



MECE E3410.001 ENGINEERING DESIGN
Professor Fred Stolfi

FINAL DESIGN REPORT

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I. EXECUTIVE SUMMARY

Purpose

This project was undertaken to explore some of the capabilities of clean, renewable energy. The design team chose to create a wind turbine that could be placed on the roof of a building in an urban or suburban environment. The goals for the semester were twofold: First, to design and build and test a wind turbine for power generation that could eventually see commercial success in urban markets. Second, the project gave the engineers on the design team experience in all aspects of mechanical design and assembly.

Description

The team chose to construct a Darrieus wind turbine. This type of turbine consists of three airfoils mounted vertically on a rotating shaft. The specific design for this project is supported by a wooden base which holds a main shaft and an auxiliary shaft which can be used for altering the gear ratios. The main shaft is held in place by two bearings that allow free rotation and torque transmission but no lateral or axial movement. Six aluminum arms, which support the three airfoils, are joined to this shaft. The airfoils are made of foam coated in carbon and are the key driving component of the turbine. Attached to the center shaft is a variable gear system that transfers power to and from a generator. A general assembly picture can be seen below in Figure I.a and full CAD drawings can be found in Appendix A.

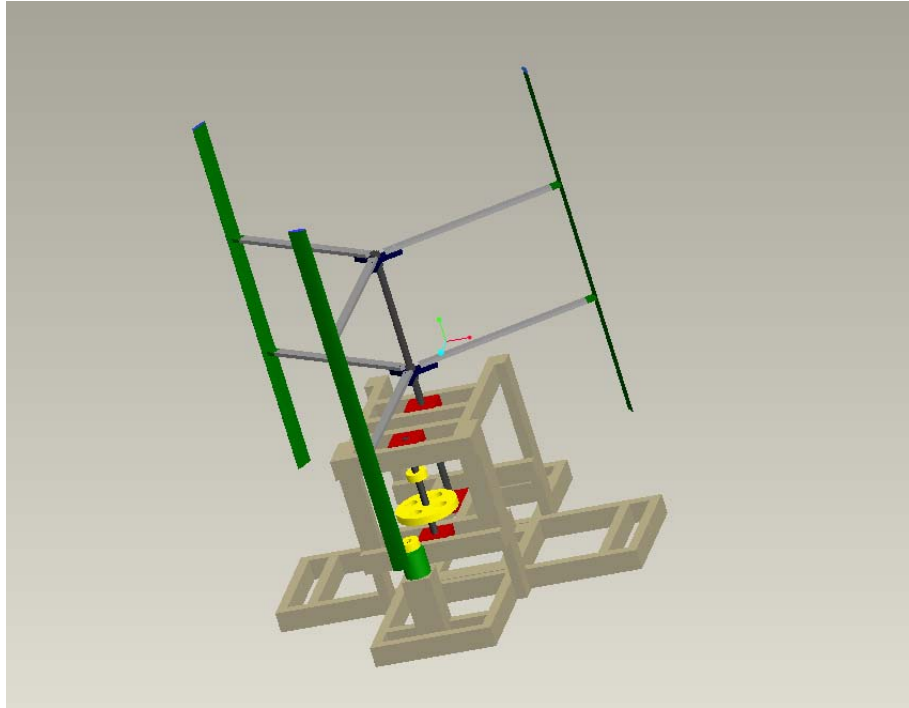


Figure 1.a: General Assembly View

Components:

The wind turbine can be broken down into several key components or systems including the base, the support structure, the airfoils, and the generator system. Each of these systems will be discussed in more detail in the report, but several are worth mentioning because they were critical to the design. These include the airfoils, the bearings, and the generator. The airfoils were critical because the power calculations depended on them being perfectly formed and smooth. The bearings were critical because the wind turbine had to be able to turn at high speeds with a very low friction. If the bearings were good, the wind turbine would also be able to start turning at low speeds. The ones chosen worked very well and allowed the shaft to rotate at speeds up to 140 rpm (limited by the battery power). The generator was chosen for its ability to generate power at a very low rotational speed of 30 rpm. Unfortunately, its start up torque of 1.095 lbf proved to be too much for the generator to turn with any consistency given the wind speeds generated by the wind tunnel.

Successes:

The success of this project cannot be measured in simple terms. There were multiple objectives entering the semester and a number of key criterion were achieved over the course of the project. The turbine was successfully designed and assembled and tested at relatively high rpm. It was also able to operate in a drag state in an unfavorable wind profile to reach a steady state rotation of 30rpm. The team also successfully modeled wind flow over the airfoils to gain a much greater understanding of the dynamics of a spinning turbine.

Weaknesses:

Despite a number of key successes and milestones over the course of the semester, the team would be remiss to not mention a key flaw in the system. The turbine has yet to consistently generate power greater than one Watt. The low velocity and small distribution of wind generated by the Mechanical Engineering wind tunnel was not enough to drive the rotor in the method for which it had been designed. A vertical wind turbine is meant to be brought to high speed by an outside motor, which was achieved, and then maintain that speed through the dynamics of the wind passing over the rotating airfoils. The team was unable to test the turbine with the kind of sustained large scale wind necessary for proper operation.

Performance and Possible Error Sources:

The wind turbine did not perform to its theoretical able to for a variety of reason. At the maximum speed of the wind turbine (60 Hz) it was only able to generate .1 W of power. This low number, however, becomes more understandable when the testing conditions and building errors are taken into account. Due to time and availability limitations, the turbine was not tested outside. All tests were run in front of a wind tunnel with an extremely focused stream of air. In addition, imperfections in the airfoils and the rotation of the aluminum shaft caused to turbine to wobble at high speeds, further decreasing efficiency.

Conclusion:

While the team achieved some notable successes, more tests and some design and manufacturing changes would be necessary to make this particular wind turbine a viable energy source in an urban environment.

II. INITIAL CONCEPT AND ENGINEERING VALIDATION

II.I Why wind power?

It is easy to say that alternative energy is needed, but how do you make the choice between all of the alternatives? Specifically, why choose wind instead of solar? It is true that for a given amount of area, a solar array might produce more power. In Central Park for example, a circular solar collector with a radius of 1 meter can give an average of 6.4 kWh/day, and a vertical axis wind turbine covering the same amount of ground will only produce 4.0 kWh/day (calculations based on numbers from *Thirty-Year Average of Monthly Solar Radiation*). However, solar power is more expensive per watt than wind. A study comparing the costs of wind and solar over one year found solar to be \$12.24 per rated watt, while wind was only \$7.02 (Source: *Renewable Energy Comparison of Wind and Photovoltaic Solar*). When looking to minimize costs, wind is a more viable option.

II.II Vertical v Horizontal Turbines

There are two main types of wind turbines: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). Each type has its advantages and disadvantages. An advantage of the VAWT is direction-independent power production – a vertical axis turbine will produce power regardless of the direction of the prevailing wind. Conversely, a HAWT needs to be oriented towards the wind. This quality of the VAWT makes it suitable for any location with high wind speeds. Another advantage of the VAWT is its stability. The generator for a horizontal turbine must be placed close to the axis of rotation, which results in a high center of gravity. The vertical turbine generator can be affixed to a stable base near the ground. The stability of the VAWT makes it safer and more adaptable to different urban locations. The design is particularly suitable for rooftops in urban areas.

Well designed VAWTs can have efficiencies comparable to HAWTs. Figures II.IIa and II.IIb are plots comparing tip speed ratio (TSR) and power coefficient (C_p). Figure II.IIa is for a VAWT and shows the power coefficient curve for a NACA 63-015 airfoil and a solidity of 0.21. This is comparable to the power coefficient curve of a HAWT shown in Figure II.IIb.

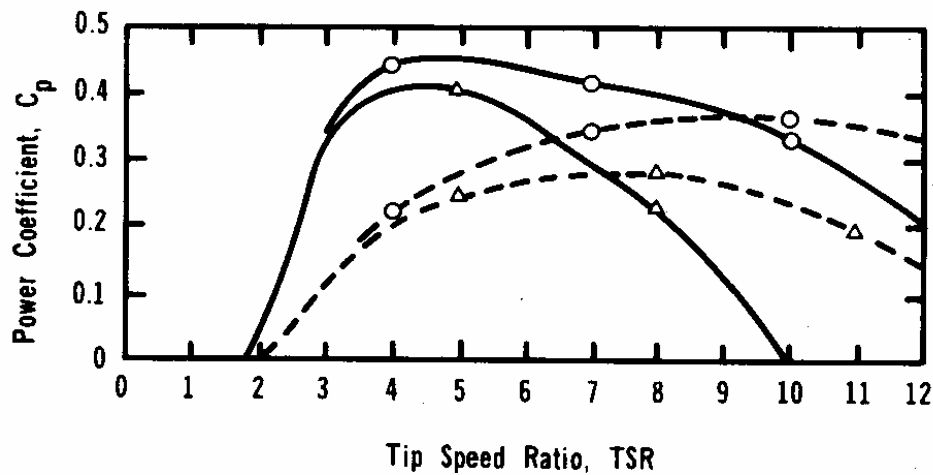


Fig. 1 C_p -TSR performance of NACA 0015 and NACA 63₂-015 airfoils (--- $\sigma=0.07$, — $\sigma=0.21$, \circ NACA 63₂-015, Δ NACA 0015).

Figure II.IIa: Power coefficient curve for VAWTs with differing airfoils and solidities
Source: Migliore

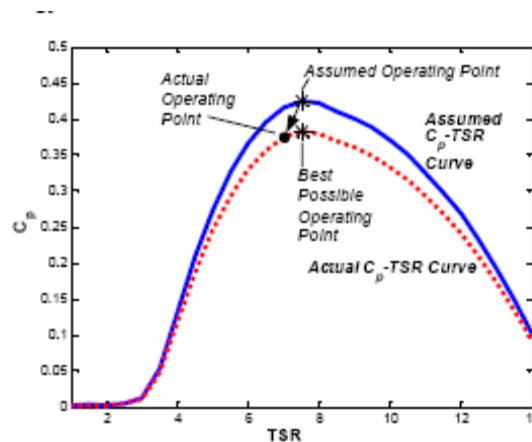


Figure II.IIb: Power coefficient curve for a HAWT

A disadvantage of the VAWT is that it is not self-starting. This can be remedied with a motor-generator which will mechanically assist the turbine to reach operating speed.

Once at operating speed the forces on the airfoils will take over and the turbine will produce power.

II.III. Aerodynamics and Power Calculations

II.III.I Basic Aerodynamics

The 3-D turbine can be modeled as a 2-D cross section, as shown below.

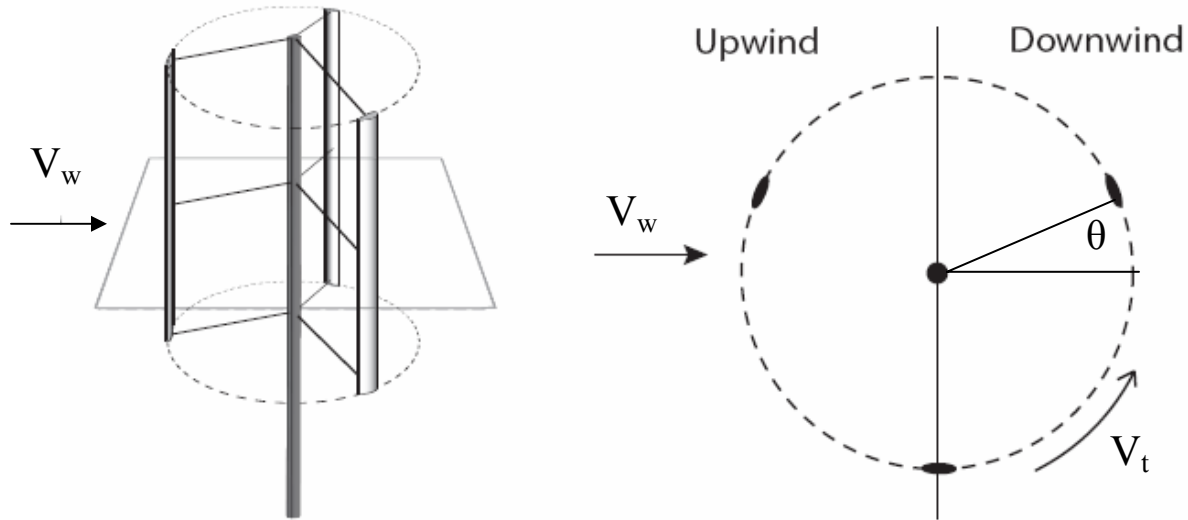


Figure II.III.Ia: VAWT model. [Source: Claessens]

The forces felt by each blade of turbine depend on wind speed, rotational speed, and the angle of attack (angle between oncoming wind and the chordline). A positive angle attack is when the nose of the airfoil points upwards with respect to the oncoming wind. To calculate torque, angle of attack α was determined for each point in the cycle. The equation for angle of attack is given as:

$$\alpha = \arctan\left(\frac{V_w \cos \theta}{V_w \sin \theta + V_t}\right) \quad (\text{Eq. II.III.Ia})$$

where V_w is the wind speed V_t is the tangential speed of the airfoils, and θ gives the position of the airfoil in the rotation cycle. The tip speed ratio (TSR) is defined as:

$$TSR = \frac{V_t}{V_w} \quad (Eq. II.III.Ib)$$

The torque is dependent on the lift and drag coefficients. Plots of lift and drag coefficients verses angle of attack are shown below. These were calculated using the DesignFoil software with a Reynolds number of 230,000 (the average Reynolds number expected with a TSR of 4).

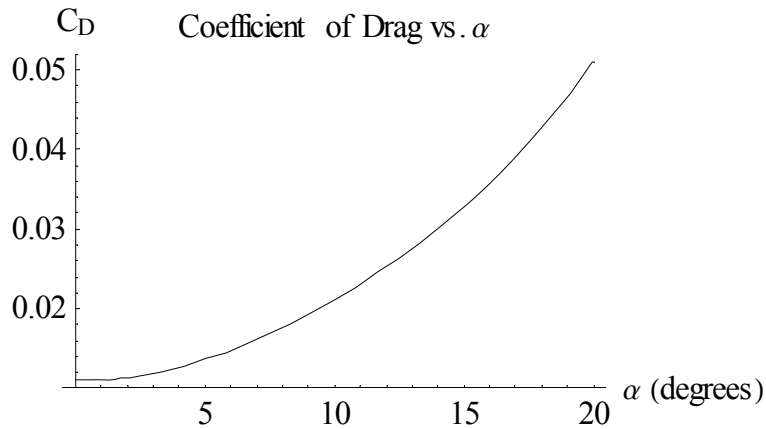


Figure II.III.Ib: C_D vs. angle of attack. Source: DesignFoil software and Mathematica

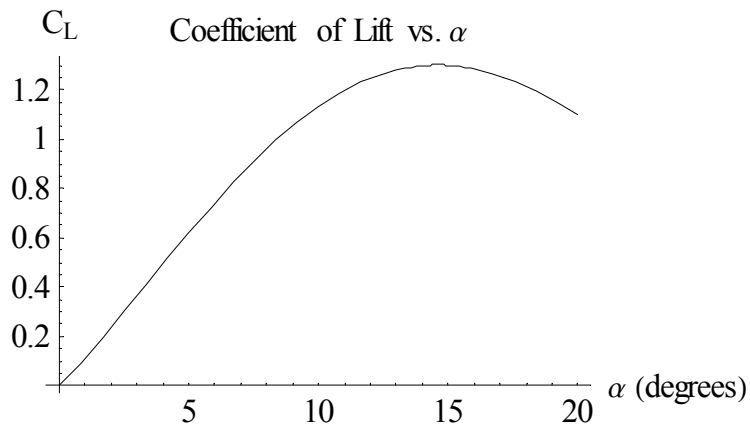


Figure II.III.Ic: C_L vs. angle of attack. Source: DesignFoil software and Mathematica

At higher angles of attack, it is apparent that drag increases significantly and lift drops off. High angles of attack also cause separation further up along the airfoil, increasing drag. At very high angles of attack, this drag takes over. It is thus important to maintain lower angles of attack throughout the rotation cycle to improve efficiency. At

low speeds, such as 30 rpm, the angles of attack get very high, as shown in the plots below.

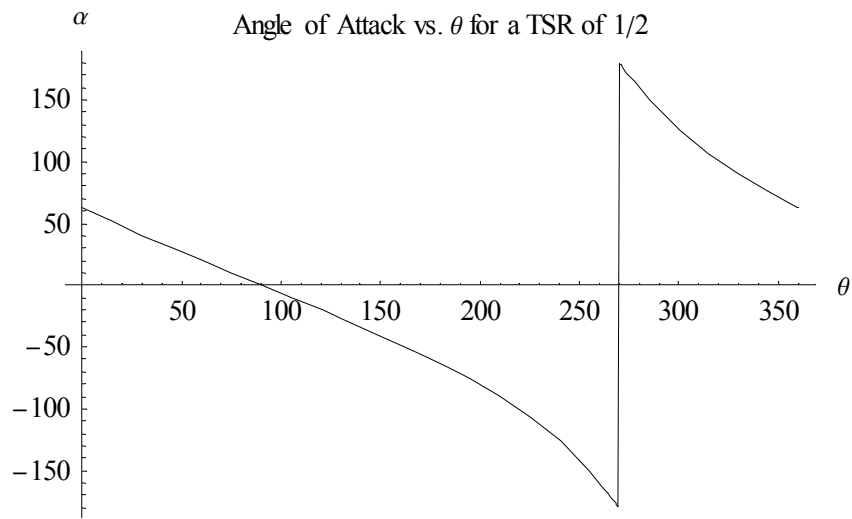


Figure II.III.Id: Angle of attack. $V_w = 6 \text{ m/s}$, $TSR = 1/2$ (Mathematica)

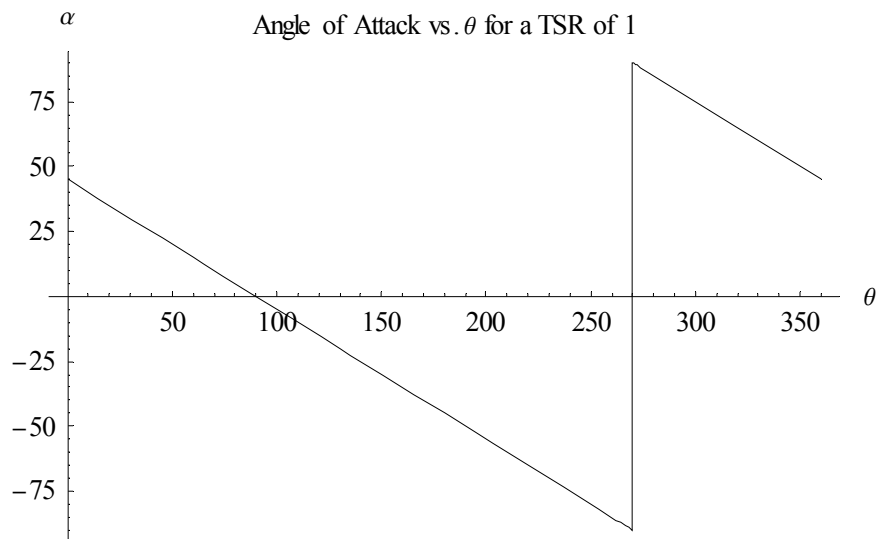


Figure II.III.Ie: Angle of attack. $V_w = 6 \text{ m/s}$, $TSR = 1$. (Mathematica)

Angles of attack for higher rotational speeds are much smaller. Figure II.III.If shows angles of attack for higher tip speed ratios.

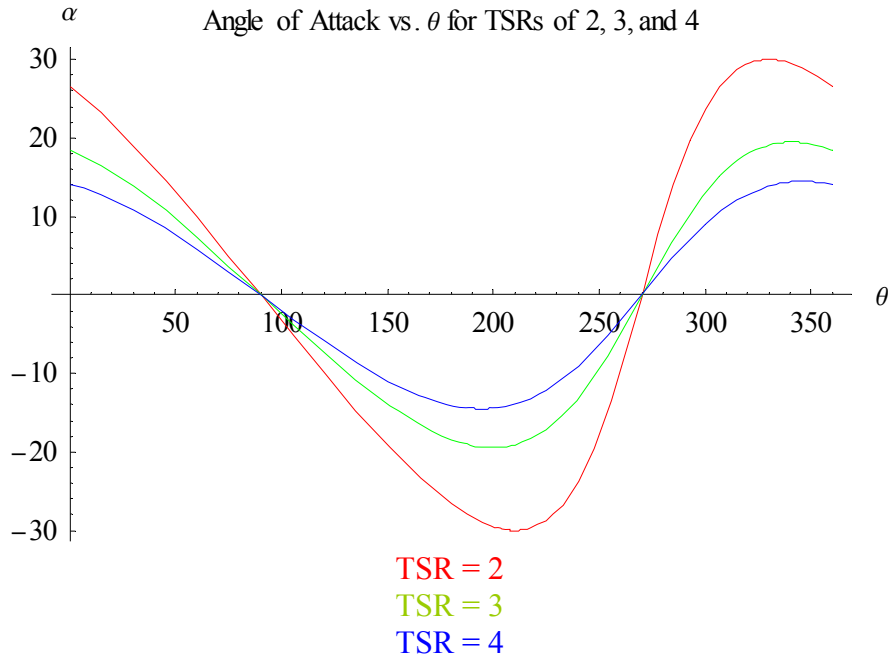


Figure II.III.If: Angle of attack. $V_w = 6$ m/s, TSRs of 2, 3, and 4. Source: Mathematica

These curves also illustrate why the turbine is not self-starting. When the turbine is not moving, angles of attack are not low enough on all blades to create the forces necessary to start the turbine.

II.III.II. Forces

The forces on the airfoil can be calculated using Figure II.III.IIa below. It is difficult to do simple analysis of the airfoils due to the large variation in airspeeds and angles of attack that the airfoils encounter as they move around the cycle. The airfoils are traveling with the chordline perpendicular to the turbine radius (they are not pitched). The rotational force from lift and drag for each blade is thus:

$$F_{motion} = L \sin \alpha - D \cos \alpha \quad (Eq. II.III.IIa)$$

Where L is the lift, D is the drag, and α is the angle of attack. The power produced by the turbine from each blade is

$$P = (L \sin \alpha - D \cos \alpha) V \quad (Eq. II.III.IIb)$$

where V is the speed of the turbine blades.

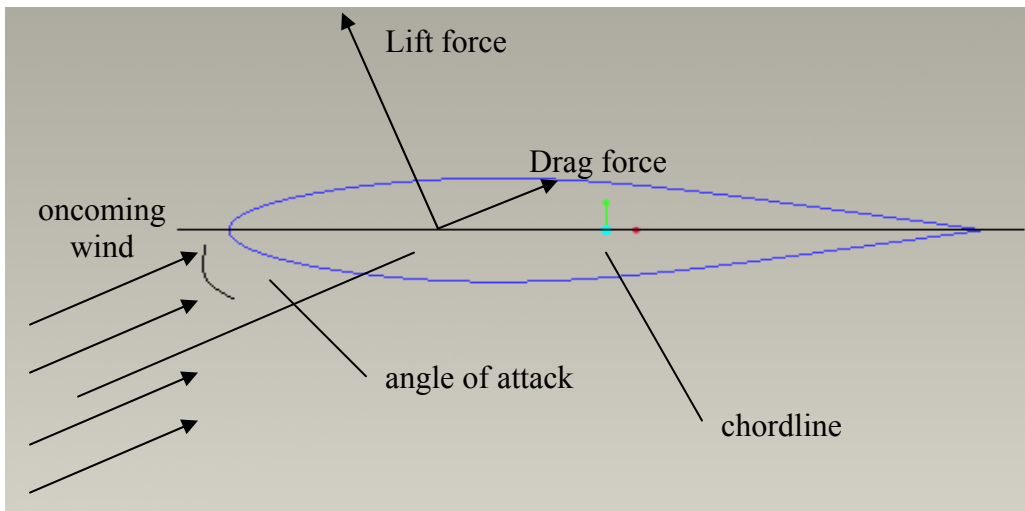


Figure II.III.II.a: Illustration of lift and drag forces

II.III.III. Available Power

The power available in the wind is proportional to the cube of the wind speed and the area of the turbine, A :

$$A = Dh \quad (\text{Eq. II.III.III.a})$$

where D and h are the diameter and height, respectively. The total power available is given as

$$P = 0.5\rho AV_w^3 \quad (\text{Eq. II.III.III.b})$$

where ρ is the density of the air and V_w is the undisturbed wind speed. This is the power that would be produced if 100% of the wind energy were harnessed. However, this would require making the wind velocity go to zero, which is not possible. On the other extreme, if the turbine did not slow the wind down at all, the turbine would not capture any energy. Between these two extremes lies a velocity change that yields the maximum

amount of power. The physicist Albert Betz proved that the maximum amount of power that can be captured is 59% of the power in the wind.

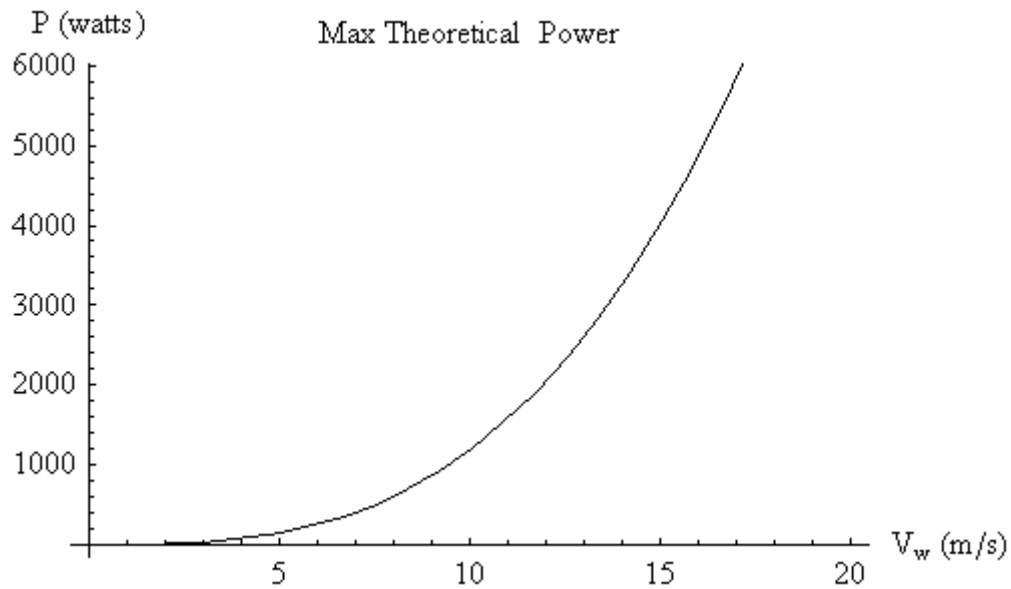


Figure II.III.III.a: Theoretical Maximum Power With Betz Limit

II.III.IV. Calculation Methods and Results

The forces on the airfoil were calculated using Fluent for two different TSRs: 2.3 and 3. A TSR of 2.3 is what can be achieved with the motor-assist. After the turbine is brought to this speed, wind forces will take over. The airfoil was imported into Gambit from Pro/Engineer and a fine boundary layer mesh was created near the surface of the airfoil. A view of the mesh close to the airfoil is shown in the figure below.

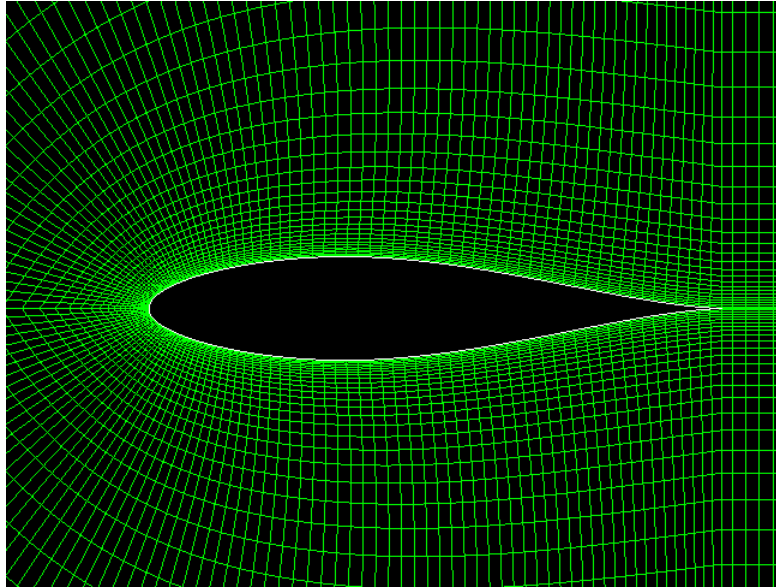


Figure II.III.IVa: Boundary layer mesh used for Fluent calculations

To find forces, the apparent velocity V_a coming into the airfoil (an addition of the wind velocity V_w and the tangential velocity V_t) was calculated and broken up into x and y components with respect to the airfoil. A simulation was then run, and the net forces in the x and y directions were reported (see Appendix B). It was found that the turbine will produce 31.4 W while spinning at a TSR of 2.3 and 58.2 W while spinning at a TSR of 3. Power calculation tables can be found in Appendix C.

II.IV. Airfoils

The first step in designing a Darrieus turbine is to choose the optimal number of blades. Blades in rotational motion leave turbulent flow in their paths. As the number of blades is increased, airfoils run into more turbulent flow and work less efficiently. However, a turbine with fewer blades has more wind passing through the turbine that does not contribute to power. An even number of blades is more likely to cause vibration problems. For these reasons, a three bladed design will yield the flattest power coefficient curve over 360 degrees of rotation. For these reasons, the three-bladed design was chosen. The blades will be symmetrical airfoils type NACA 63 018. This airfoil profile was found to have the most optimal performance for use with Darrieus wind turbines [Source: Migliore]. The NACA 6-series airfoils are designed to increase the

amount of laminar flow and reduce drag. A profile of the airfoil chosen is shown in the figure below.

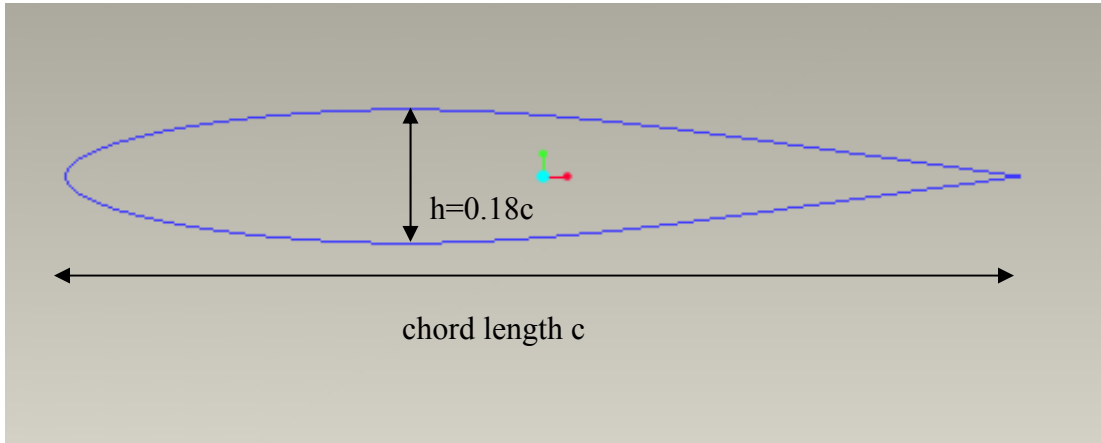


Figure II.IV.a: Profile of an NACA 63-015 airfoil

The tip speed ratio is an important design aspect. Most Darrieus wind turbines are designed to have a TSR between 4 and 6. Power curves show that optimal TSRs for a Darrieus design with wind speeds of 6 m/s are between 4 and 8, depending on solidity (see Appendix II.IV). Lower TSRs have been shown to reduce noise generation, an important issue in urban settings. With this as a consideration, a TSR of 4.0 was chosen. TSR varies with wind speed. To achieve a TSR of 4.0 at a wind speed of 6 m/s with the 63-018 airfoil, the solidity (ratio of total blade area to total frontal area) should be 0.20 as shown in Figure II.IV.a below.

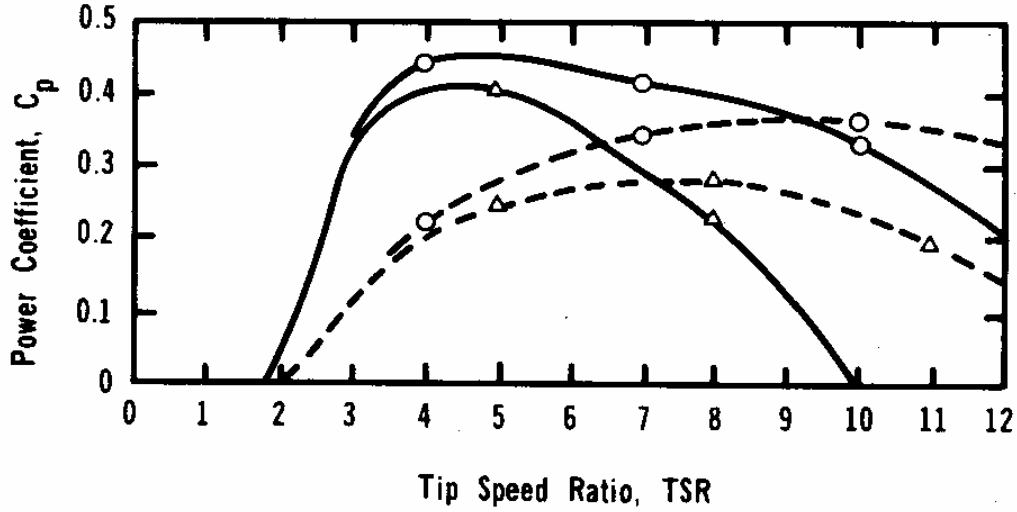


Fig. 1 C_p -TSR performance of NACA 0015 and NACA 63₂-015 airfoils ($---$ $\sigma=0.07$, $—$ $\sigma=0.21$, \circ NACA 63₂-015, Δ NACA 0015).

Figure II.IVa: Power coefficient vs. TSR for 4 different airfoils

A solidity of 0.20 for 6 ft diameter gives a blade chord length of 12 cm. Airfoil coordinates for this chord length can be found in Appendix II.IV.

The torque felt by the turbine depends on wind speed, rotational speed, and the angle of attack (angle between oncoming wind and the chordline). To calculate torque, angle of attack was determined for each point in the cycle. The airfoils are assumed to be traveling with the chordline perpendicular to the turbine radius (they are not pitched). The rotational force from lift and drag for each blade is thus:

$$F_{motion} = L \sin \alpha - D \cos \alpha \quad (Eq. II.IV.a)$$

Where L is the lift, D is the drag, and α is the angle of attack. The power produced by the turbine from each blade is

$$P = (L \sin \alpha - D \cos \alpha)V \quad (Eq. II.IV.b)$$

where V is the speed of the turbine blades. Using these correlations, power was calculated for each of 3 blades with a wind speed of 6 m/s.

II.V Support Structure

The support structure was designed to be stable, durable, and semi-portable. Generally speaking, the supporting elements would need to be stable enough to withstand repeated loading, high winds, and potentially high torques. Additionally, the system would need to be semi-portable, in that it should be able to be transported and set up in a reasonable amount of time, in roughly 1 hour. This led to the selection of aluminum as a main material for construction, as it is lightweight, has a prescribed amount of rigidity and stress resistance, and is low cost. The supporting sections that were not made of aluminum were constructed primarily out of wooden 2x4s which have the advantage of being sturdy, easily available and easy to work with.

II.V.I Central Shaft

The 54 inch central aluminum hollow shaft is the major component in the support structure. It was designed to withstand both axial and repeated loading stresses. Since a safety factor of 2.0 was selected for the axial load, and the weight of the airfoils and supporting arms were calculated at roughly 25 pounds, the shaft had to support an axial force of 50lbs. Further calculations showed that axial loading would not be a large concern, as the stresses from repeated loading due to rotation would far outweigh those of axial loading. Calculations of these stresses are shown in appendix II.V.I. A summary of stresses in the arm and shaft are shown below.

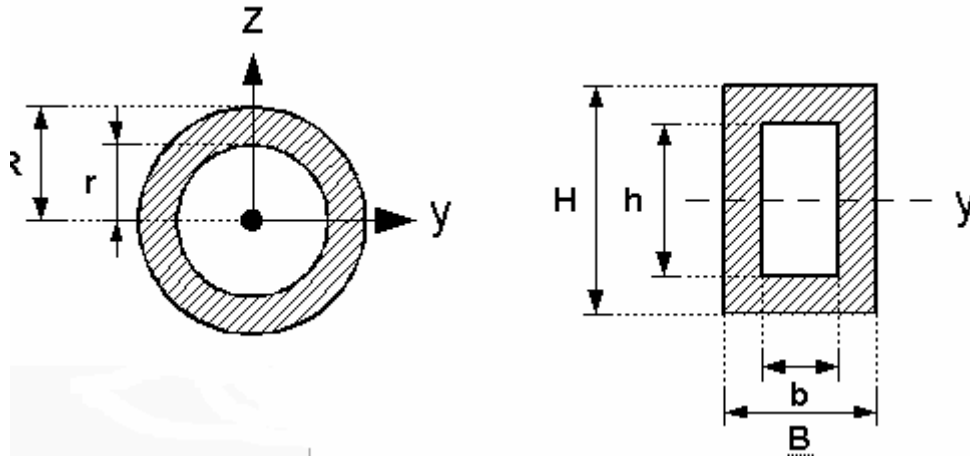


Figure II.V.a Cross Sections of Central Shaft and Aluminum Arm, respectively

The figure above shows the cross sectional areas for the central shaft and aluminum arms. In this case $R=.5$ inches, $r=.37$ inches, $H=1$ inch, $B= 1.5$, $h = .75$ and $b = 1.25$ inches.

II.V.II Aluminum Support Arms

The second major component of support design was the aluminum arms that join the airfoils to the shaft. The arms need to be lightweight and rigid to support the loads and promote free rotation. Hollow, rectangular aluminum beams were chosen as the most cost effective solution. The arms face two main loads. Axially load due to the rotation of the arms was calculated to be negligible given the length of the arms with respect to the force acting outwardly on the airfoils. Similarly, the bending force from the weight of the airfoils was insignificant, causing a bending of less than .1 inches at a maximum.

	Cross Sectional Area (in ²)	Max Axial Load (lbs)	Max Axial Deformation (in)
Central Shaft	.049	25	.152
Aluminum Arm	.5625	15.7	..0263

	Bending Moment (in ⁴)	Max Bending Load (lbs)	Max Bending Deflection (in)

Central Shaft	.02525	15.7	1.364
Aluminum Arm	.081055	5	.0795

Tables II.V.a and II.V.b detail axial and bending stresses on aluminum members

Calculations for the above tables are found in appendix II.V.I and II.V.II. As is apparent, the deflections from bending are much greater than that of axial loading on the members. Further, the deflection of the central shaft of 1.364 inches at the furthest point from the main bearing is disconcerting. Future design revisions should focus on increasing the moment of inertia of the shaft, increasing its rigidity from young's modulus, or decreasing the length of the shaft that is cantilevered (perhaps making it a solid, or changing the material to steel).

II.V.III Connections and Brackets

The majority of joining techniques in the turbine were designed to be assembled and disassembled on site, yet strong enough to resist all loads. For this reason, as well as ease of manufacturing, nuts and bolts were used in nearly all of the 38 joints in the rotating portion of the turbine. If either a nut or bolt is lost, it can be easily replaced from stock, and a team assembling the structure needs only a screwdriver and pair of pliers to secure the turbine.

Initially, the connector was designed with as a small circle with three bars extending out to meet the arms, however after a structural analysis using ProEngineer it was deemed that a full circle design would be much more resistant to bending. This analysis is included in the Appendix II.V.III.

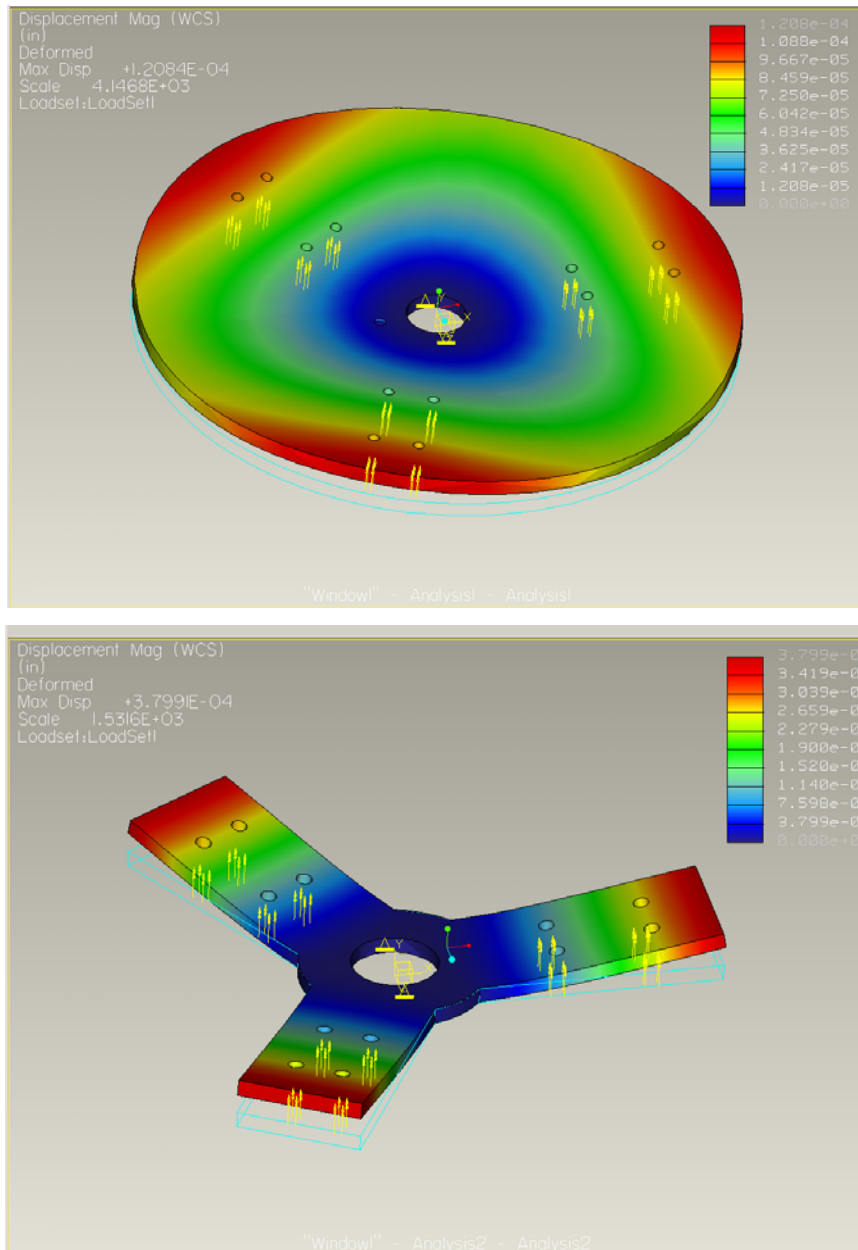


Figure II.V.a Stress analyses for differing connector designs

This ProE model shows that with a circular disc a maximum displacement of .00012 inches occurred, while a spurred design would result in a displacement of nearly four times as large with proportional stresses. It was decided then to machine a circular disk. Mr. Stark later pointed out that an added benefit was reduced machining time and complexity of G-Code.

Lastly, steel was employed to increase the structural integrity and performance of the airfoils. Steel brackets were used to support and separate the sections of airfoils on each blade. The brackets are welded to steel rods which extend through the 36 inch length of the airfoils and the steel system serves to support the system vertically. A system of guide wires was installed to counter act the large centrifugal force acting on the rotating turbine.

II.V.IV Bearings

The support structure and bearing system for the vertical axis wind turbine is made up of bearings that are used to facilitate the movement of the turbine without using valuable mechanical energy. Each bearing was chosen because it would fit the desired shaft and because they had a high dynamic load. A high dynamic load was critical to the selection of the bearings because it is related to the speed and stability of the rotation. A low dynamic load could mean that the bearing can be easily misaligned or that it will stall at high speeds. The bearings for the turbine must be able to withstand high speeds and gusts from winds; it must also be able to rotate with great ease to reduce the amount of energy lost to the system. A stalling bearing could be the difference between 10Watts of power and 20Watts of power. The more energy the system uses to run, the less the output power will be.

A pillow block bearing is used to support the rotation of the shaft of the turbine. With expectant speeds of approximately 200 rpm, the pillow block bearing is ideal for managing this. The pillow block bearing can support forces up to 674.426829 lbf, as stated by the manufacturer, SRK Group.



Figure I.Ia – Pillow Block Bearing

The tapered roller bearing has a dynamic load capacity of 6069841.46 pound force, as indicated by the manufacturer, MSCDirect. This bearing is made of a cup and a

cone piece. The cup is the outer piece that is used to hold the cone. The cone is the inner piece that contains the roller bearings on a circular tilt. This device was used in the project to support the main shaft and allow for free range rotation. It was pressed into an aluminum pillow block to allow greater stability during use.



Figure I.IIb – Tapered Roller Thrust Bearing

The needle roller bearing can bear substantial axial loads according to the manufacturer (MSCDirect) who states that it has a maximum load of 140,280.78 lbf. The placement of this bearing is at the top of the smaller shaft used to step up the ratio from 1:3 to 1:9.



Figure I.III – Needle Roller Bearing

A small single row thrust bearing is steel and made from a single bearing track on a 90 degree angle. It has a limiting speed of 1000 rpm, as stated by Applied Industrial Technologies. This was also used for the small shaft. It was pressed into an aluminum pillow block to allow greater stability during use.



Figure I.IV – Small Single Row Thrust Bearing

II.V.V Base

The base was designed with two goals in mind: portability and structural integrity. It is mainly comprised of 2x4's held together with epoxy and wood screws, and its modular design allows for transport—no single piece weighs more than 40 pounds. The three pieces combine to form a secure unit. The modules are held together with four three-inch long bolts as well as ballast weight, if necessary. The base has two six foot long intersecting lower units which combine for a total footprint of 20 square feet. Once a site is selected, it can be assembled in minutes.

II.VI Generator System

The final step in creating energy for the wind turbine is to convert the mechanical energy of the turbine into usable electrical energy. In order to achieve, a chain, sprocket and motor/generator system was developed. In the following section the reasons and justifications of this system will be discussed.

II.VI.I Motor/Generator:

A permanent magnet alternator generator/motor was selected to both power the turbine and convert the energy from rotational to electric. The circuitry of this system will be discussed later in this section. By rotating the copper coils found on the stator around magnets located in the rotor, a current is produced. Understanding Faraday's law of induction helps to clarify this principle.

The specific generator/motor selected was the 900 RPM Ametek Permanent Magnet DC Motor. Several sellers cite this generator for wind turbines due to its ability to operate at extremely low RPM, approximately 300 RPM. The following chart displays

the power curve of the generator/motor across different loads.

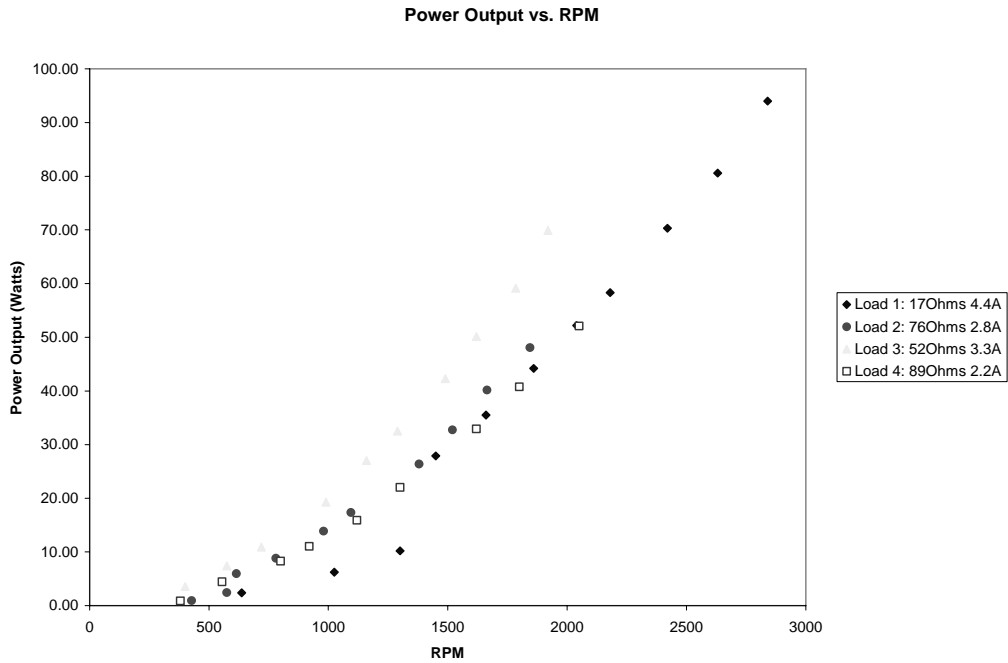


Figure II.VI.a: Power Output Curves for Generator

To develop these power curves, the generator was connected to the shaft of another generator and then spun. From this, the volts and amps produced were measured. To see how the generator reacted under different loads, various resistances were placed into the circuit. To find the RPM of the shaft, a strobe light was connected and adjusted the light pulse until the shaft appeared to stand still. The reading on the strobe light indicated the RPM of the shaft. The schematic of the test circuit may be seen in Figure II.VI.b below.

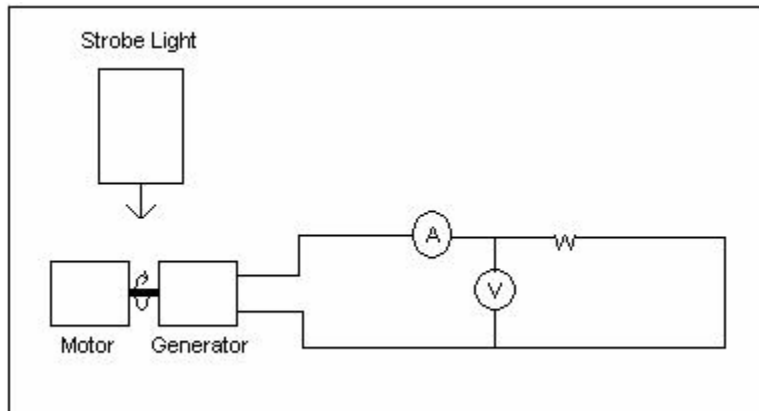


Figure II.VI.b: Test Circuit Schematic

Due to the difficulty in reading the strobe light, no readings were possible below 450 RPM. By extrapolating along the power chart, however, it is clear that even at 300 RPM the generator produces energy. The slow rotation associated with the wind turbine make this generator ideal for this purposes. The data associated with this experiment may be found in Appendix D. Further clarification about RPM speeds may be found in the next section.

II.IV.II Chain and Sprocket System

This system changed dramatically as testing progressed, but the initial analysis of the situation is included below because it informed later design choices. According to the manufacturer the slowest RPM the generator may operate at is approximately 300 RPM, but the generator rotates at slower speeds. Manufacturer specifications may be found in Appendix C. To solve for this problem, the RPM from the turbine to the generator theoretically had to be stepped up nine times. This ratio was decided upon after taking the ratio of the maximum generator RPM, 1800 RPM, and the maximum generator speed, 200 RPM. To accomplish this task, chains and sprockets were incorporated into a design for two systems to step up the RPM. Chain and sprockets are advantages for this purpose for several reasons. The chain, size 25, has links that may be easily broken and reconnected to allow for flexible and adjustable distances between sprockets. Also sprockets made for size 25 chain are more easily interchanged. Unlike a timing belt system, which has many variables, size 25 chain will fit with any sprocket made for that size chain. These characteristics allow for the chain and sprocket system to easily evolve and adjust as we assembled.

To step up RPM, two systems were originally designed. The first system was supposed to go from the main turbine shaft to an intermediate shaft. The sprockets 1 and 2, on the two shafts have a 3:1 ratio respectively. This means the sprocket on the second shaft rotates three times faster because it has a third number of teeth of the first. The second system goes from sprocket 3 on the intermediate shaft to sprocket 4 on the generator shaft. Sprocket 3 now has three times more teeth than sprocket four therefore creating another 3:1 ratio. By the end of the two chain and sprocket systems the RPM

would have been stepped up nine times. A rough sketch of the original, but not final, system may be seen in the picture depicted below.

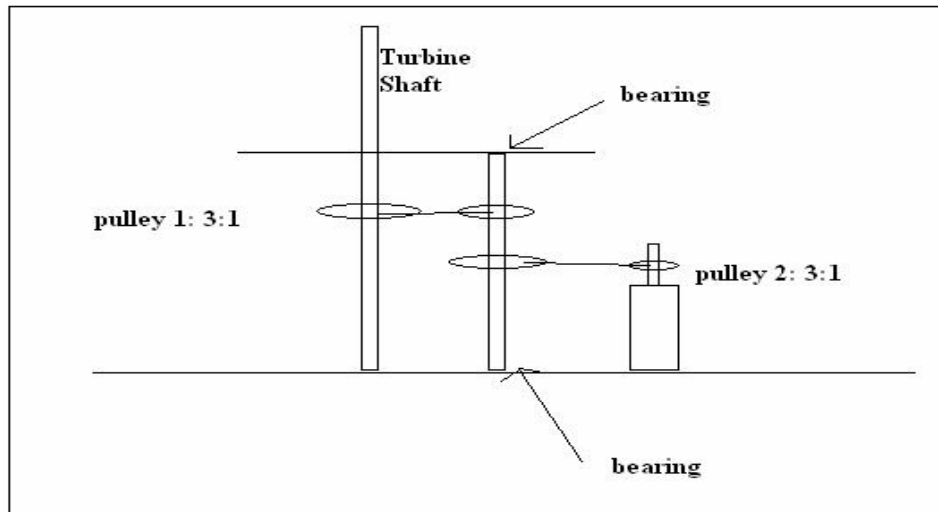


Figure II.VI.c: Chain-Sprocket System

The contact between the sprockets and chain, however, has friction that will dissipate energy. The following equation is used to calculate the amount of energy lost.

$$P_{lost} = \frac{1}{5} \left(\frac{1}{t} + \frac{1}{T} \right) * Hp \quad (Eq II.VI.a)$$

Where P_{lost} is the power lost, t is the number of teeth on one sprocket, T is the number of teeth on the other, and Hp is the amount of horsepower produced. For our specific system the most energy lost is approximately 2%. This indicates that the energy lost to friction is negligible. After the pre-analysis the system seemed sound, but many changes that will be discussed later.

II.IV.III Electrical Circuit

The final step is to connect the electrical circuits to the generator/motor. This circuit achieves two purposes. The first is to supply battery power to the motor so it starts spinning. By running the two chain and sprocket systems backwards, motor to intermediate shaft and from intermediate shaft to main turbine shaft, the generator/motor

acts as a motor to begin the turning of the wind turbine. This helps to start the turbine spinning in wind gusts. The second part of the circuit is to present a visual for the energy being generated from the wind turbine. This is done by lighting up a series of light bulbs. The circuit changes easily between the two tasks by a flip of a switch. A full schematic may be seen in the diagram below.

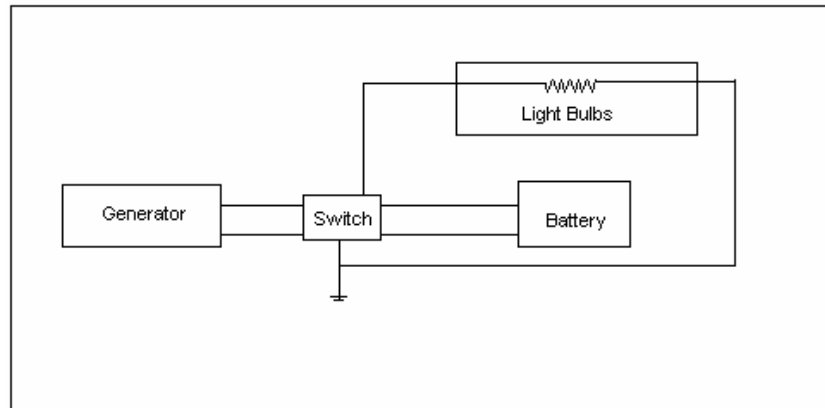


Figure II.VI.d: Electrical Circuit

III. DESIGN PROCESS

The design changed in many ways, large and small, as manufacturing progressed. Some changes were a result of material availability while some were made in an effort to improve the initial design. The following sections will detail the final stages of design and building.

III.I Airfoils

The airfoils were fabricated from extruded polystyrene (EPS) foam. The foam was chosen due to its manufacturability and lightweight properties. The foam could easily and quickly be cut into the airfoil shape with a hotwire. The airfoils would come out smooth and require little to no sanding. The foam was also lightweight, and could be easily be wrapped with carbon fiber fabric for stiffness. The carbon fiber fabric used was a carbon/S-glass weave. This weave is a bit lighter and cheaper than an only carbon weave. The carbon/S-glass weave gave the strength needed without the higher cost. The carbon/S-glass weave was then coated with an epoxy-resin mixture. This gave the airfoils stiffness.

Two 3/16 diameter steel rods run down the center of the airfoils. These rods have two purposes. First, they give the airfoils extra strength, insuring that they will not bend or crack. They also provide a point of attachment: the steel rods are welded to small steel brackets that are bolted to the aluminum arms.

III.II Support structure (aluminum bars, steel shaft, brackets, collars)

The support structure is comprised mainly of aluminum due to its fixture as a lightweight, machinable and low cost material. The design went through many iterations involving various joining techniques until the present solution was achieved. It is easy to assemble, and none of the manufactured parts require intricate machining—although accurately locating through holes was assisted by the CNC machine. Other machining processes included cutting rods and shafts to length as well as welding steel brackets to rods.

One illustration of the evolution of the design was the generator mount. Original designs called for this mount to be a completely separate structure housed 12 to 18” outside the main turbine housing. However, it became apparent the chain and wood could be saved with the construction of a support plate of plexiglass and aluminum brackets. These items were sketched, machined, and assembled within a day. The design process was interesting, as it was heavily weighted towards initial calculations for major components in the early portion of the semester, while in the end of the semester decisions were made based on available materials and time constraints.

III.III Base

Material selection for the base was a relatively quick operation. While metal work was an option (i.e. a fully aluminum or steel base), the cost of wood and ease of working with 2x4's outweighed the convenience of an on-site metal working shop. This decision ultimately proved incredible useful, as a power drill and miter saw were the only power tools required to assemble the three modules. After a learning curve period for carpentry, the team was able to assemble a sturdy, level, and modular base as was called for in the original design.

III.IV Generator System

The generator system changed the most as the design process continued, as the team tried to generate power from a slow moving turbine and overcome the forces of friction and evil.

III.IV.I Circuit Changes

The preliminary designs for the circuit box remained relatively the same. There's a three-pronged switch that connects the generator/motor to light bulbs or the battery, or it can be placed in the off position. One significant change is the addition of a dial so the amount of power supplied to the motor from the battery may be controlled manually. This is so the turbine won't start spinning as fast as possible when it's initially connected to the battery. The dial was added for safety considerations, since rotation can begin at lower speeds which are steadier. The final product may be seen in the picture below.



Figure III.IV.a: Final Circuit Box

III.IV.II Chain-Sprocket System Alterations

In theory, the chain and sprocket systems worked, yet unknown factors posed many problems that forced the original design to be reevaluated. Although ideal for wind turbines, the generator lacked sufficient specifications provided by the manufacturer. As a result start up torque, power curves, torque output curves were missing. After assembling the two chain-sprocket systems, the required start up torque of the generator was great enough to make the turbine stopped spinning. The reason for this was because

when stepping the RPM up nine times, the torque finally generated decreased to a ninth of its original value. This small torque couldn't turn the generator's shaft. To remedy this problem, the sprockets located on the intermediate shaft were completely eliminated and a single chain-sprocket system was created that ran from the main turbine shaft directly to the generator shaft. Figure III.IV.b clarifies this system

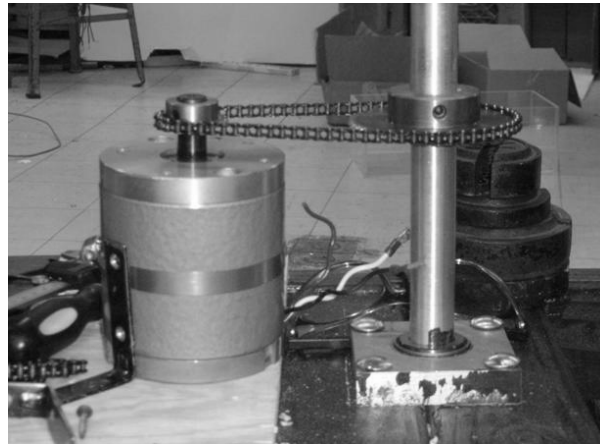


Figure III.IV.b: Actual Chain-Sprocket System

This new system didn't decrease the torque as much and the turbine was able to spin the generator shaft. The new 2.5:1 ratio between the two sprockets, however, wasn't enough to step up the turbine RPM to the minimum RPM the generator needed create a pertinent amount of energy.

III.IV.III Start-up Torque

To further investigate the relationship between torque and gear ratios, an experiment was developed to measure the start-up torque of both the 2.5:1 and 9:1 ratio. A string was tied around the main shaft of the turbine that ran over a pulley. The string was wound several times around the main shaft and then multiple weights were placed on the opposite side of the string. Weights were placed on the end until the turbine just started to spin. Figure III.IV.c will clarify the set up.

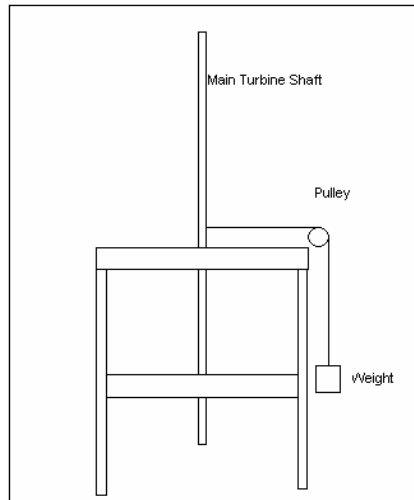


Figure III.IV.c: Start-up Torque set-up

From this experiment, the 9:1 ratio the torque required to start the entire system, chain-sprocket system and generator, was 5.095ft-lbs. With the 2.5:1 ratio system, however, it was 1.095 ft-lbs. From the high force required to start up the 9:1 chain-sprocket system, it's clear that the high ratio decreases the torque significantly.

III.V Assembly

The wind turbine consists of many parts that had to fit together in a variety of ways. Many methods of joining were used. The two halves of the airfoils were glued together using a strong epoxy; the 2x4s of the base were screwed together; the generator is connected to the shaft using chain; the steel brackets were welded to the rods; and the aluminum connectors are attached to the shaft with a bolt and collar system. All of these methods were necessary because so many very different materials were used in construction. In many cases, the difficulties of assembly were foreseen and taken into account in the initial design. For example, the team anticipated trouble connecting foam airfoils directly to aluminum arms and, as a result, designed the airfoils to have metal rods through the center so that they could be connected to the center shaft. Other problems, however, came up in the course of building. For example, until the base was built, it was very hard to solidify exact plans for securing the generator to the base, especially since the location of the generator depended so heavily on the length of the purchased chains and how flexible they proved to be.

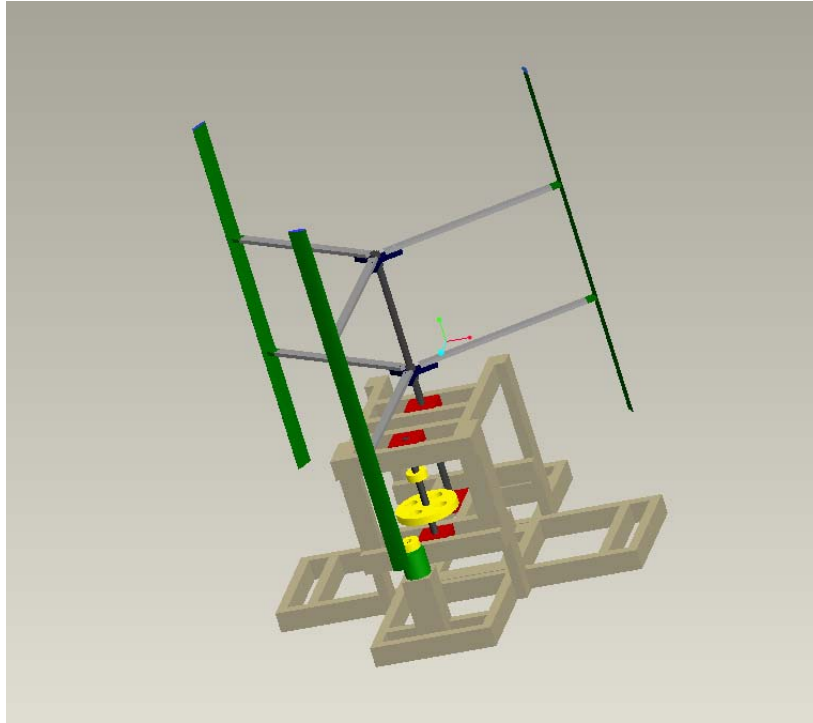


Figure III.V.a: Assembly Drawing

Many decisions on the assembly were influenced by time constraints and the availability of materials. For example, the steel wire that runs between the air foils was chosen because a method of joining them was needed immediately and that wire was in the machine shop. Other decisions were influenced by the material properties required. For example, when unforeseen brackets were required for the top and the bottom of each airfoil, steel was chosen because these brackets had to be welded to the steel rods that run through each airfoil. On the whole, the assembly is solid and safe. No parts of the turbine show signs of shakiness at their connections.

III.VI Packaging and Shipping

The entire system was designed to be able to break down and be reassembled in as little time as possible. The base is made of two wooden constructs that fit interlocking to each other. They crisscross each other, forming a plus-sign shape, which is critical to the stability as it provides a large base. The vertical part of the base is 3 feet in height by 30" in length, it is fairly compact. Inside the vertical base, the generator and batteries are

housed; having this setup serves the purpose to maintain a compact flow. The blades can detach from the main shaft and be transported.

Complete reassembly takes about 20 minutes. Which, considering the size of the system is very fast, one way we could have helped with that is to make the holes connecting the arms to the connecting pieces larger, having holes cut so precisely makes it hard to align, however the connections are tighter than if the holes were larger. The tightness of holes may not be as critical as we originally assumed because it may be counterbalanced by the force of rotation for the blades.

IV. RESULTS

IV.I Testing environment

Ideally the wind turbine would have been tested in a wind tunnel with 6 m/s wind, as this is the average wind speed that the turbine was designed for. However, access to such a wind tunnel was not available. The group did not have access to a car, and so could not transport the turbine to a windy location in the city. There were also no roofs with the appropriate wind speeds that the group had access to. Due to these difficulties, the wind turbine was never tested in the environment which it was designed for.

The turbine was tested in front of a low speed wind tunnel. Unfortunately the wind tunnel used did not generate enough wind to drive the turbine at the rated speed. The wind tunnel gave a small amount of wind, which allowed the team to measure rpm and power with different gear ratios. This testing environment had the advantage of being a controlled location where the wind could be turned on and off. On the other hand, the stream it generated does not accurately reflect natural conditions. The flow was far too focused as can be seen from the wind profile below, which was taken when the wind tunnel was set to 55 Hz. The wind profiles with different settings (40-60 Hz) can be found in Appendix E. The grid represents the total area of our wind turbine that faces the wind. As Figure IV.I.a shows, only a very small portion of that grid is hit by the focused wind from the wind tunnel.

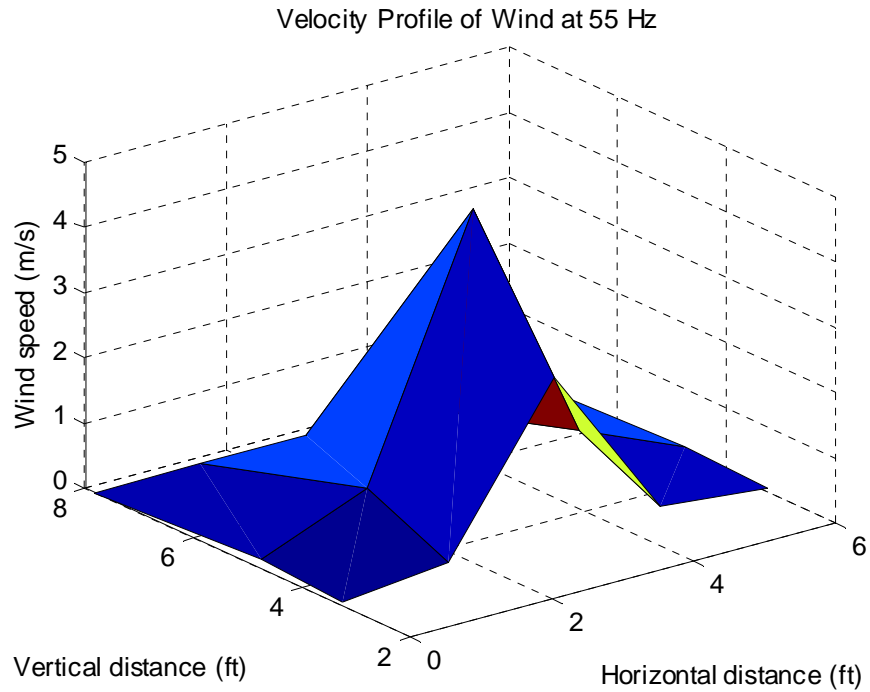


Figure IV.I.a: Sample wind profile

The focused nature of this wind fails to make the best use of the whole area of the wind turbine. The output stays artificially low because only a small section of each airfoil is working. In a fuller velocity profile with higher wind speeds, the wind turbine is expected to work as designed.

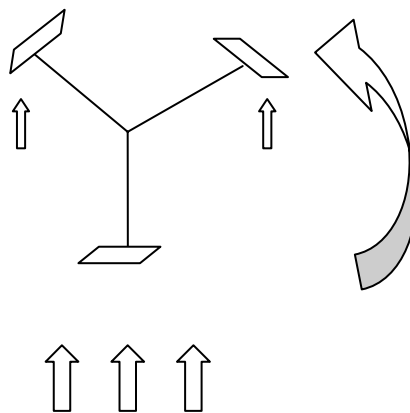


Figure IV.I.a: Wind – Expected Conditions

Because of the limitations of the lab and the positioning of the turbine relative to the wind tunnel, the wind only acted in a counterclockwise direction. This allowed the turbine to produce a small amount of power, but this power was mostly due to drag.

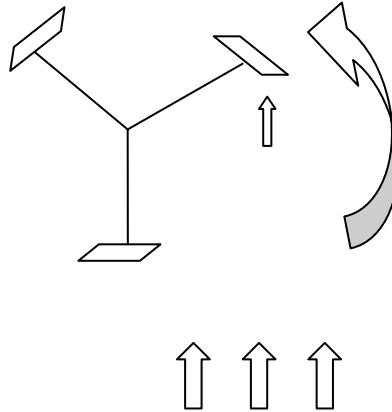


Figure IV.I.b: Wind in Lab Setting

A model of the turbine running in this setting was made in Fluent. The forces acting on the airfoils were found with the assumption of a 6 m/s wind. The actual max wind speed with the wind tunnel at full power was 6.4 m/s. However, this wind speed was only hitting the center of the airfoils; the ends of the airfoils received only a small amount of wind. The forces on each airfoil as they move through the cycle are shown in the table below.

First Airfoil		Second Airfoil		Total
θ_1 (deg)	F_1 (N)	θ_2 (deg)	F_2 (N)	F_{tot} (N)
180	-0.42	300	-0.43	-0.85
190	-0.53	310	-0.53	-1.06
200	-0.62	320	-0.66	-1.27
210	-0.68	330	-0.69	-1.37
220	-0.64	340	-0.61	-1.25
230	-0.55	350	-0.52	-1.07
240	-0.45	0	-0.71	-1.16
250	-0.31			-0.31
260	-0.25			-0.25
270	-0.21			-0.21
280	-0.20	Third Airfoil		-0.20

290	-0.30	θ_3 (deg)	F_3 (N)	-0.30
300	-0.43	180	-0.42	-0.85
310	-0.53	190	-0.53	-1.06
320	-0.66	200	-0.62	-1.27
330	-0.69	210	-0.68	-1.37
340	-0.61	220	-0.64	-1.25
350	-0.52	230	-0.55	-1.07
0	-0.71	240	-0.45	-1.16
			$F_{avg, cycle}$ (N)	-0.91
			V_t (m/s)	3.00
			Power (W)	-2.74

Table IV.Ia: Forces on the airfoils in the 2nd half of a cycle at a speed of 30rpm.

This is a very small amount of power. Working an environment that the turbine was designed for would yield a much higher theoretical power.

IV.II .I. Power output

The results from experiments testing power generation in relation to wind speed show a direct correlation, visible in Appendix IV.II. As the wind speed increased, the power output increased. The maximum wind speed, 60 hertz, produced a power of 0.175W, and as the velocity of the wind was decreased in 5 hertz intervals, the slope of the line was 0.001538.

While connected to the turbine the generator did produce some energy, but minimally. The chart below shows the amount of power produced by the turbine over various resistance loads.

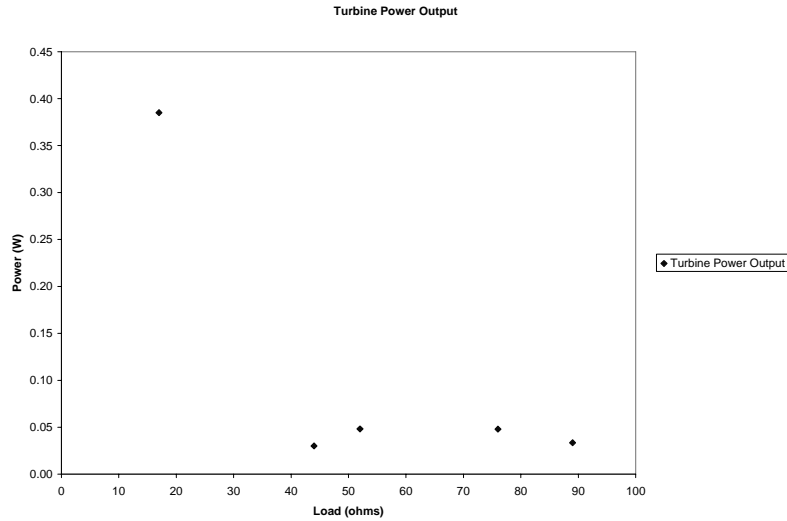


Figure III.IV.d: Turbine Power Output

On average the power produced is .11W. This was calculated by using the power equation:

$$P = IV \quad (Eq. II.IV.a)$$

Where P is power, V is voltage, and I is the amps measured. From this curve the load across the turbine that will generate the most energy may be derived. In this case most of the loads resulted in producing about .05W, yet with a 17Ω load it produced .3W.

To measure the power output with relation to wind speed an anemometer was set up to measure the wind speed, a load of 17 ohms was placed in series with an amp meter and parallel to a volt meter. After starting the wind tunnel at various hertz, amp, and volt measurements were taken after the turbine reached steady-state, when the volt meter remained steady. The following graph summarizes the results.

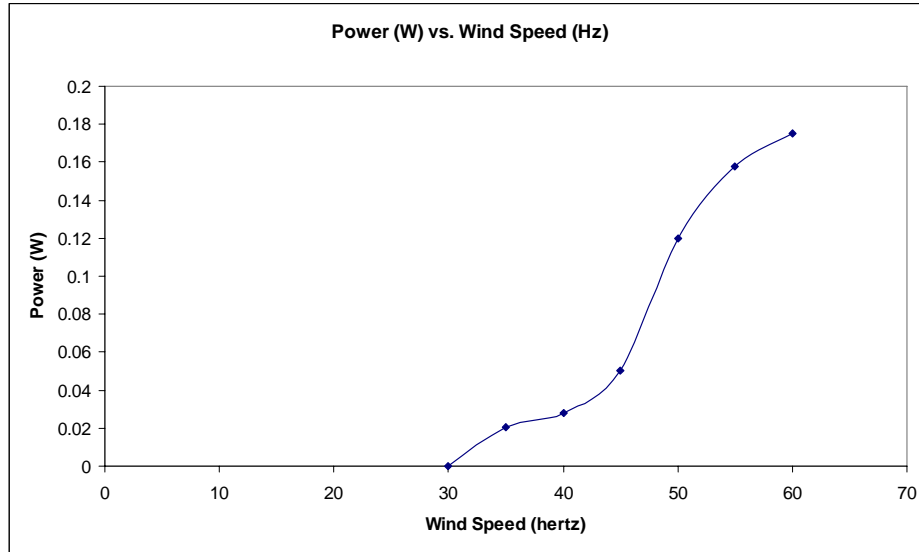


Figure III.IV.e: Power vs. Wind Speed

The results are not unlike those found with the power curves created earlier for the generator. The power output was significantly less because of the low RPM. The shape of this curve was expected when considering the information generated by the generator power curves.

As the turbine is not self-starting, the motor must get it up to the working speed before it can generate power. The ability of the motor to do this was tested in the lab. It was found that the motor was able to get the turbine up to the desired 140 rpm.

IV.III Structural integrity

The turbine was constructed from materials that were analyzed for strength and durability. The base was made from 3.5"x1.5" planks of wood and designed to support the wind turbine, smaller shaft, generator and prevent tipping over. The intention of the wind turbine is to provide power in urban areas; therefore, it would be placed on rooftops, so the structure must be strong enough to prevent tipping and breaking apart. The shaft was chosen for aluminum's stability with torsion and ease to machine. For future experiments, the group would try a hollow steel shaft or a solid aluminum shaft. These two choices theoretically might cause less vibration and bending, especially at higher rotation.

Another critical part of the design was the airfoils, designed from foam covered in carbon fiber and epoxy. The airfoil design that was used was calculated to produce the highest values for the turbine design. The arms that connect the airfoils to the shaft are hollow rectangular tubes. These tubes provide much more stability than a flat piece of aluminum of the same thickness. There is a minimal resistance produced by the tube but this is compensated by the reduction in vibration in the arms. Thin steel rods connect the airfoils to the arms; these rods are flexible but are still able to provide a firm backbone to the airfoils.

The connectors of that hold the arms to the shaft are made of aluminum with a thickness of 0.3", although these could be thinner, this thickness maintains stability against the forces pulling the arms outward and keeps them at 90 degrees from the shaft as the turbine spins. A thinner connector could be subject to bending and may not keep the arms up at the correct angle.

Bearings were selected based on size, type, maximum dynamic load and maximum revolutions per minute. Having a high maximum rpm meant that the shaft would be able to rotate with any given wind speed. A large dynamic load prevents the bearing from stalling, allowing the shaft to glide with ease over the bearing.

IV.IV Sources of error and limitations

Several areas of error may be found in the power generation and conversion section. The sprockets were mostly aligned by looking at them, an occasionally using a level. even with the level the sprockets weren't perfectly aligned, but more approximated. Error may also be found in the bending of the shafts the sprockets were mounted on. In order to ensure tension in the chain they were pulled tight with caused the shafts to deflect. Many of these small imperfections in the system create many sources of error.

There are also sources of error in the airfoils which could have reduced the power output. First, the simulations run in Fluent assumed smooth airfoils, with a perfect NACA 63-015 shape. The actual airfoils are not completely smooth. They have imperfections on the surface which could change the nature of the airflow, and thus the forces acting on them. The NACA 63-015 airfoils were designed to reduce turbulence. However, the imperfections in the airfoils could increase the amount of turbulence

encountered near the trailing edge of the airfoil. This would increase drag and reduce the net force in the direction of motion.

In addition to structural limitations, the group was limited by their inability to obtain an anemometer until the last minute. Wind data was taken for the wind tunnel but due to time constraints, few points could be taken at each wind speed. This resulted in wind profiles that might not fully express the exact behavior of the environment. In addition, because this wind data was obtained so late, the group did not realize what a faulty test environment they were working in until it was too late to find an alternate location. It is clear from the wind profiles that only a small fraction of the wind was hitting the airfoils at any one time which partly explains why it was so difficult for the turbine to maintain rotation.

IV.V Cost Analysis

The group was given a budget of \$500. As it stands the group has used \$393.83. One of the larger purchases, the generator, was purchased through Ebay, which enabled us to save over \$100; however, the drawback to this was that we did not have specifications on the performance of the generator. To compensate, the group conducted experiments to test the output of the generator and construct a chart of values. The turbine is assembled from inexpensive parts and several parts the group constructed. There are a total of 27 off the shelf parts purchased by the group. A large number of materials were salvaged from the machine shop and the wood for the base was donated. The nuts, bolts, screws, metals for the arms, collars and connectors, attachments for the generator were all taken from the machine shop. The group manufactured the airfoils, brackets, collars, connectors, arms, pillow blocks for the tapered roller and small collar bearings, and the base.

As a marketable product, the return on power would payback for the cost of the machine. If used in New York, the turbine could drastically reduce the cost of electricity for homeowners. Con Edison customers could pay \$10 - \$20 per month for wind power supplied by Sterling Planet. Each month Con Edison customers pay \$12.38 for the first three therms and 54.38 cents per therm thereafter. The average house uses 300 kilowatts per month. Using the wind turbine to offset these costs could result in savings of

hundreds of dollars over time. If the wind turbine was developed further, the power output would increase greatly. This machine has significant potential to be a successful tool in the movement towards more green power usage in New York City. Being inexpensive, easy to assemble and highly efficient, this product is a promising future investment. A full analysis of cost can be found in Appendix F.

V. Ethics

The group upheld the Code of Ethics as outlined by the National Society of Professional Engineers. The Vertical Axis Wind Turbine (VAWT) was designed to be structurally sound and safe for use in compliance with instructions. The group designed the VAWT with a large base for stability and used outside sources for advice and confirmation of procedure. Being students of Mechanical Engineering, the group members are not experts in all aspects of necessary for this project, outside assistance on certain parts was required. These areas included testing for the generator and developing the control system.

One of the most important aspects to our project is the environmental aspect. Wind power a clean, reusable resource for energy. Harnessing this power is a very good way to protect the environment by reducing the amount of fossil fuels used and therefore a reduction in the amount of pollution released into the atmosphere. Being able to produce a successful and efficient wind turbine was critical to the group design.

VI. CONCLUSION

As stated, the main goals of this project were twofold: to design and construct a wind turbine that can operate in an urban environment as well as giving the engineers the opportunity to complete a full design exercise.

In this second context, the project can be seen as a success. The design team has earned invaluable experience in the practices of Mechanical Engineering and have developed the abilities to perform analysis, design, refine, and construct a viable mechanical operation.

However, the project cannot be described as a complete success, as measured power output was nowhere near a level viable for commercial development. The theory,

design, and construction of the machine are in alignment with high performance at high RPMs, yet no stable testing environment was found. It is likely that the turbine will perform to its expected capacity (60W). It is important to emphasize the successfully designed, constructed and tested components of the turbine:

- The turbine is stable at battery induced RPMs up to 150.
- The bearings, shaft, and support components have held stable in all tests
- The “Modular” base is designed to be semi-portable, and this qualitative concept was achieved.
- The power transmission system has been used at varying gear ratios to deliver energy to and from the blades and generator.

The team considers the semester a success, and would look forward to the opportunity to refine the design and the construction of the turbine with added time and resources.

VII. ACKNOWLEDGEMENTS

We’d like to thank Bob Stark, Walter Khan, and Professor Stolfi for there relentless aid throughout the semester. Additionally we’d like to thank Wade McGillis for assisting us with data collection and Green Isle Contracting for their generous donation of lumber.

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