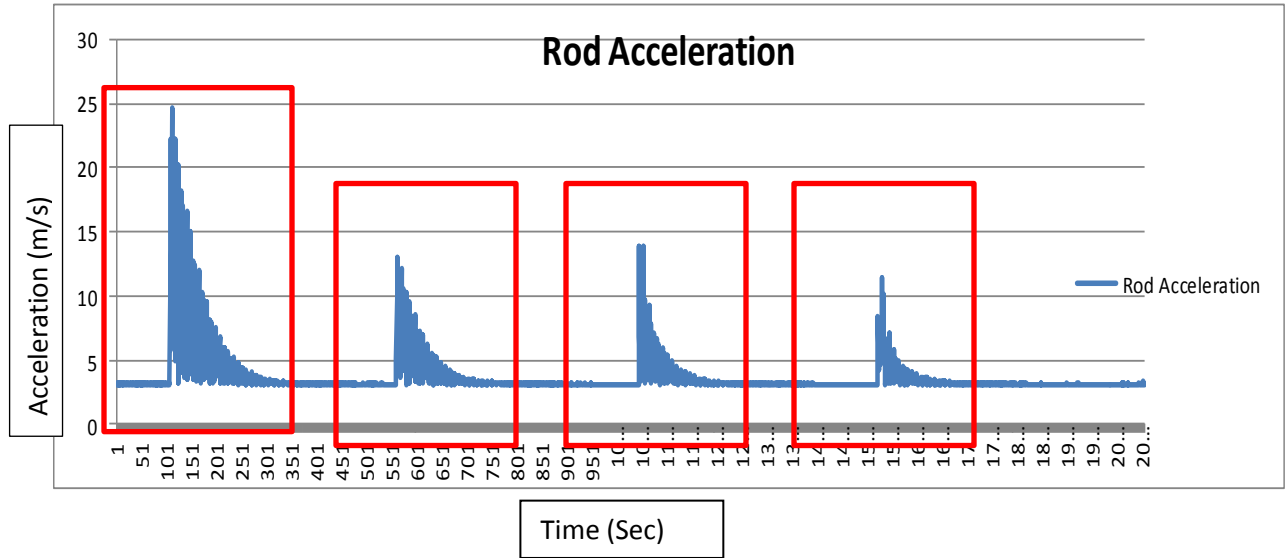
Figure 4.2 Rod Acceleration- without vibration isolators
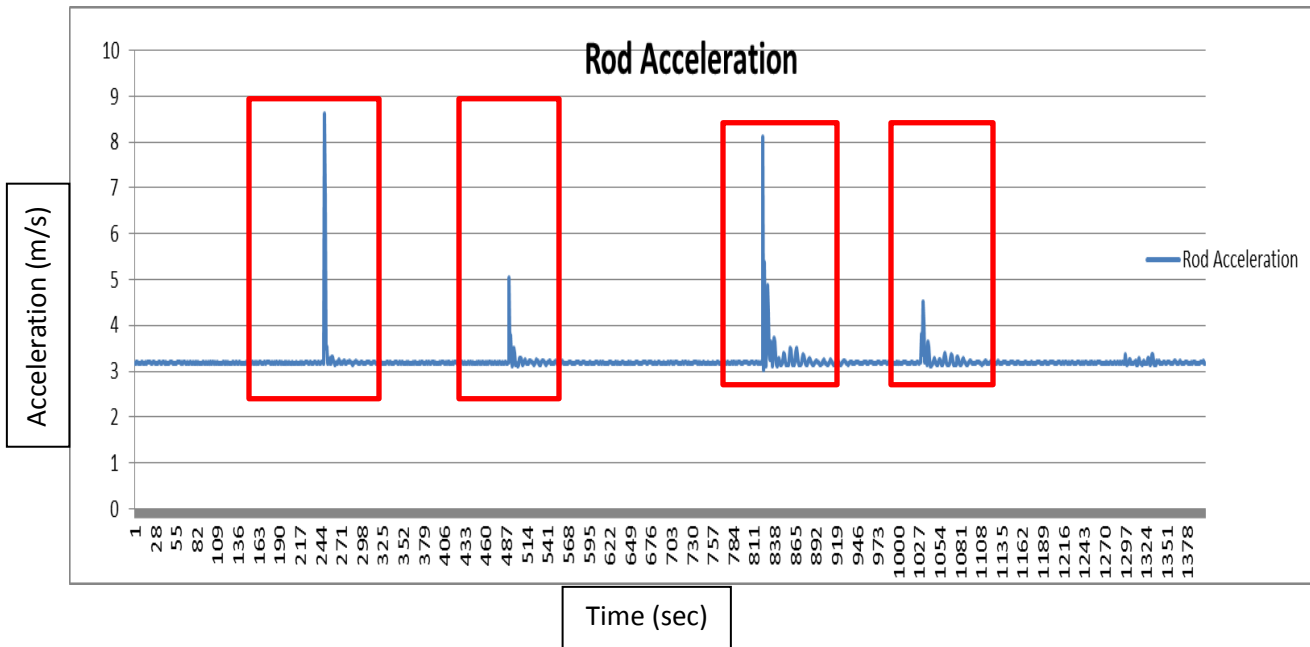
Figure 4.3 Rod Acceleration-With vibration isolators

Figure 4.4 Picture showing rod accelerometer

The vibration experienced by the actual model house structure was not as drastic as the vertical shaft. On the horizontal stud, the maximum deviation from the structure's natural frequency was a maximum of 2.6 Hz for the mount without the vibration isolators, while the deviation from the natural frequency was a maximum of 1.9 for the mount with the vibration isolator. On average, for the horizontal studs, the vibrations experienced lasted between 5-10% longer for the mount without vibration isolators. The data accumulated from the 45° angle truss were also very similar. The amount for the 45 degree truss deviated from the natural frequency by 1 unit from the different mounts. The

vibrations experienced by the mount with the vibration isolators were able to dampen the

initial vibrations but the frequency lasted just as long.
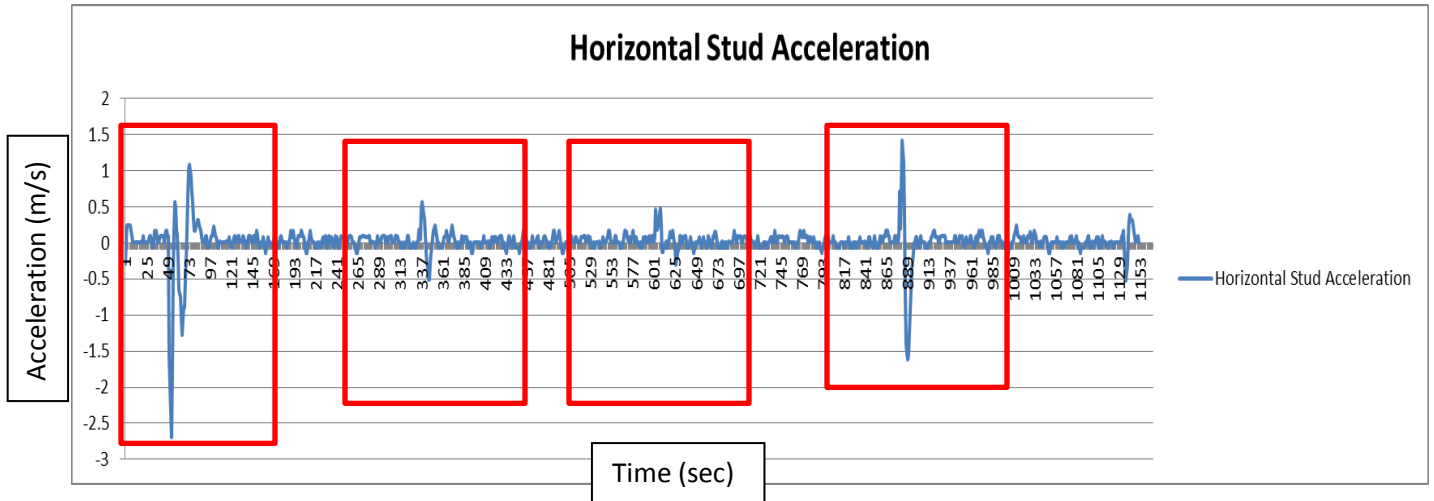
Figure 4.5 Wall Stud Accelerometer- without vibration isolators
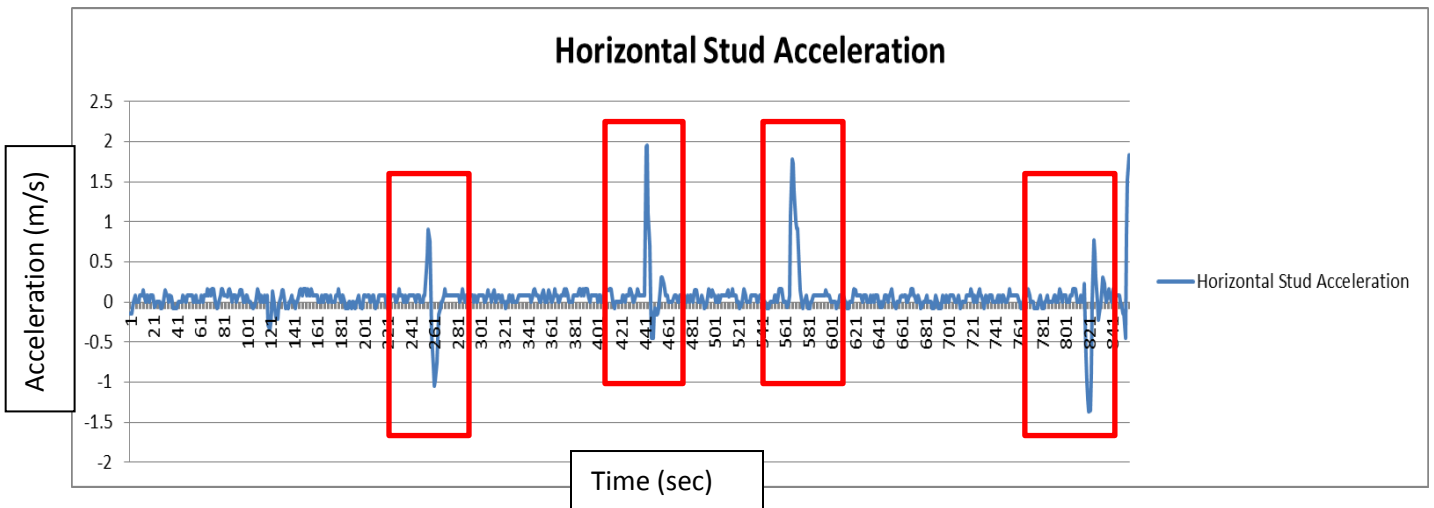
Figure 4.6 Wall Stud Accelerometer- with vibration isolators

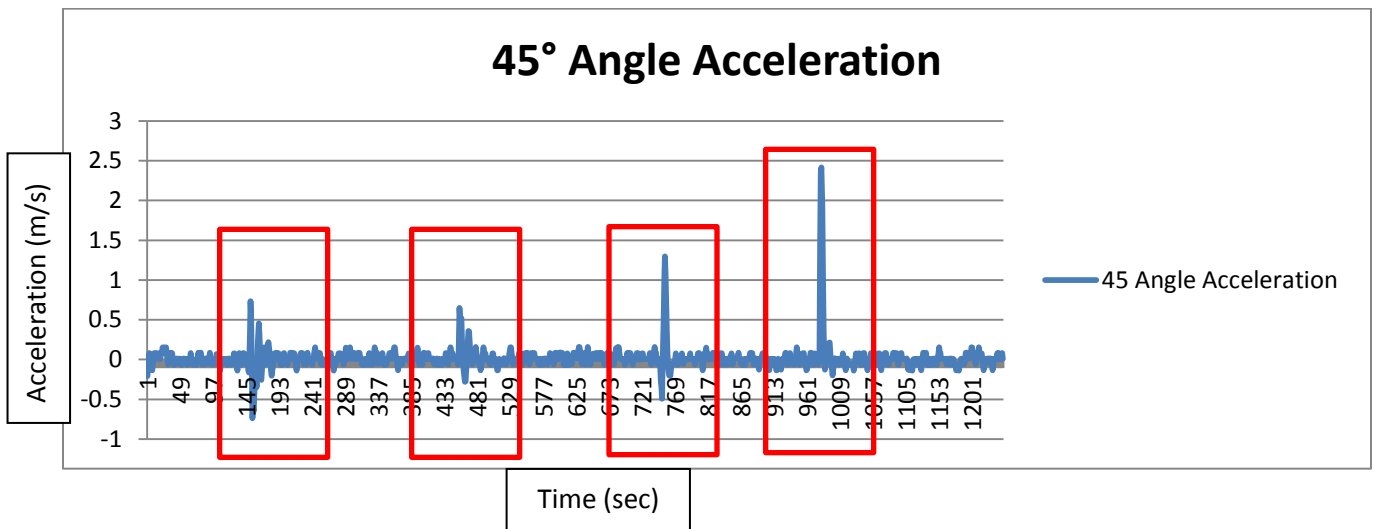Figure 4.7- Depiction of horizontal stud accelerometer

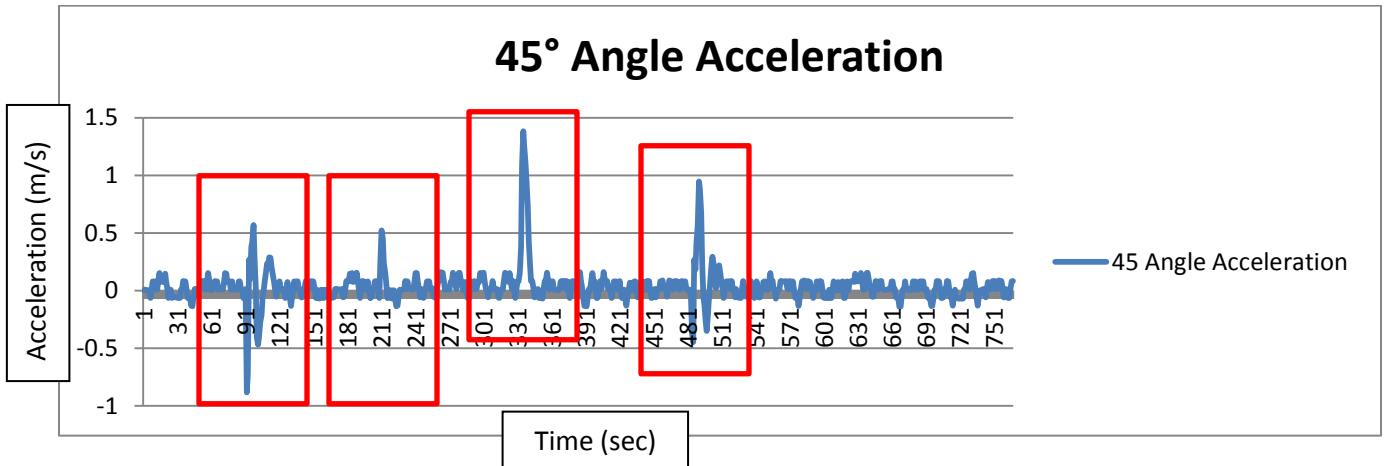Figure 4.8- 45° Truss Acceleration- without vibration isolators

Figure 4.9- 45° Truss Acceleration-with vibration isolators

Figure 4.10- Picture showing the 45° Truss Accelerometer

4.2.1 Vibration Analysis

Using our test set up with accelerometers, we analyzed the effectiveness of the vibration isolator by assessing the decay rate on the rod, and on the building simultaneously. Figures 4.11 to 4.14 show the acceleration peak data.
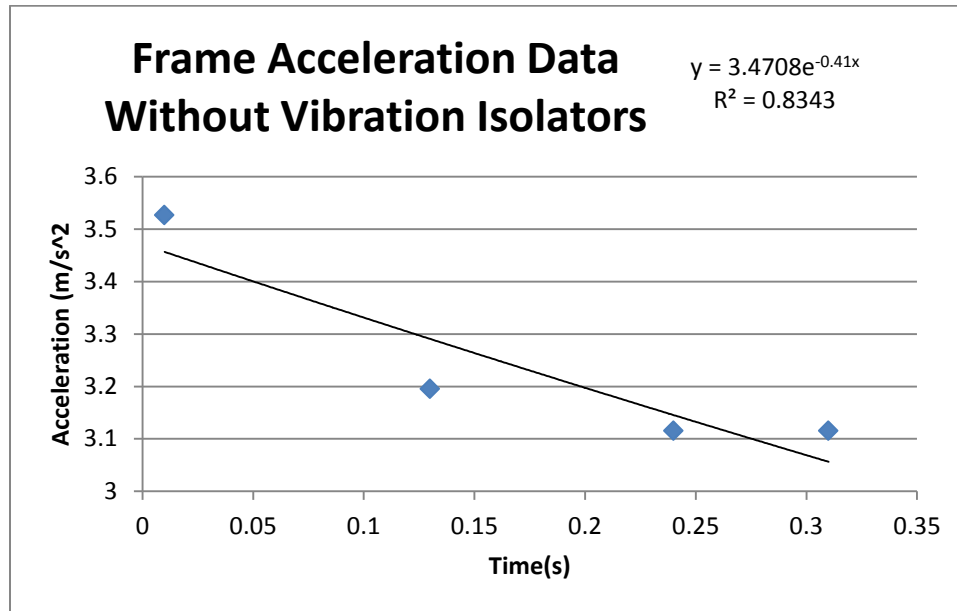

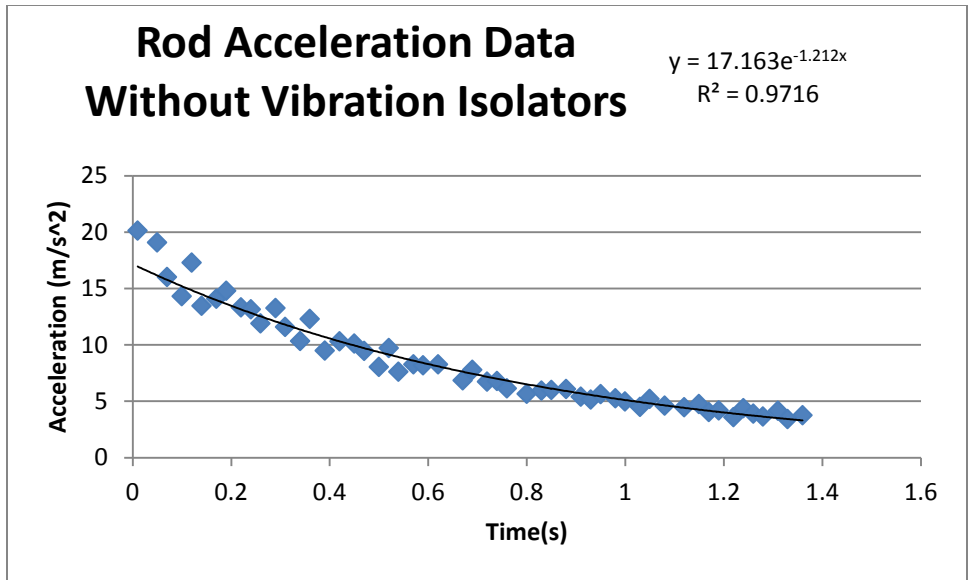Figure 4.11 Frame Acceleration Peaks- without vibration isolators

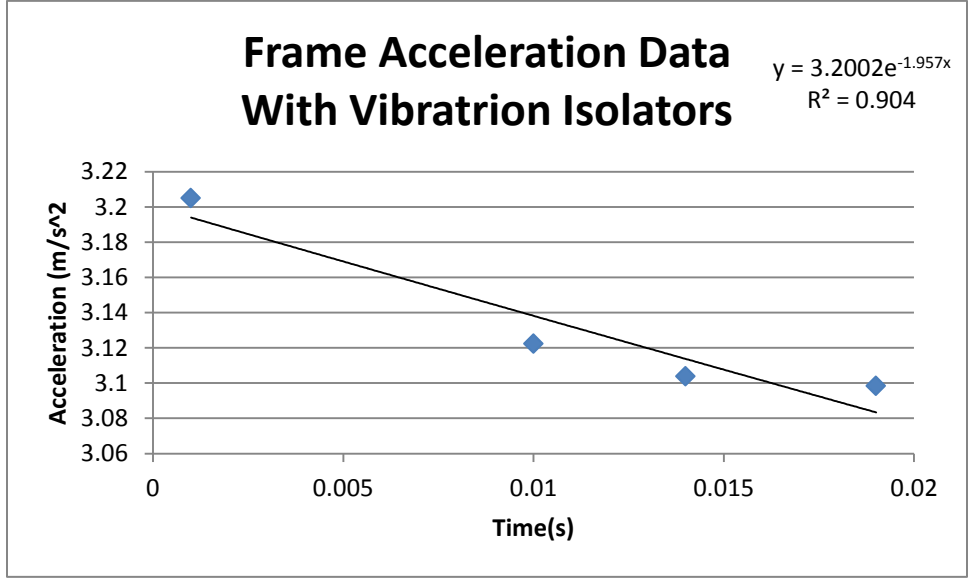Figure 4.12 Rod Acceleration Peaks- without vibration isolators

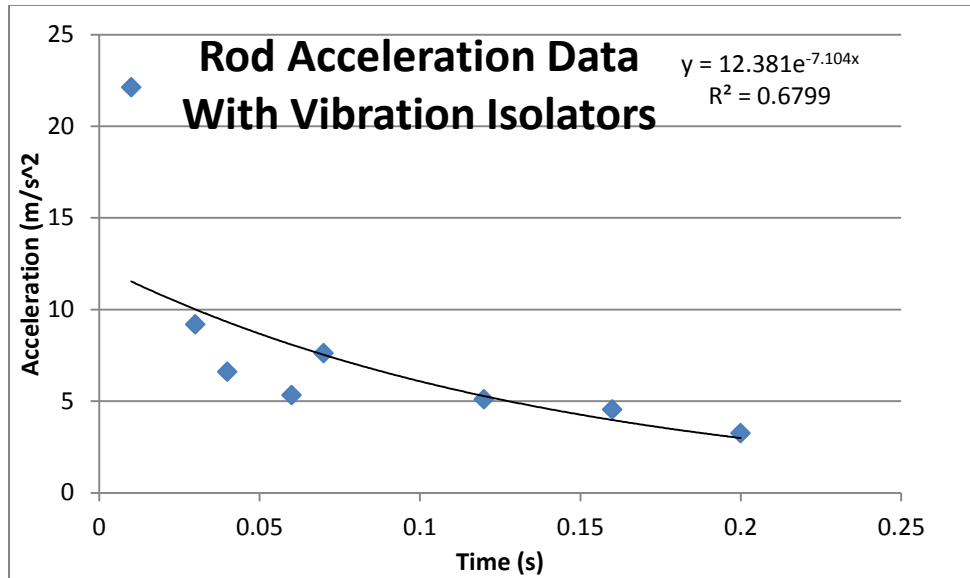Figure 4.13 Frame Acceleration Peaks- with vibration isolators

Figure 4.14 Rod Acceleration Peaks- with vibration isolators

Figures 4.11- 4.14 contain the recorded peaks of the acceleration data and have an exponential trend line that represents them. There is some error in the charts as the data only recorded every 1/100th of a second and did not necessarily record the data at the peaks. Also the trend lines do not have great R^2 values to analyze, except with figure 4.12. This is because the initial peak was dampened quickly, either by the vibration isolator and/or the frame of the structure. Figure 4.14 show that the trend line does not have an ideal fit, adding room for error. Even with the errors one can tell that the vibrations were significantly slower and decayed faster with the vibration isolators than without them.

Figure 4.15 Decay Rates of vertical shaft and model house frame

Vibration Isolator	Rod Decay Rate (s^{-1})	Frame Decay Rate (s^{-1})
With	.059072	.510238
Without	.693297	2.40044

Figure 4.15 demonstrates that the vibrations in the shaft and model house with vibration isolators clearly have a smaller decay rates than the decay rates for these structures without the vibration isolators. The largest difference was with the frame, in which the decay rate with the vibration isolators was .51 sec^{-1} as compared to the decay rate without vibration isolators, which was 2.40 sec^{-1}.

4.3 Wind Atlas Analysis and Application Program Results

The purpose of the Wind Atlas Analysis and Application Program (WASP) for this project was to be able to detail wind patterns in the Worcester area, specifically around WPI. By entering wind velocity data that WPI has been recording for the past couple of years, WAsP would be able to compute graphs and provide insight into the feasibility of installing a VAWT at WPI.

Figure 4.16 shows the map of the WPI campus with red circles indicating the three locations of the anemometers, Daniels Hall, East Hall, and the Campus Center. Figure 4.17 shows a picture of WPI's Daniels Hall. The arrow depicts the location of where the anemometer on the roof is located.
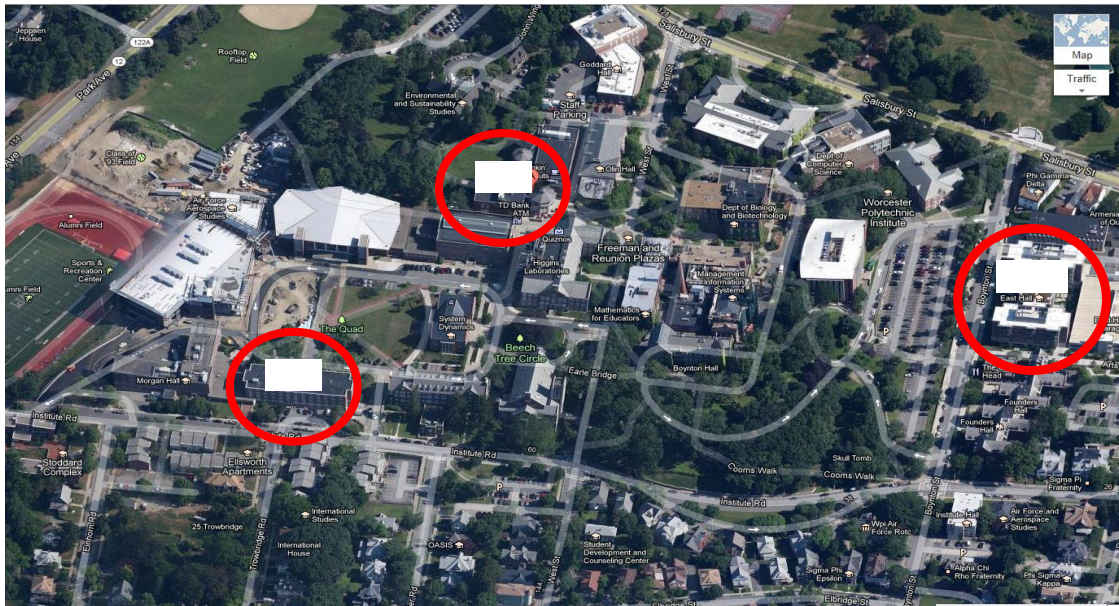
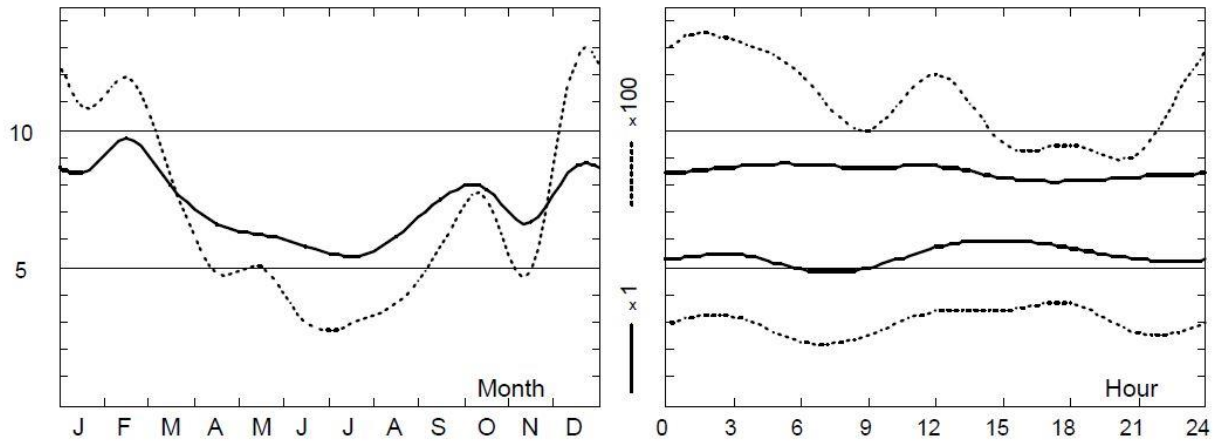Figure 4.16: Campus map showing anemometer locations

Figure 4.17 Daniels Hall

Graph 1: Daniel Hall's monthly wind speed   Graph 2: Daniels Hall's daily wind speed

Figure 4.18: Daniels Hall Monthly Wind Speed
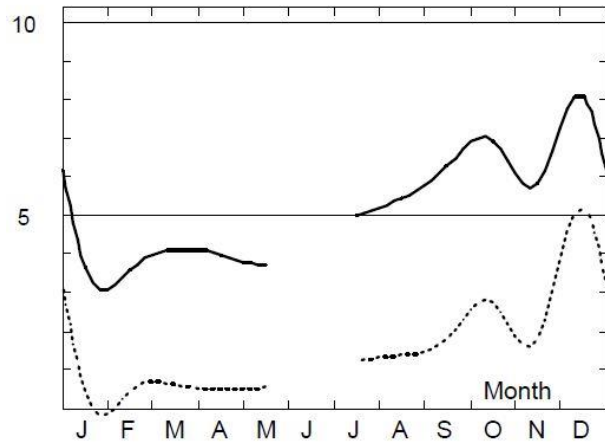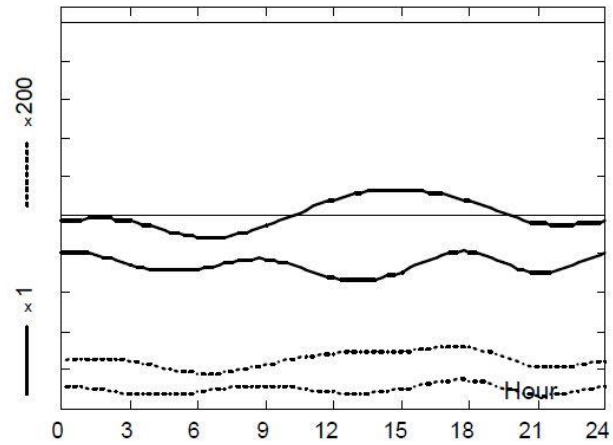

Figure 4.19: East Hall

19.0 m agl, mean 5.2 m/s, st dev 3.0 m/s, cube 312. m³/s³

Graph 3: East Hall's monthly wind speed   Graph 4: East Hall's daily wind speed

Figure 4.20: East Hall Monthly Wind Speed
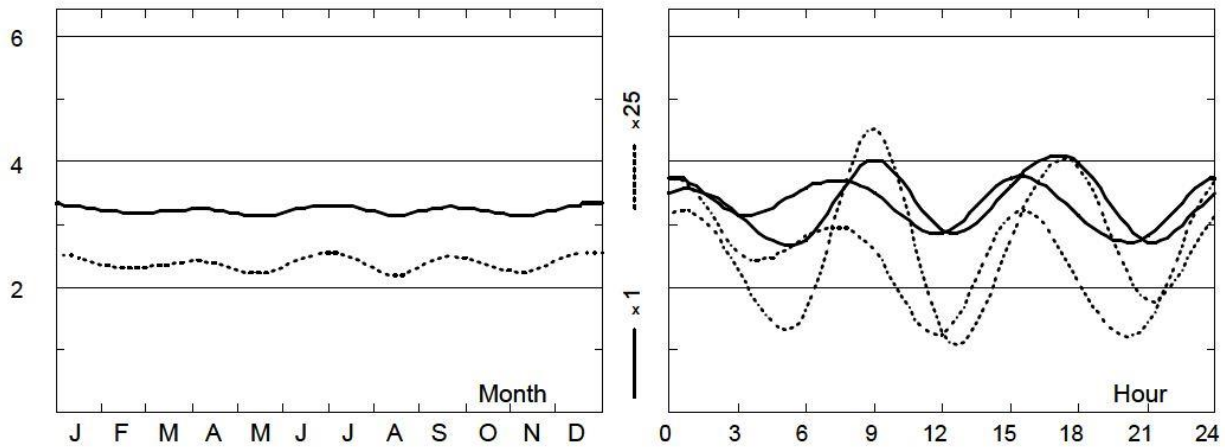
Figure 4.21 Campus Center

Figure 4.22: Campus Center Monthly Wind Speed

Wind velocity was monitored at 3 locations on the WPI campus. The locations

include Daniels Hall, East Hall, and the Campus Center. Daniels Hall is the best site on

Worcester Polytechnic Institute for a VAWT to be mounted. In the Figures 4.18, 4.20, and

4.22, WASP was used to develop plots of the wind data. These data are shown as dotted lines and black lines. The dotted lines are the different wind speeds recorded in meters per second and the black line are the average wind speeds in meters per second. In Figure 4.18; Graph 1, shows the wind speeds throughout the year of 2011 and how the speeds change over the months and Graph 2, shows the wind speeds on a daily basis. From the average wind speed we can determine the average wind classifications and wind power, based on the height of the anemometers. Daniels Hall's wind speed average of 7.2 m/s is a class 3 wind speed. However, this value is very close to class 4 with an average wind density around 400 W/m^2. This value is extremely promising for home wind turbine use.

East Hall falls into the wind class rating of 2 and the Campus Center has a rating of 1. These are not good results for typical wind power production since class 4 is normally the lowest class considered to have potential for typical home wind power generation. The data show that improved enclosure and funnel design can be important since velocities in these areas do not have substantial wind power generation potential.

5.0 Conclusions and Suggestions

From our research we were able to come up with many important conclusions and suggestions which will benefit the future development of personal vertical axis wind turbines. We were able to design a VAWT system that improved power output by 70% as compared to the previous project. From our results we were able to recommend new design aspects to improve the system and efficiency.

5.1 Turbine Design

The turbine performance testing and results from the research in this project showed that the split Savonius is the best design that has been tested to this point at WPI. The reason is due to the large surface area of the split Savonius which enables it to capture maximum amounts of wind. We believe that further research should be done with various Savonius designs because of this fact. The Savonius turbine designs are simple and cheap to manufacture, and are also not greatly affected by turbulence in the wind. The design we feel that has particular promise is a Savonius in a Savonius design that is shown in figure 5.1. This design is an improved version of the split Savonius that we utilized. This design increases the surface area to capture wind energy.
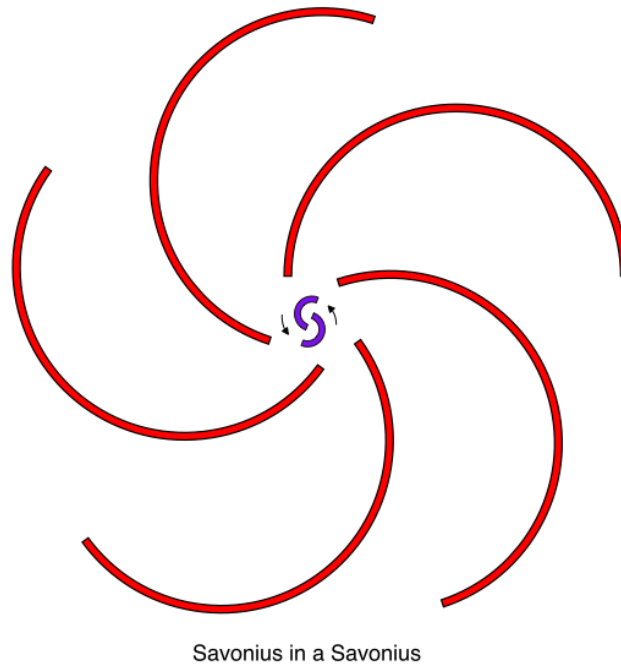
Savonius in a Savonius

Figure 5.1 Savonius in Savonius design

Another suggestion to improve the Savonius design in our opinion would be to create a more aerodynamic backing to the Savonius cusp. This design would reduce the energy it requires to spin with the wind. The basic concept is shown in the figure 5.2.
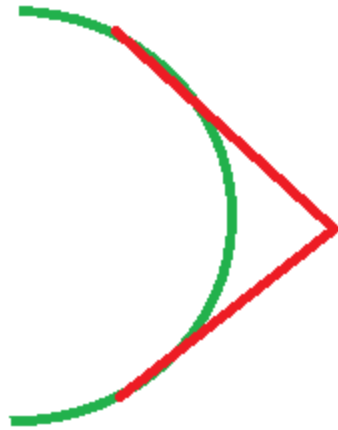
Figure 5.2 Savonius cup with aerodynamic backing

The green cusp above represents the original Savonius design and the red lines represent a simple backing to the Savonius design. Ideally, this will allow the Savonius to rotate into the wind more efficiently, thus increasing the rate of revolution. While we do not expect this to make a significant difference, our testing demonstrates that even small differences in wind speeds lead to significantly improved power output.

5.2 Turbine Shrouds and Enclosures

Our data clearly indicates that shrouds improve power output of vertical axis wind turbines. The exponential power output gained from increasing the rotation speed of the wind turbine is crucial in order to make an efficient rooftop wind turbine. The most important thing we concluded is that the enclosure should be designed based on of the wind turbine design. Each wind turbine design performs differently depending on the nature of the shroud.

Our test indicated a funnel into the turbine was not effective for our cases. The poor performance was attributed to a pressure differential that was created inside the funnel as compared to the pressure outside the funnel, which likely created an acceleration of the wind around the funnel. For future work, our suggestion is to utilize a funnel that is similar to the concepts used for Japanese ocean turbines. This concept has the funnel in reverse behind the enclosure. This creates a vacuum like-effect, drawing extra wind into the enclosure, which in return increases velocity inside the turbine. The concept is shown in figure 5.3.
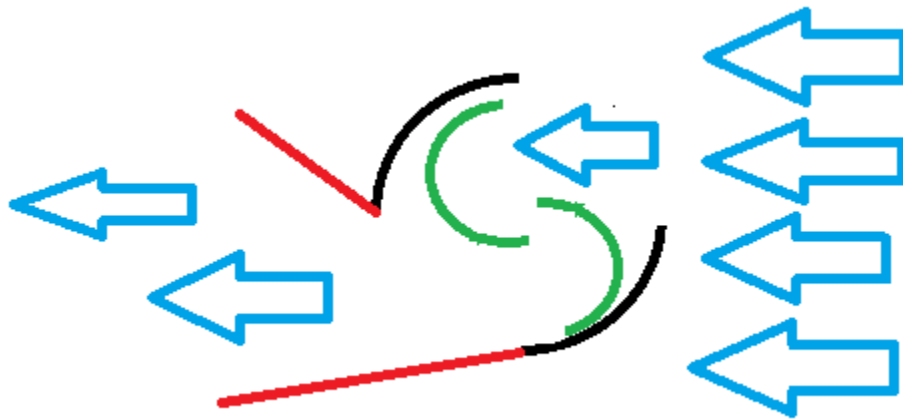

Figure 5.3- Reverse funnel concept

The blue arrows represent the wind, the green lines represent the split Savonius turbine, the black lines represent the currently used enclosure, and the red lines represent the funnel concept which we believe could improve wind speeds into the enclosure.

5.3 Mounting System

The mounting system that this project used is considered a proactive design. This means that the system tends to reduce vibrations after a vibration pulse is produced. Future testing can be completed with a proactive design, which can include adding a dampening system to turbine itself and trying to prevent the vibrations from occurring at the source. Another suggestion is to consider different materials, such as neoprene or silicon, which might be superior to a rubber vibration dampening system. The design used in this project was a single stage dampening system, with the only dampening source located at the base of the mount. Other research might want to consider multiple stages of dampening at various sections of the mount.

A more advanced approach to completely eliminate vibrations would be using a type of active vibration dampening system. This would be a very sophisticated system that would actively eliminate vibrations from occurring in the system. This approach would likely require some sort of energy to function and could possibly use more energy than the wind turbine produces. Systems like this are being researched into but have not been used on turbines. This would require a turbine that maximizes performance so it could overcome the energy required to run an active vibration dampening system.

5.4 WAsP and Wind Power Potential

The WASP software package provided an approach for assessing wind velocities and wind energy resource potential. An anemometer is a device for measuring wind speed, and is a common weather station instrument. The WASP Climate Analyst can import data that has been recorded from an anemometer to display these graphs. Throughout the year of 2011 the data collected from the anemometer stationed on top of Daniels Hall and East Hall was provided to analyze wind patterns for potential VAWT installation. For future recommendations, the data collected from the anemometer should be formatted to the WASP software. If the format is set up correctly it can save time on converting the values recorded. An anemometer that can measure direction can unlock the true potential of this program because without it the WASP software. With the data, this software package can also be used to develop more complete distributions of wind velocity and wind energy resource potential.

5.4 Overview

Even though we were able to make improvements to the previous work that was handed down to our group, there is a never ending process to always improve upon inventions and new designs. Wind turbines are a start for society to lessen the damage done to the earth by not using energy sources that produces pollution. Hopefully this project was able to advance research and testing on VAWT systems and give insight for other groups to complete further testing and improve efficiency and performance of vertical axis wind turbines.

References

Saha, U. K., S. Thotla, and D. Maity. "Optimum design configuration of Savonius rotor through wind tunnel experiments." *Journal of Wind Engineering and Industrial Aerodynamics* 96.8 (2008): 1359-1375.

F.L. Ponta, J.J. Seminara, A.D. Otero
On the aerodynamics of variable-geometry oval-trajectory Darrieus wind turbines
Renewable Energy, 32 (2007)

J.D.K. Bishop, G.A.J. Amaratunga
Evaluation of small wind turbines in distributed arrangement as sustainable wind energy option
Energy Conversion and Management, 49 (2008), pp. 1652–1661

M.H. Mohamed, G. Janiga, E. Pap, D. Thévenin
Optimal blade shape of a modified Savonius turbine using an obstacle shielding the returning blade
Energy Conversion and Management, 52 (2011)

Rehan Jamil, Zahid Hussain, Vertical axis wind turbine – A review of various configurations and design techniques, Renewable and Sustainable Energy Reviews, Volume 16, Issue 4, May 2012, (http://www.sciencedirect.com/science/article/pii/S136403211100596X)

Tetsuya Wakui, Ryohei Yokoyama, Wind speed sensorless performance monitoring based on operating behavior for stand-alone vertical axis wind turbine, Renewable Energy, May 2013 (http://www.sciencedirect.com/science/article/pii/S0960148112006970)

Daegyoum Kim, Morteza Gharib, Efficiency improvement of straight-bladed vertical-axis wind turbines with an upstream deflector, Journal of Wind Engineering and Industrial Aerodynamics, Volume 115, April 2013
(http://www.sciencedirect.com/science/article/pii/S0167610513000354)

Islam Abohela, Neveen Hamza, Steven Dudek, Effect of roof shape, wind direction, building height and urban configuration on the energy yield and positioning of roof mounted wind turbines, Renewable Energy, Volume 50, February 2013
(http://www.sciencedirect.com/science/article/pii/S0960148112005381)

Windterra, 2012
http://www.windterra.com/Windterra%20V5_files/Page429.htm

Howard, Clark National Geographic Daily News, August 20, 2012
http://news.nationalgeographic.com/news/energy/2012/08/120820-helix-wind-collapse/

Rao, Singiresu S., and Fook Fah Yap. Mechanical vibrations. Vol. 4. Reading, MA: Addison Wesley, 1995.

Jureczko, M. E. Z. Y. K., M. Pawlak, and A. Mężyk. "Optimisation of wind turbine blades." Journal of Materials Processing Technology 167.2 (2005): 463-471.

Lu, Lin, Hongxing Yang, and John Burnett. "Investigation on wind power potential on Hong Kong islands—an analysis of wind power and wind turbine characteristics." Renewable Energy 27.1 (2002): 1-12.

Ciang, Chia Chen, Jung-Ryul Lee, and Hyung-Joon Bang. "Structural health monitoring for a wind turbine system: a review of damage detection methods." Measurement Science and Technology 19.12 (2008): 122001.