Session VC 1

DESIGN OF A PORTABLE WINDMILL

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Abstract

The paper presents the development of conceptual alternate designs and working design of a portable windmill that can be used to supply electrical power in remote locations, such as camping areas where large gas or diesel-powered generators are not feasible because of shipping costs, or an increasing number of fire bans instituted during dry seasons. Campers and hunters affected by fire bans need a portable power supply to provide lighting, heating, and cooking. Data was collected on wind speed, power requirement, and shipping space available in most car trunks. The collected wind data, power requirements, and shipping limitations were reviewed, and design specifications were developed for the design of a portable windmill. Two alternate conceptual designs were developed for the windmill. The two designs were reviewed for manufacturing and cost considerations. One of the two concepts was selected for development into a working design of the windmill and its components. Synthesis, analysis, and working drawings, that include assembly and detail drawings of components, were developed for the selected design concept. Designs for windmill components such as: blade, hub, gearbox, shafts, tail fin, and frame, etc. were developed. Standard components were used in the design of the windmill wherever it was possible. Capabilities of the proven CAD program, Pro/ENGINEER, and FEA program, ANSYS, were used in designing the windmill components. Finite element analysis results and working drawings of the intricate mechanical components of the windmill are provided in this paper.

Introduction

The purpose of this project is to design a portable windmill to supply electrical power in remote locations. The need for a portable power supply arises from the increasing number of fire bans instituted during dry seasons, and sometimes permanently in some camping areas. Campers and hunters affected by the fire ban need a portable power supply to provide lighting, heating, and cooking. The portable windmill would also replace gas or diesel powered generators in situations where only a little power is needed and the operating costs would be too high because transportation of supplies would be difficult. The design of the windmill consists of three different sections: data collection and specifications; conceptual design; and working design.

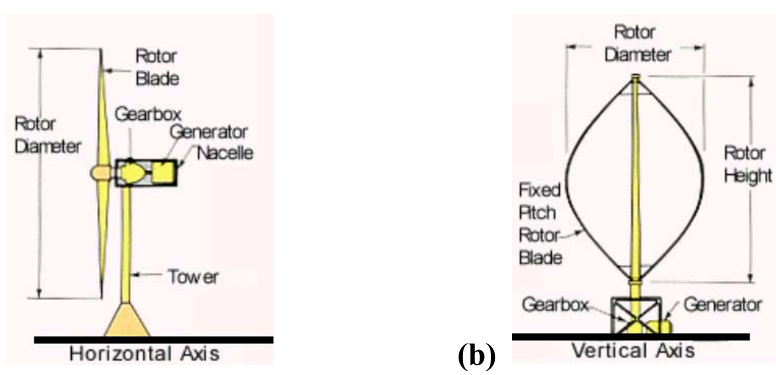
Data Collection and Specifications

Design specifications are a response to the output requirements needed and operating conditions encountered while the unit is in use. In order to produce the design specifications some information was collected. It was found, for example, that the approximate trunk space in a family car was around 15 ft^3. This information helps set the standard for the total volume the windmill may take up while broken down. The specification for wind speed comes from the Beaufort Scale for wind speed, where it gives descriptions of what different wind speeds do to there surroundings. These descriptions were used define the wind speed required to obtain the vital power output. The design specifications for this project are as follows:

- **Power Output:** 1.34 Hp @ 25mph, 12-48 volts, DC
- **Max Weight:** 75 lbs.
- **Working Dimension:** 12′ x 12′ x 20′ (L x W x H)
- **Shipping Space:** 6′ x 2′ x 1′
- **Wind Speed:** 5 to 40 mph

Conceptual Designs

The two conceptual designs considered for development were the vertical-axis windmill turbine (VAWT) and horizontal-axis windmill turbine (HAWT) shown below in Figure 1.



(a) (b)

Figure 1 Conceptual Designs

The VAWT benefits from the fact that it does not matter whether it is upwind or downwind, however the design has very poor efficiency, needs to be started, and is rather slow for electricity production. The HAWT has a higher overall efficiency and can operate with a slower wind speed than the VAWT. However, the HAWT requires a tail fin to direct the rotor and blades into the wind so that it will capture the wind effectively. The HAWT was chosen for the development of a working design due to the reduced efficiency of a VAWT, and the problem of harmonics.[1] A conceptual diagram of the HAWT is shown in figure 2 below.

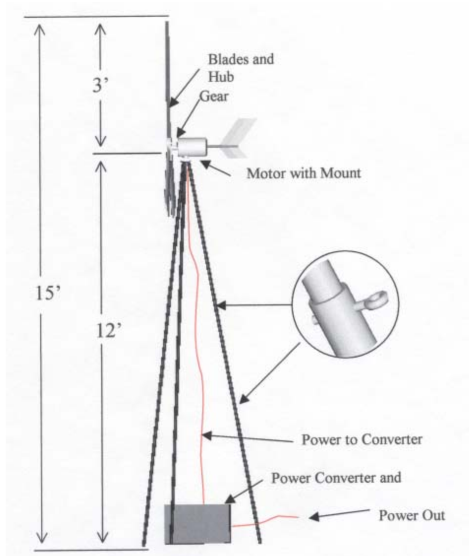


Figure 2 Conceptual Diagram of HAWT

Working Design

The working design will utilize the flowchart shown in Figure 3 below as a guide through the design process.

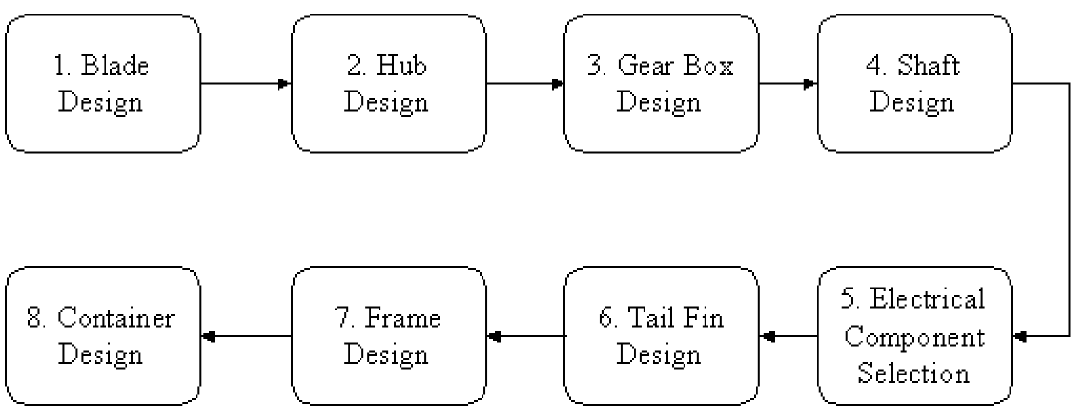


Figure 3 Design Sequence of Windmill

The initial step to the working design was to design the blade to meet the power requirements for the portable windmill. The length of the blade was determined by deriving the power from the wind and using approximate efficiencies for the rotor, generator and gears.[2] The blade length was chosen to be 5-ft which will achieve 1.34 hp at 19 mph. The blade profile chosen was the NACA 4412.[3] The NACA 4412 profile is commonly used for windmill applications. The chord length was determined by equating the thrust force to the lift forces while neglecting drag. The chord length was determined by plotting chord width as a function of blade length. The actual chord lengths are summarized in Table 1.

Table 1 Chord Length

Radius, r (in)	Chord Length, C (ft)
0	9
15	8
30	7
45	6
60	5

The angle of attack was chosen to give the maximum lift and minimal drag. The angle of attack was determined to be 5º.[4]

The next step was to design a hub to attach all the blades to a common shaft. The hub was designed to fit a blade with a chord length of 9 inches at the root. The hub was designed with two plates instead of a solid plate to minimize the weight. The hub base is equipped with a shoulder to house the shaft with a key. The hub cap is a flat plate bolted to the hub base to secure the blades. The material selection for the blade frame and hub was based primarily on weight. The blade will consist of a molded frame wrapped with an aircraft fabric. Aluminum 6061 T6 was chosen as the material due to its lightweight and strength.[5] The blade is covered with Air Tech Fabric Cover Kit™, which consists of primer/filler/UV barrier, surface tape, and polyester fabric.[6]

The finite element analysis program ANSYS 5.6™ was used to analyze the stresses of the blade connecting tab and the bolt connections for a single blade.[7] The blade was modeled using SHELL63 with distributions of real constants that approximate the blade profiles. The lift force was modeled as a pressure over the top of the blade. The drag force was modeled as a distributed force along the leading edge of the blade. The centrifugal force was modeled as a force acting on the tip of the blade. The blade-connecting tab was constrained in the x and y-direction at the bolt holes. The planar surface of the blade-connecting tab was constrained in the z-direction. The resulting factor of safety based on von Mises stress was found to be 3.1, and is shown in Figure 4 below.

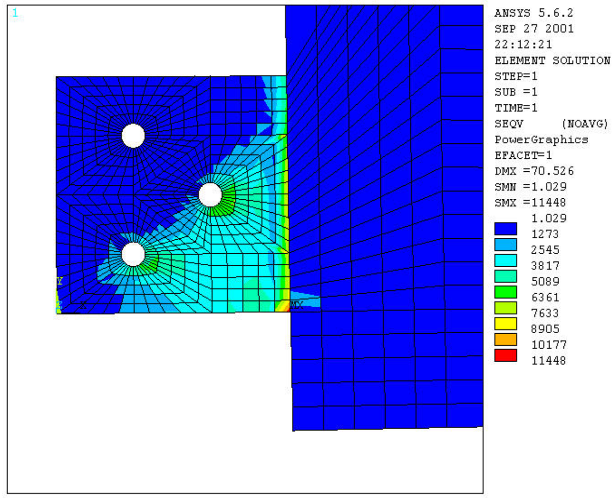


Figure 4 FEA approximation of Blade Root

The next step was to select the generator and gearbox. The generator needed to meet the required power specifications and operate at low RPMs (<4500RPM). The low RPM requirement was to keep the size and weight of the gearbox to a minimum. The gearbox ratio selection was to be between 1:2 and 1:7 to match the generator RPM. The generator and gearbox needed to be lightweight and compact in size to keep the overall design portable.

The generator chosen was a PMG 600 from Windmission of Denmark.[8] The generator meets the power specifications and is lightweight and compact. The gearbox was sized to match the selected generator using the input RPM, power input from the wind and power output from the generator. The gearbox selected was a 1:3 speed increaser from Stock Drive Products/Sterling Instrument™.[9] With the above specifications for the windmill, a simulated power curve was generated. The electrical power to wind speed can be seen in Figure 5.

Figure 5 Simulated Windmill Power Curve

The next step was to size the shafts provided by the gearbox and the generator manufacturers to fit the windmill design. The minimum input shaft diameter (gearbox) was found to be 0.6 inches using the maximum shear stress theory.[10] Applying a factor of safety of 2.5, the diameter was found to be 0.8 inches. The nominal input shaft size was chosen to be 1 inch giving a factor of safety of 4.9. The key for the input shaft was sized to be 1/4″ x 1/4″ x 1″. The minimum output shaft diameter (gearbox) and input shaft diameter (generator) was found to be 0.4 inches using the maximum shear stress theory. Applying a factor of safety of 2.5, the diameter was found to be 0.6 inches. A nominal input shaft size was chosen to be 3/4 inch giving a factor of safety of 6.0. The key for both shafts was sized to be 3/16″ x 3/16″ x 1 1/4″.

The output shaft of the gearbox and input shaft of the generator are to be connected by a rigid coupling supplied by McMaster-Carr Supply Company®.[11] The coupling will have:

- Bore Diameter (BD) = 0.75″
- Outside Diameter (OD) = 1.5 ″
- Overall Length (OL) = 2.25 ″

This coupling can handle up to 3200 in-lbf. The sleeve will be held in place with two setscrews.

The assembly of the gearbox and generator are to be connected and supported using a pivot. The pivot will consist of a hollow body, two flange mounts and a tubular connection for mounting of the frame. A drawing of the pivot may be seen in Figure 6 below.

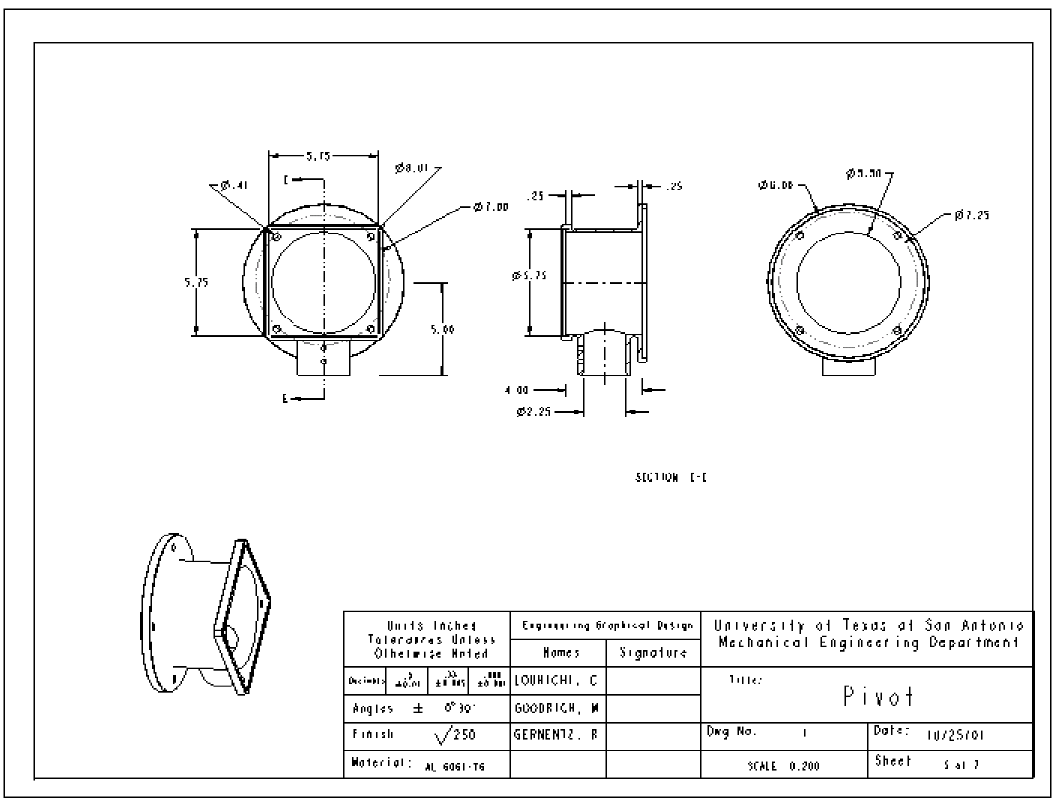


Figure 6 Pivot Drawing

The next step was to design a frame to allow the windmill assembly to rotate freely with respect to the frame and the ground. The tripod was the frame chosen for this application. The tripod will allow for portability as well as stability. The tripod is to have an upper support pole to allow for clearance of the blades. The upper support pole needs to be at least 6 feet in length to provide proper clearance of the blade with respect to the frame. The frame is to be at least 7 feet high to allow for blade clearance with respect to the ground to prevent injuries to people.

The dimensions for the upper support pole were calculated and found to be:

- Inner Diameter (ID) = 2.50″
- Outer Diameter (OD) = 2.75″
- Thickness (t) = 0.125″
- Length (l) = 6′

A bushing assembly was developed to attach the upper support pole to the pivot. The bushing chosen for the bushing assembly was an Aluminum-Backed Frelon Flanged Bearing from McMaster-Carr. The bushing is retained on the bushing assembly with a snap ring. The bushing is also attached to the pivot with a pair of setscrews. This allows the pivot to rotate freely about the bushing assembly. An assembly drawing of the pivot assembly is shown in Figure 7, which demonstrates how the busing and insert interface with the pivot.

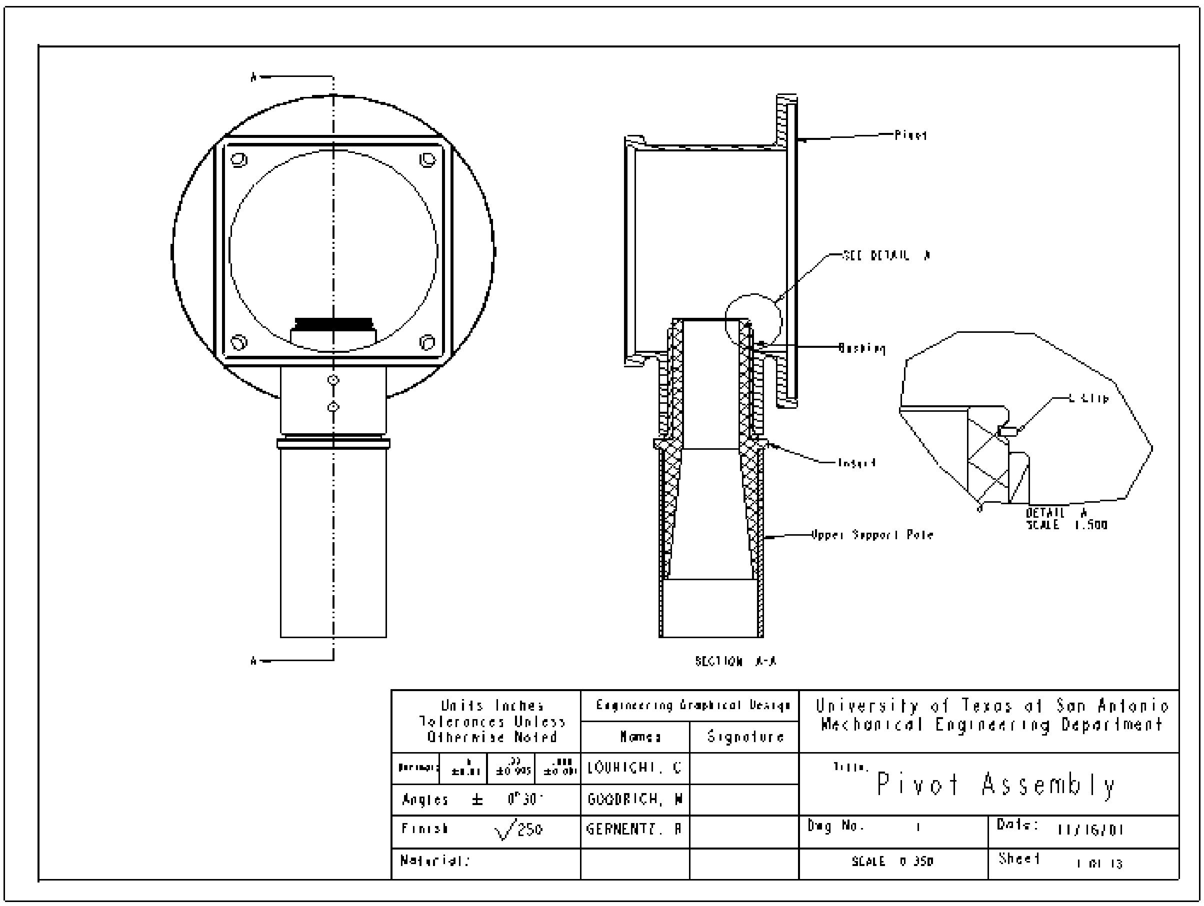


Figure 7 Bushing Assembly

The next step was to attach the upper support pole to the tripod. This was to be done with a main support assembly. The main support assembly was designed in PRO/Engineer 2000i[2] and was analyzed with ANSYS 5.7 using solid 45 elements.[13, 14] Symmetry was used in order to simplify the model and reduce the number of elements. In order to use symmetry, one must satisfy two conditions. The first condition is that the model must be geometrically symmetric. The second condition is that the load also must be symmetric. For this tripod model there is a plane of geometric symmetry every 60 degrees when looking at the tripod from the top view. In order to use this symmetry however the load must also be symmetric about this plane. To do this the moment due to the axial wind force on the blades must be orientated so that the axis of rotation is perpendicular to the plane of geometric symmetry. This observation simplifies the model greatly and also aligns the greatest forces along the weakest points on the main support giving the analysis a conservative conclusion. The factor of safety for the main support was found to be 2.8 using Von Mises stress theory. The ANSYS plots are shown in figure 8 below.

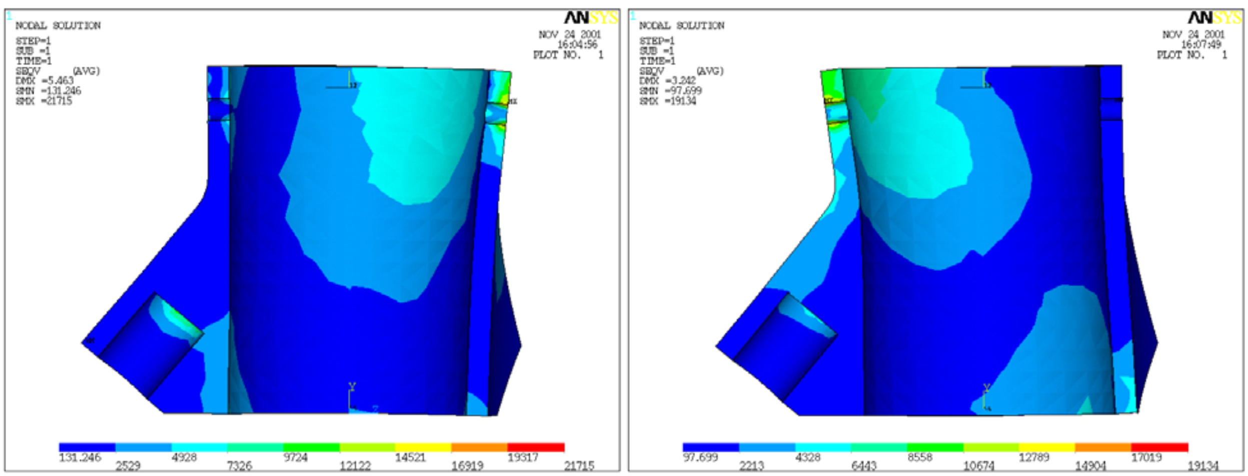


Figure 8 Main Support FEA Both Loading Scenarios.

As shown in the figure above there is a spot for a shear pin to be used to support the upper support pole and keep it from falling through the main support. The minimum diameter for the shear pin using stainless steel was found to be 0.07 inches with a factor of safety of 2.5. The pin chosen was a quick release self-locking pin from McMaster-Carr.

The tripod legs were chosen to be 40° from vertical to achieve a small working area. To attain a 7-foot clearance the legs were chosen to be 9′-1/4″. The dimensions for the tripod legs were calculated and found to be: [15]

- Inner diameter (ID) = 0.625″
- Outer diameter (OD) = 0.75″
- Thickness (t) = 0.0625″
- Length (l) = 9′ ¼″

The tripod legs are to be manufactured from two separate segments so that they may be stored within the specifications given. A solid coupling and two pins will connect the two segments together. Once again a quick release self-locking pin from McMaster-Carr will join the legs to both the main support and to the coupling. The legs of the tripod are equipped with a base to prevent penetration into the soil. The base has a hole, which is to be used with a stake to hold the frame in place during high winds. The stake must be inserted into the soil at a 90-degree angle with respect to the tripod leg. The stake size will vary depending on the condition of the soil.

The next step was to design a tail fin to keep the windmill facing the wind in order to provide the maximum output. The tail fin will consist of two separate pieces. The minimum area for one side of the tail fin was found to be 3 ft.[2]

The wiring from the generator to the ground will make use of a slip ring inserted into the upper support pole. The slip ring will allow for the rotation of the generator about the frame without twisting the wiring. The slip ring will be provided by The Pandect Group.[16]

Conclusion

The final design of the portable windmill consists of a rotor with three blades equally spaced around a hub. Each blade is five foot long, utilizes the NACA profile 4412, a 5º angle of attack, and a chord length varying linearly from 9 in at the root to 5 in at the tip. The finite element analysis on the blade root shows that the connecting tab is properly sized to handle the forces acting on the blade. This is based on a factor of safety of 3.1 using the Von Mises stress criteria.

The generation section of the windmill utilizes the PMG 600, provided by Windmission of Denmark. This generator is capable of providing the power needed at low RPM's. The gearbox is a 1:3 speed increaser provided by Stock Drive Products/Sterling Instrument™. The gearbox and the PMG 600 are both lightweight and compact in size, which is a very important factor in this portable windmill design.

The windmill frame consists of a tripod with an upper support pole, bushing assembly and main support. Each tripod leg will consist of two equal segments with a length of 54 inches. A coupling will be used to connect both segments and will add a length of ¼″. This gives a combined length of 9′ ¼″ for the tripod leg. With an angle of 40° from vertical for a 9′ ¼″ leg will give a clearance of 7 feet. The legs will be equally spaced 120° apart. The upper support pole will have a length of 6 feet to provide proper clearance of the blades for safety purposes. A main assembly will be provided to connect the upper support pole to the tripod legs. This main support is the weakest link in the frame because of the magnitude of the moment that it must withstand. However the main support has a factor of safety of 2.8 at a 40 mph. A bushing assembly located between the upper support pole and the power generating assembly will allow the power generating assembly to rotate freely about the upper support pole. A tail fin will be provided to assure the windmill will be facing the wind for maximum power output.

The final weight of the windmill is 73.9 lbm. The overall working dimension is 12′ x 12′ x 20′ and the storage space is 6′ x 2′ x 1′. The windmill design will provide 1.4 hp at a wind speed of 24 mph.

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