Optimization of a Savonius Rotor Vertical-Axis Wind Turbine for Use in Water Pumping Systems in Rural Honduras

by

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Abstract

The D-lab Honduras team designed and constructed a wind-powered water pump in rural Honduras during IAP 2007. Currently, the system does not work under its own power and water must be pumped by hand. This thesis seeks to explore a variety of mechanism and aerodynamic changes to allow the system to function as designed. The novel modifications to the Savonius rotor that were made do not seem to improve its performance. Within the constraints of the installed components, the current rotor should perform well pending other changes. The most promising improvements to the system are weight reducing and friction reducing measures, and in combination with understanding the wind conditions in the immediate vicinity of the rotor, changes will be made this summer so that unassisted wind pumping will be possible.

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1. Introduction

1.1. Background

During the January 2007 IAP semester, the author as part of the D-Lab Honduras team constructed a wind-powered water pumping system with the members of the Nuevo Paraiso Enterprise in the rural village of Guadalupe Carney, Honduras. The system to supply water to livestock, seen in fig. 1, combines a two stage Savonius vertical-axis windmill with a rope and washer pump to retrieve water from an existing well. Construction was done almost exclusively from materials purchased locally with the help of local technicians, machinists, and farmers.

Figure 1: Two views of the wind-powered water pumping system installed on the property of the Nuevo Paraiso Enterprise in Guadalupe Carney, Honduras.

Although more efficient rotor designs exist, the Savonius rotor was chosen for this application because it accepts winds from any direction and because it can be easily constructed from widely available materials, namely 55 gallon oil drums, plywood, nuts and bolts, and plumbing pipe. The major technical challenge associated with the system was integrating a windmill with a vertical axis of rotation with a rope and washer pump that requires a horizontal axis. An automotive rear differential was used to change the direction of the rotational axis by 90 degrees. The rope pump component of the system works well and pumping water by hand is easy. Even so, the rotor does not currently drive the system. Since the goal of the project was to provide low maintenance, automatic wind pumping and since much of the cost of the system was due to the wind-power components, the author hopes to explore a variety of improvements throughout the system that will allow the rotor to power the pump on its own.

1.1.1. Community

The village of Guadalupe Carney, also known as the Movimiento Campesino del Aguán or MCA, was founded by landless peasants in the aftermath of Hurricane Mitch. The hurricane devastated Honduras in 1998, leaving more than 20% of the country's population homeless, almost 1.5 million people total (NCDC, 2006). Peasants from across the country moved to the unoccupied land that became Guadalupe Carney after the hurricane in order to start their lives over. Following violent clashes with wealth landowners, residents of the MCA secured land rights to their area of the Aguán River valley formerly owned by the Honduran military. They have set up about 40 diverse collective businesses called enterprises, including a diary, jewelry making, orange blossom wine production and bottling, and various agricultural pursuits. Each enterprise consists of ten to twenty families who work together on common business goals.

In Honduras, the D-Lab team worked with the Fundación San Alonso Rodríguez (FSAR), a technology based non-governmental organization (NGO) located in the city of Tocoa, about a 45 minute drive from the MCA. The FSAR has undertaken extensive water and sanitation programs together with MCA residents and is well respected in the community. They have helped supply chlorinated drinking water from more pure mountain sources, but electricity is only available to the wealthiest members of the community due to the cost and bureaucratic hurdles involved. The director of the FSAR suggested working with the Nuevo Paraiso Enterprise to build a wind-powered water pump for supplying water to the enterprises approximately forty head of cattle. Members of Nuevo Paraiso live in the village, but own a property a several kilometers away and walk or ride bicycles to the property every day. While grass grows over several acres of the property, the cattle graze in a small area near a creek where they have access to water. A working wind-powered water pump would allow the farmers to distribute water to more of their property and therefore use the grazing land more efficiently.

1.1.2. Rope and Washer Pump

Waters pumps are generally categorized as either lift pumps or suction pumps. Impeller based pumps, like many mechanized rotary pumps, and piston pumps, like the classic farm style hand pump, are both types of suction pumps. The rope and washer pump, seen in fig. 2, is a style of lift pump. The Archimedes screw and rope and bucket also employ lift methods. For a suction pump to work, the pump element, either the impeller or piston, has to be submerged in water. When a suction pump is run dry, it usually cannot overcome the compressibility or greater leak rate of air in the system. Additionally, running an impeller pump dry can damage it because the pump spins too fast without the resistance normally provided by water. Therefore, suction pumps usually have to be primed, being filled with water before operating. The rope and washer pump is appropriate for use at the MCA site in Honduras because there was an existing well, the construction methods are simple, the materials are available in the city nearby, and the concepts behind its operation are easily understood by watching it work. Additionally, rope pumps are a familiar technology in Central America having been successfully disseminated in Nicaragua. Lift pumps always have a working pump element under the water's surface giving the advantage that they do not need to be primed. This is ideal for a wind powered pump since winds are intermittent and a pump that needs to be primed would run dry and stop working.

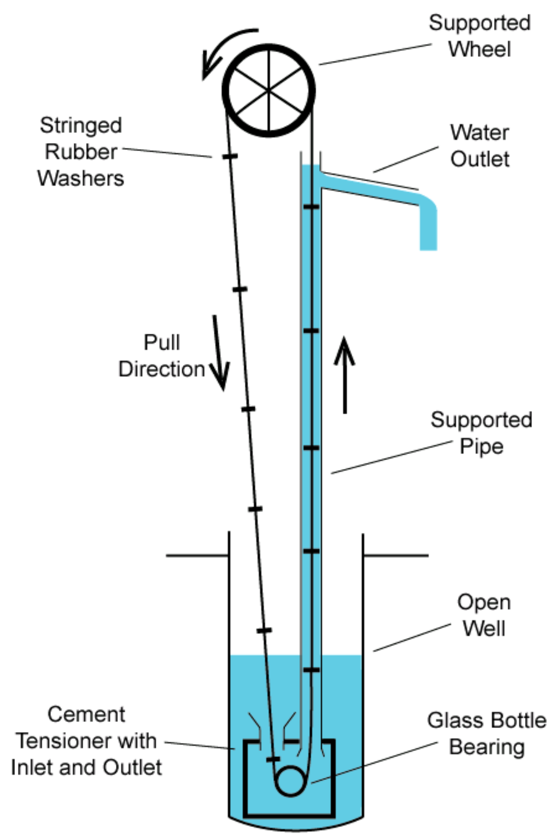


Figure 2: A rope and washer pump lifts a cylindrical column of water by pulling rubber washers down into a well and up through a section of pipe.

A rope and washer pump consists of five basic elements, the rope, the washers, a wheel, piping, and a guide. Washers are threaded at evenly spaced intervals onto the rope with knots tied on each side of the washers secure them in place. The rope with washers is placed through the pipe and attached guide. The guide is lowered into a well and the ends of the rope are tied together after the rope is looped over a wheel. Turning the wheel pulls the rope and washers through the pipe lifting a cylinder of water up to the top of the pipe. The water then flows out an outlet pipe.

The thickness of the rubber washers is small relative to their spacing on the rope. Therefore, the flow of water out of the rope pump is roughly constant. Ignoring the volume occupied by the rope, the overall flow rate of the pump depends on the inner diameter of the pipe, d, the radius of the wheel, R, and the rotational speed in rad/s, ω. The rope travels through the pipe at constant velocity, v, where,

$$v = 2\pi R\omega \, . \tag{1}$$

Assuming no leak conditions, multiplying the velocity of the washers through the pipe, v, by the cross-sectional area of the pipe, A, where

$$A = \pi\left(\frac{d}{2}\right)^2, \qquad (2)$$

yields the volumetric flow rate of water through the pump,

$$m = \frac{\pi^2}{2} d^2 \cdot R \cdot \omega \cdot \qquad (3)$$

To approximate the leak rate, requires knowing the gap size, x, between the washers and the pipe and calculating the combined contributions of Couette flow and Poiseuille flow. Couette flow is an upward drag based flow due to the side of the washer acting as a moving wall and the pipe as a stationary wall with a viscous fluid between. Poiseuille flow is pressure based flow in a viscous fluid between two stationary walls, and in the rope pump, Poiseuille flow would act downwards with gravity. Calculating leak rates is important where tolerances between the washers and pipe walls are loose. The no leak condition, however, is a good approximation of the flow rate of the system installed in Honduras since the gap between the rubber washers and the pipe wall is small.

The total force to pull the rope, F_{pull}, consists of three major components, the force of friction, the force of viscous shear in the water, and the force of gravity against the column of water in the pipe.

$$F_{pull} = F_{friction} + F_{shear} + F_{gravity} \qquad (4)$$

In the installed system, friction is the largest component. Gravity contributes more as the pumping height increases and diameter of the pipe increases because the mass of the water column being pumped is much larger. The power, P, to run the rope pump is equal to the force to pull the rope multiplied by the velocity at which it is pulled, yielding,

$$P = F_{pull} \cdot v \,. \qquad (5)$$

In this application, the force to pull the rope will be provided by the Savonius rotor or by hand when there is not enough wind.

1.1.3. Savonius Rotor

The Savonius rotor is a vertical axis wind turbine (VAWT) developed in the 1920's by a Finnish engineer, Captain S.I. Savonius. As seen in fig. 3, the Savonius rotor consists of two hollow, half cylinders displaced from each other. Commonly the two halves overlap by about one third of their diameters. The Savonius rotor can be constructed from simple materials using common tools. The system installed by the D-Lab team uses a rotor made from plywood, oil drums cut into two halves, nuts and bolts, and steel tubing and sheet which were made into flanges to attach the rotor to a shaft. Savonius rotors are robust and do not require precision machining or tight tolerances like those needed to make modern airfoils. Explaining an airfoil and teaching someone how to make one is also much more difficult than explaining a Savonius rotor. Relying on modern rotor designs would impede the spread of wind power in rural settings.

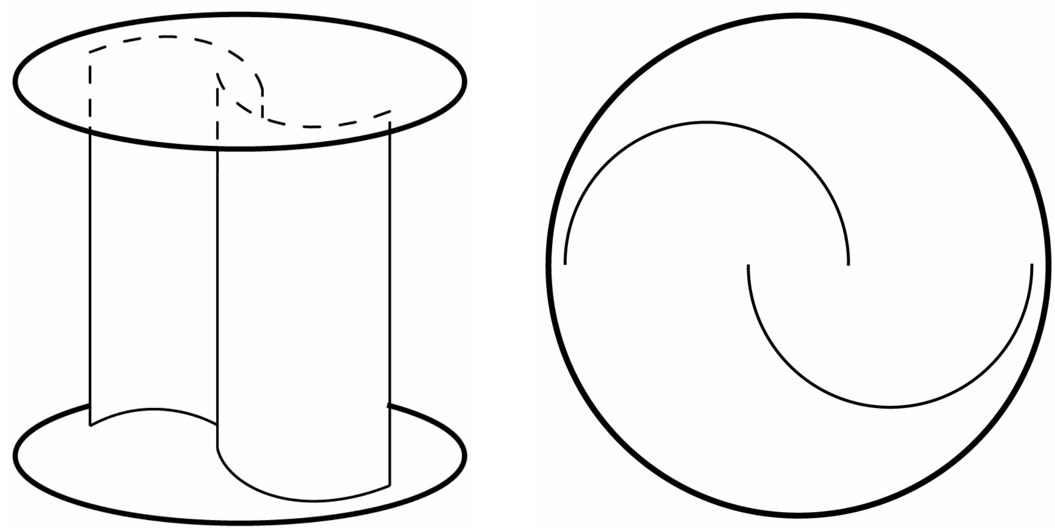


Figure 3: Savonius Rotor shown in diametric projection and top view. Separation between the two half cylinder blades allows for airflow through the rotor that creates lift.

When turning, the Savonius rotor presents the wind with a concave and a convex section, and derives most of its power from drag. The drag coefficient for a flow perpendicular to the convex face of a half pipe is 1.2, while the drag coefficient for the concave section is nearly twice as high at 2.3 (White 2003). Therefore, the force on the concave side of the rotor is higher, inducing a torque that turns the rotor. In addition to the torque due to drag, flow through the gap between the two rotor blades causes lift with thrust out the back face of the rotor helping it turn in the desired direction. Drag based rotors generally have high starting torque but lower efficiency when compared to modern lift based rotors (Wortman 1983). Rotors of different sizes can be compared by determining the non-dimensional parameter of the torque coefficient, C_T, the power coefficient, C_P, and the wind speed to tip speed ratio, μ. For the Savonius rotor,

$$C_T = \frac{T}{\frac{1}{2}\rho V^2 S d}, \qquad C_P = \frac{P}{\frac{1}{2}\rho V^3 s}, \text{ and } \qquad \mu = \frac{\pi d}{60}\frac{N}{V}.$$

Due to symmetry to with respect to the flow direction, vertical axis wind turbines accept winds from any direction equally. This contrasts with horizontal axis wind turbines (HAWT) that must face into the wind to achieve maximum power. Often, in low tech solutions, HAWT's are pointed in a fixed direction to take advantage of a single predominant wind direction. When winds change directions, a fixed HAWT does not run efficiently. In more advanced applications, the nacelle, or head, of a horizontal axis turbine rotates at the neck if the direction of the wind changes adding an additional layer of mechanical complexity.

1.2. Objectives

The overall goal of this thesis is to take an existing system, the wind-powered water pump constructed by the D-Lab Honduras team last January, and improve its performance. The team was in Honduras for four weeks, but finished construction of the windmill with only three days left in the trip. Those last days in Honduras were not very windy and the pump did not turn on its own. The rotor turned at 70RPM to 100RPM with a large amount of torque on one windy day during the trip after the tower was raised and the rotor mounted, but before the pump was connected. At this date, our understanding is that the rotor has not self started in the four months since the team left Honduras.

This thesis seeks to explore the wind-powered water pump as a whole. Understanding the rotor, the pump, the distribution system, the bearing surfaces, and the environment surrounding the system will help in making improvements. Members of the D-Lab Honduras Team, possibly including the author, will be traveling to the MCA over the summer to make modifications that should allow the Savonius rotor to self start and turn the water pump on its own. This work should serve as a guide for making those improvements and will help make similar systems constructed in the future successful from the start.

1.3. Summary of Results

Optimizing the performance of the wind-powered water pumping system currently installed will largely focus on improvements and modifications to mechanical system rather than the rotor itself. Savonius rotors are not as efficient as lift based rotors but are extremely easy to construct. Design decisions with regard to the rope and washer pump used, the drive train implemented, and the welded structure already installed dictate that the system remains a VAWT approximately the size of the currently installed rotor.

A novel window Savonius rotor developed by the author does not improve rotor performance. This is likely due to the disruption of flow around the rotor that may interrupt the lift generating component. Since the standard Savonius rotor was the best performing prototype in testing, those traveling to Honduras this summer to work on the system will not make changes to the aerodynamics of the rotor. What should help improve the system are efforts to reduce friction and possible internal stresses that make be making the pump and rotor harder to start. From documented performance tests, reducing the moment of inertia of the rotor seems like a promising way to shift its torque to speed curve upwards towards higher torque at all speeds.

2. System Integration and Installation

It is critical to make an affordable pump system if it is going to be replicated in other communities in Honduras. A breakdown of costs of the entire system is included in table 1. While the system is about 60% more expensive than a similar system developed in neighboring Nicaragua, it is a first attempt and costs can be reduced in future models when the system is optimized and working.

Table 1: Itemized budget of the wind-powered water pump system.

Item	Unit Cost (USD)	Qty	Detailed amount	Amount (USD)
Windmill tower materials and welding				850.32
galvanized pipe 2"	48.69	5	243.45	
galvanized pipe 1.5"	38.63	9	347.67	
saw blades	1.00	5	5.00	
anti-rust paint (1 gallon)	11.91	1	11.91	
box of welding electrodes 60/13 1/8	9.00	1	9.00	
welding labor (2-3 days)	210.00	1	210.00	
bag of cement	5.82	4	23.29	
Windmill parts and materials				146.85
Oil drum	7.94	2	15.88	
plywood sheet 1/2"	23.29	2	46.57	
Paint (1 gallon) for plywood	10.32	1	10.32	
Paint thinner (1 quart)	1.85	3	5.56	
Brush	1.59	2	3.18	
metal pipe HG 1"	23.29	1	23.29	
metal pipe 1-1/4" (5ft)	9.26	1	9.26	
metal pipe adaptor from 1" to 2"	1.59	1	1.59	
bronze flanged-sleeve bearing	6.70	2	13.40	
U-bolts	1.06	4	4.23	
Assorted hardware (bolts, washers, etc.)	0.04	280	11.20	
Grease	2.38	1	2.38	
Spare metal sheet for support bracket	0.00	1	0.00	
Water pump parts				86.33
Sand bucket for guide mold	1.48	1	1.48	
Wood for guide mold	0.00	1	0.00	
bag of cement (½ bag, from above)	0.00	1	0.00	
polypropylene rope	25.00	1	25.00	
rubber 1/2" (1sq ft) [Buna, durometer 60A]	30.00	1	30.00	
Used truck tire	21.17	1	21.17	
Spare pipes for wheel	0.00	6	0.00	
PVC pipe 1"	3.70	2	7.41	
PVC adaptor from 1" to 2"	0.85	1	0.85	
PVC T of 2"	0.42	1	0.42	
PVC pipe 2" (spare: 25cm)	0.00	1	0.00	
Water tank parts				214.08
bag of cement	5.82	11	64.04	
Wood for mold	5.29	12	63.51	
Rebar 3/8" (lower pillars)	4.23	16	67.74	
Rebar 1/4" (upper pillars)	1.59	8	12.70	
pipe 2" (2m) for horizontal support	2.65	1	2.65	
Tie wire (lb)	0.69	5	3.44	
Car parts				91.35
Differential	79.39	1	79.39	
Hand break	7.94	1	7.94	
Oil 90 (1qt)	2.01	2	4.02	
Spare brake wire (3m)	0.00	1	0.00	
Total Cost of windmill and water pump				**1388.92**

The Nicaraguan system, which costs about $850, also employs a rope pump but uses a drag based horizontal axis wind turbine in place of the Savonius rotor. While it seems natural that a windmill with a horizontal axis of rotation can turn a pump that also requires a horizontal axis of rotation, it is actually quite complicated. The shaft that supports the rope pump must be fixed in all directions other than the desired direction of rotation. If the head of a HAWT is also fixed so that it can directly drive the rope pump shaft, the turbine becomes inefficient when winds change direction.

To deal with changing wind direction, the Nicaraguan pump uses a tensioned rope to transmit power from the windmill shaft to the pump shaft. Their design allows for the head of the windmill to rotate up to 270 degrees, but the rope tends to bind and jump from the tensioners at the extremes of rotation. For the head of a HAWT to be able to rotate in full circles and turn a fixed horizontal shaft of a rope pump, the axis of rotation has to be changed twice, first to a vertical axis and then back to horizontal. In this case, transmitting torque to the pump will also result in a torque on the head of the windmill that will push it out of the path of the wind. The use of the Savonius VAWT with a single angle drive provided by a car differential avoids these complications. Since there is no rope transmission that can come loose, the Savonius system installed in Honduras is very low maintenance which is beneficial since the farmers who own the property do not live at the site.

The system has two towers. The steel tower holding the rotor and the reinforced concrete tower that supports the water tank were constructed to allow for gravity based distribution of the water. Their current heights depended of the elevation of the property. The single most expensive component of the system was the galvanized steel tower that was constructed to support the rotor, constituting about 60% of the system's cost. The costs of this initial wind-powered pump were split between the community partner, the FSAR, and D-Lab, with the members of the Nuevo Paraiso Enterprise providing labor. Costs, however, can be reduced dramatically to levels competitive with the Nicaraguan design if the steel tower can be replaced with one made of reinforced concrete like the one that supports the water tank.

2.1. Rope and Washer Pump

Until just before the trip to Honduras, the D-Lab team members understood the concepts behind the operation of a rope and washer pump, but had focused on the design of power transmission from the rotor. Several critical elements of the rope were learned during construction on site. A previous group had tried to construct a rope and washer pump at the site and in removing it from the well the D-lab team gained useful insight.

A rope and washer pump requires a sturdy wheel with sufficient friction to pull the rope. Many times bicycle wheels are used in the first attempt at making a rope and washer pump. While a pump using a bike wheel can be hand driven by pulling on the rope directly, it is not adequate for mechanized systems. When a rotating shaft drives the rope pump instead of a person pulling on the rope, there must be sufficient friction between the rope and the wheel for them to move together. An inexpensive way to accomplish this is use sidewalls cut from a truck tire mounted together to form a V shape, as seen in fig. 4. Truck tires are used instead of car tires because their larger diameter results in a greater rope velocity per turn. The deep channels of the V shape also keep the rope from slipping off of the wheel when it turns. Also, polypropylene rope slips

Figure 4: Pump wheel constructed from truck sidewalls of truck tires with a welded steel hub.

less against the wheel than nylon rope. To prevent unnecessary wear on the rope, it is important to hold the washers in their place with knots on both sides. Otherwise, the washers slide along the rope resulting in uneven spacing that causes uneven flow and wear of the rope.

The last major component of the rope pump is the tensioner and bearing surface that is placed at the bottom of the well. Fig. 5 shows the mold and sacrificial mold core used to cast this

Figure 5: Wooden mold and sacrificial mold core that holds the shape of the cavity for the tensioner and bearing that sits at the bottom of the well.

component in concrete. This piece serves a dual purpose, keeping the rope tight, so that it does not slip on the wheel, and guiding it up the pipe.

The bearing surface consists of a glass bottle filled with concrete for strength. It is cast in a cavity in a concrete block. The mold core used to create cavity in the concrete was made of a plastic bucket with holes cut in it for two large diameter pieces of PVC pipe to act as water inlets and two holes through which the concrete filled bottle is placed. There are also two holes in the lid of the bucket, one of which has a large PVC reducer going to a smaller diameter that guides the rope into the tensioner and one with a reducer that guides the rope up the pipe. The technician who helped make the tensioner added two handles made of rebar after pouring the concrete into the mold. These proved extremely useful as the finished piece weighed over 30 kg and had to be lowered to the bottom of a well using ropes.

2.2. Savonius Rotor

The Savonius rotor was chosen for this application because it is a compact vertical axis wind turbine with high starting torque that is easy to construct. A VAWT was highly desirable because it could be coupled to the rope pump with a single right angle drive using an existing component, a car differential that provided bearings with proper alignment. The two stage rotor was made of two 55 gallon oil barrels cut in half, with each half displaced from each other and bolted to a piece of plywood. Fig. 6 shows several common wind turbine configurations and the

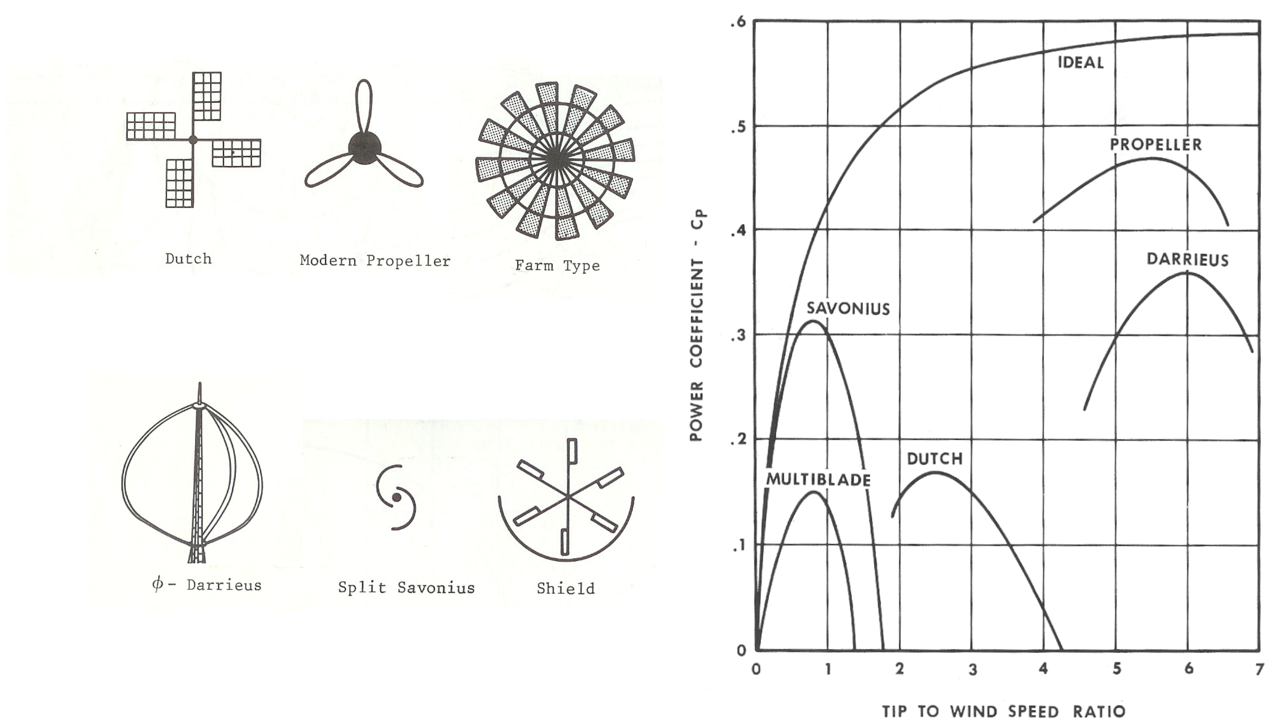


Figure 6: Common wind turbine designs and non-dimensional representation of their power v. speed curves (Wortman 1983).

their associated non-dimensional power v. speed curves. While the Savonius rotor cannot compare to the with modern lift based turbines that use precise airfoil shapes, its performance meets or exceeds the other drag based windmills.

2.3. Water Supply System

The goal of the wind-powered water pumping system is to distribute water to fields farther away from the small stream on the property owned by the Nuevo Paraiso Enterprise. The D-lab team anticipated placing the rope and washer pump near the ground, but surveying the site showed that a raised reservoir tank was needed to get a sufficient pressure head to deliver water to all parts of the property. The elevation of the property, seen in fig. 7, required that the base of the tank be at 3 meters above the ground level at the well. This was so that the hydrostatic pressure,

$$P = \rho g h \ ,$$

where, ρ is the fluid density, g is the acceleration of gravity, and h is the height of the water column, was sufficient to overcome head losses in the piping system. Raising the reservoir off the ground required the construction on the reinforced concrete tower to support it.

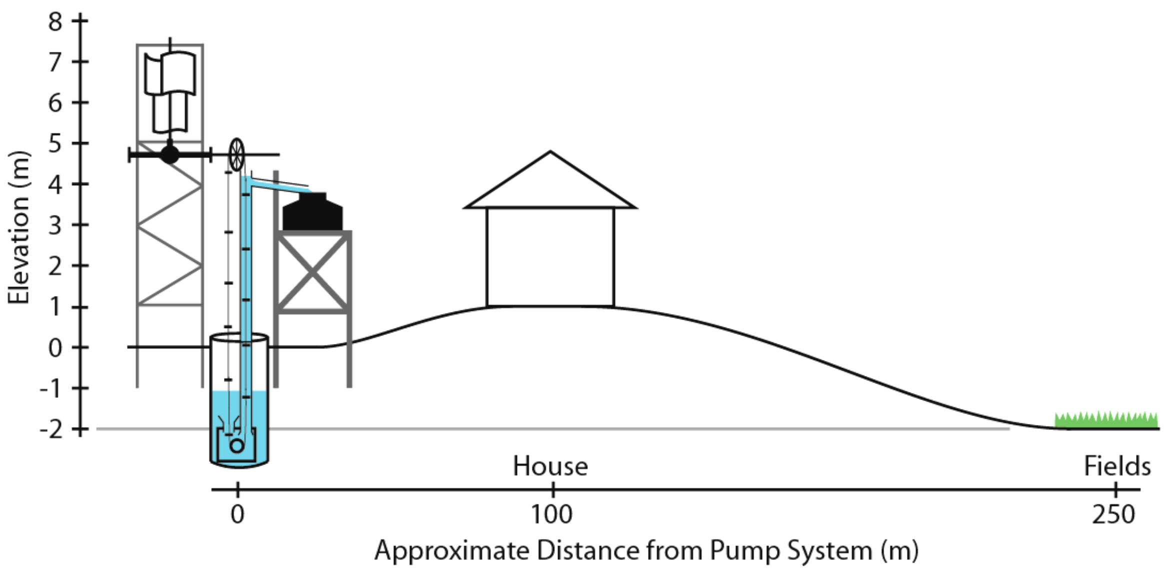


Figure 7: Scale diagram showing the height of the significant features of the pump system and the elevation of the area around.

3. Mechanism Optimization

The most promising area of improvement for the wind-powered water pumping system involves changes to the mechanism itself to reduce the load that the rotor must overcome. In making these changes it is important to understand the elements in the power train and the design decisions behind their selection. Fig. 8 is a detailed schematic of the system components from the rotor through the pump wheel.

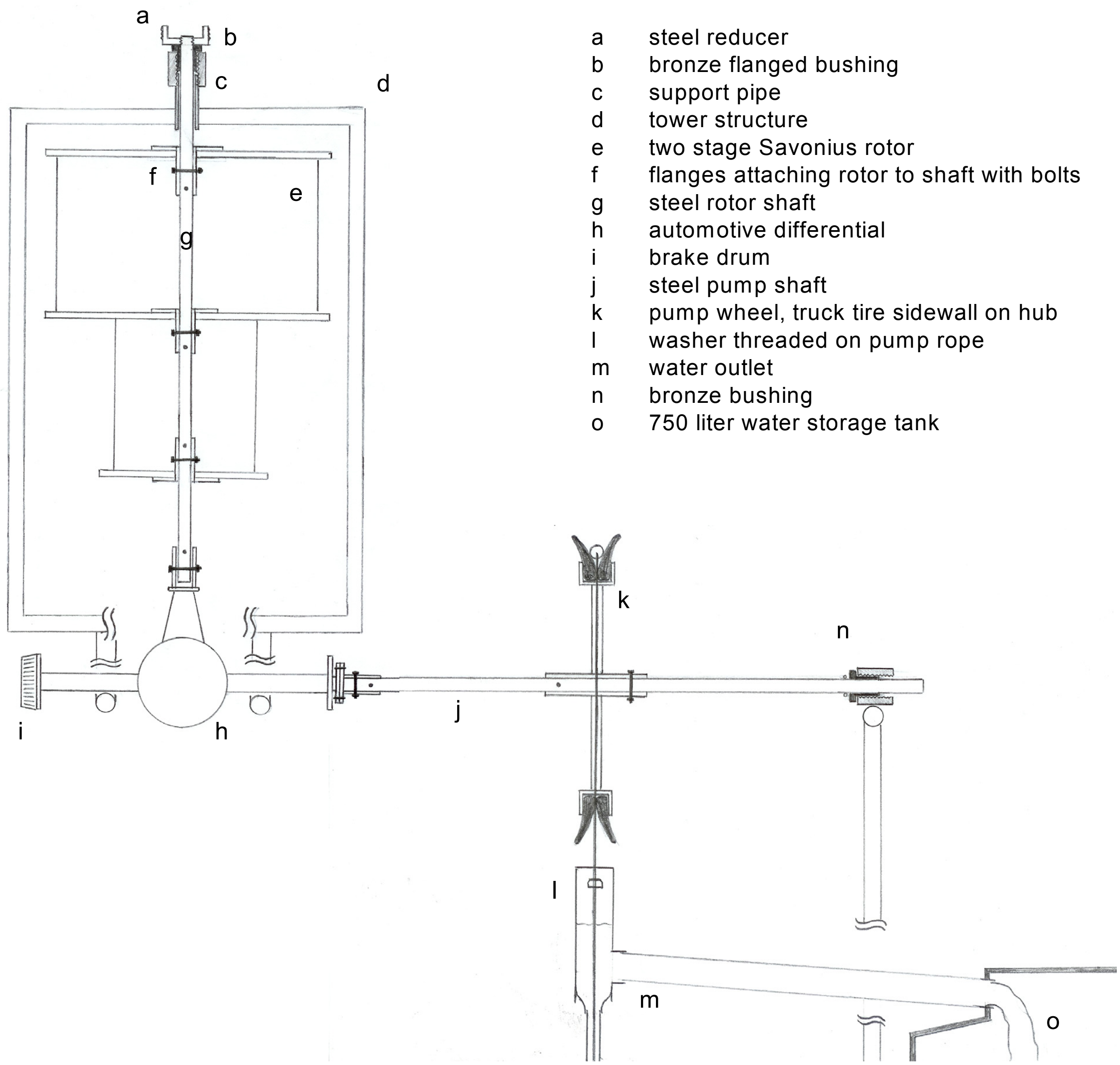


Figure 8: Schematic of the wind-powered water pumping system as installed in Honduras. Important components are labeled. Not-to-scale.

The reducer (a) is threaded onto the rotor shaft (g) and bolted through flanges (f) on the Savonius rotor (e). The reducer is supported on the oil impregnated, flanged bronze bushing (b), which bears the weight of the rotor through the support pipe (c) welded to the tower structure (d). At the bottom of the rotor shaft is an automotive rear differential (h) from a 1982 Mazda. The torque of the Savonius rotor enters the differential at the drive shaft input, and with a 2.5:1 increase in torque, turns the pump shaft (j) attached to the right wheel hub. The pump wheel (k) is bolted to the pump shaft and supported on the other end in an oil impregnated bronze bushing (n). The brake drum (i) is on the left. When the pump is supposed to operate under wind power, the brake is locked with a hand brake lever (not shown). To disconnect the pump from the rotor, the hand brake is released and that side of the differential becomes the lower resistance path. Since the differential is non-locking, the pump, as the higher resistance path, does not turn in the same way that a car wheel on solid ground stays still when the wheel on the other side slips in the mud. With the brake locked, the pump wheel turns pulling the rope with the threaded washers (l) through a pipe in the well (not shown) and up to the outlet (m). The water then flows into the storage tank (o) where the pressure head due to gravity is used to distribute water to the fields.

3.1. Bearing Surfaces

The only components of the pump system that were not purchased in Honduras were the rope, the rubber for the washers, and the oil impregnated flanged bronze bushings that support the rotor shaft and the pump shaft. An appropriate substitution can be made for the rope, and the rubber for the washers can be replaced with material cut from the tire sidewalls that are used to make the pump wheel. This leaves only the bronze bushings.

Oil impregnated bronze against steel is relatively low friction with the coefficient of friction, μ, equal to about 0.25. This is still significantly higher than friction would be if the bushings were replaced with rolling element bearings with coefficients of friction on the order of 0.05 to 0.1. At the time the D-lab team constructed the windmill, they were unsure whether or not the bearing on the differential could support a thrust load, so the weight of the windmill was placed on the steel reducer at the top of the rotor shaft against the flanged face of the bronze bushing. The exact weight of the rotor is unknown, but it may be as much as 40 kg. Assuming μ=0.25m, about 5in-pounds of torque is being robbed from the system by the weight of the rotor on the bronze bushing. The end of the pump shaft on the side of the reservoir tank is supported by an identical bushing that does not have any thrust load, but is being loaded radially with the weight of the pump shaft, the wheel, and the water column being lifted. This contributes to a roughly equivalent frictional loss on the pump side of the system.

The thrust load from the rotor shaft can easily be supported by the car differential, since the rotor is connected to the drive shaft input. This part is designed for much greater dynamic loads when driving. Taking the steel reducer off the top of the rotor shaft transfers the load to the differential, which has a rolling element bearing and therefore reduces the friction. This may have an additional benefit as well. Currently, the rotor's weight is being supported by the bronze bushing, but the bolts holding the differential end of the shaft in place are not perfectly aligned resulting in the rotor oscillating up and down slightly as it turns. If the rotor is just lifting off the bushing at the top, this effect is negligible. The other extreme is possible as well. If the oscillation is putting the shaft into tension at some point in its revolution, the system has to overcome internal stresses as well as friction in order to rotate. Removing the reducer from the top of the shaft combined with immobilizing the joint at the differential will eliminate this possibility. Replacing the two bronze bushing with automotive wheel bearings could reduce the frictional load at those two points by 60% to 80%.

An additional source of resistance in the system can also be eliminated very simply. After purchasing the differential, the D-lab team drained and replaced the fluid inside but filled the entire differential housing with fluid. Proper use only requires a couple inches of fluid in the housing, enough for the ring gear to dip into the fluid and distribute it on the other gears. The contribution of viscous drag here is significant and can be reduced by draining the fluid again and replacing it with a smaller amount of lightest weight appropriate oil. The forces of the differential due to the rotor will be much lower than those experienced while driving, so heavy lubrication is unnecessary.

3.2. Moment of Inertia

The last major mechanical change to the system involves weight reduction. Documents for constructing Savonius rotors implied using a full circle of plywood above and below each of the oil drum, each circle weighing about 8 kg. The plywood on the rotors installed in Honduras has been partially cut away reducing the weigh of the wooden part of the rotor by about 45%. This also reduced the moment of inertia of due to the wooden part of the rotor by 64%. Instead of three complete circles, the plywood has been cut into two sheets with two lobes, on the top and and bottom of the rotor, and one with four lobes, in the middle, as seen in fig. 9. Removing

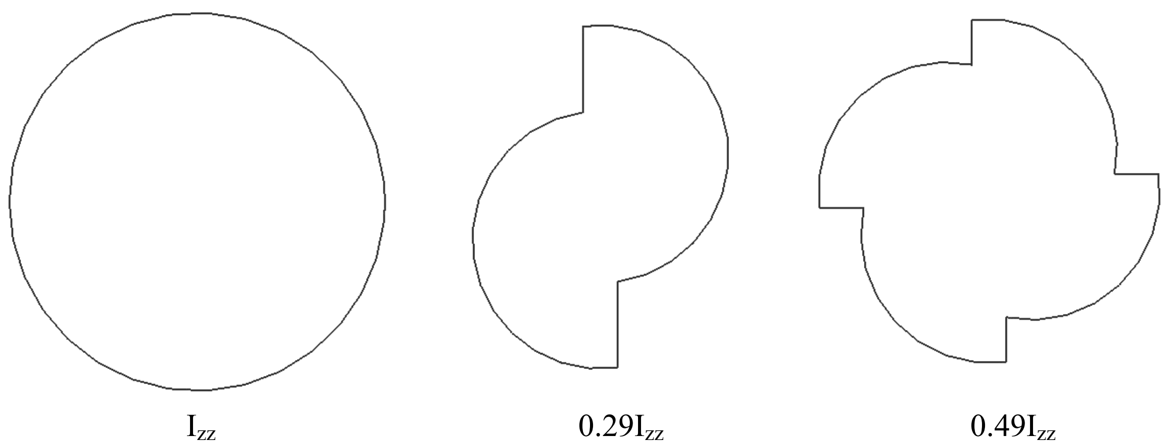


Figure 9: The suggested shape of plywood for the rotor is a circle, but material has been removed resulting the two shapes to the right. The relative moments of inertia of the shapes are listed below each one.

the additional border of plywood around each drum yields two lobe and four lobe shapes with moments of inertia of 0.16Izz and 0.28Izz respectively. This is an additional reduction of 44% of the current amount leaving only 20% of the moment of inertia of the full circle configuration. This additional weigh savings of 27% will reduce the friction of supporting the thrust load as well.

Currently when pumping by hand, the rotor acts as a flywheel that smoothes the operation. Reducing the moment of inertia of the system also reduces this effect, but should allow the rotor to begin turning in softer winds more easily. Performance data in fig. 10 suggests that low inertia Savonius rotors can have a torque increase of about 25%. Coupled with decreases in friction loads, wind pumping should be possible eliminating the need for hand pumping.

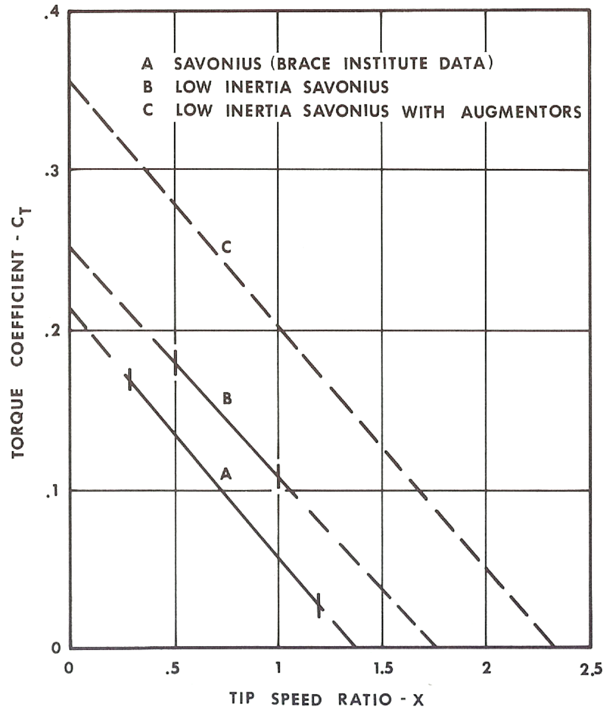


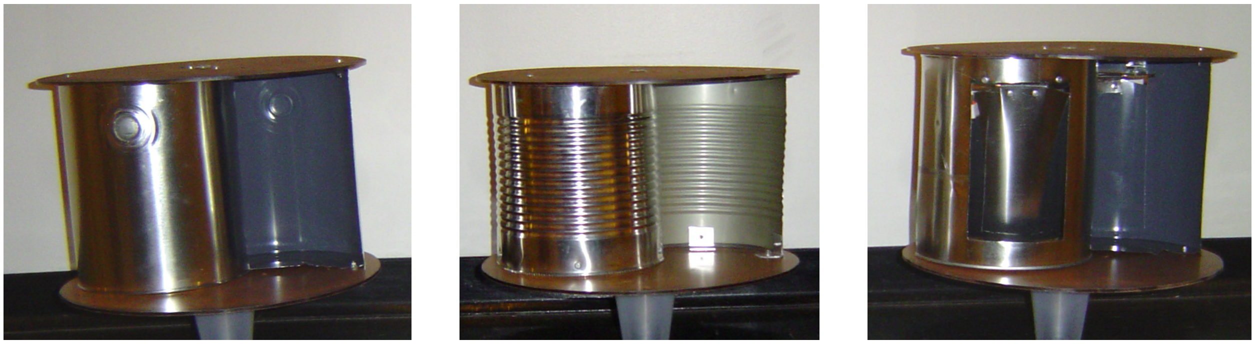
Figure 10: Representative non-dimensional torque v. speed performance of Savonius rotors. The source does not explain physical mechanism behind augmenters, but implies that they increase wind speed (Wortman 1983).

4. Savonius Rotor Testing

Aerodynamic tests of three scale model rotors were conducted using the author's 1991 Toyota Celica convertible with the added "wind tunnel" package. The apparatus for wind testing was a wooden frame attached to the passenger seat of the vehicle, as seen in fig. 12a. The headrest was removed and the headrest posts were used to locate the apparatus. In order to align it vertically, the seat angle was adjusted. A third leg to secure the fixture was locked into place by sliding the seat backwards until the leg made contact with the back seat. The results suggest that the standard Savonius rotor already installed in Honduras is the best performer.

4.1. Model Rotors

The three rotors used in testing are shown in fig. 11. Each was approximately 8 inches tall and made of a one gallon can cut in half and attached to two 1 foot diameter circles of fiberboard. Delrin bushings served reduce friction of the models rotation on a fiberglass shaft.



(a) (b) (c)

Figure 11: Three small scale Savonius rotors used in testing. (a) Standard Savonius rotor (b) Ridged Savonius rotor (c) Window Savonius rotor

Model (a) is a standard Savonius rotor with smooth sides constructed from a one gallon paint can. The section where the handle was attached was ground off and filled with epoxy to smooth the surface.

A variation on the standard Savonius rotor is seen in model (b). This ridged Savonius is an exaggerated approximation of the ridges found on oil barrels. The one gallon food can used was slightly smaller in both height and diameter than the paint can.

The window Savonius, model (c) was a novel solution constructed by the author in an attempt to further reduce the drag on the low drag side of the rotor. The goal was to build a one way valve that would let winds flow through the low drag, convex side of the rotor but not through the concave high drag side, thereby creating and even larger difference in force on the two sides of the rotor.

4.2. Rotor Testing

Wind testing of the model rotors was conducted to determine two parameters, the no load speed of the rotor and the stall torque. Additionally a direct comparison test was conducted to try to determine which rotor design had the best starting characteristics. Photographs of the apparatus for all three tests are seen in fig. 12.

The direct comparison test was the simplest and was inspired by the work of Captain Savonius in developing his rotor. By placing two rotor, one designed to run clockwise and one designed to run counter clockwise on the same shaft and exposing them to a flow, a significantly better performing rotor will overpower the other and both rotors should turn in the direction of the one with better starting characteristics (Calvert 1979). To conduct the test, each of the three possible rotor pairs were placed on the same shaft, with each rotor style testedon the top and on the bottom to rule out differences in flow closer to and further from the windshield. This resulted in six different configurations. The car was driven at increasing speed up to 40 mph to see which direction the rotors would begin to turn in.

(a) (b) (c)

Figure 12: Three different tests were conducted on each rotor, (a) the direct comparison test, (b) no load speed testing, and (c) stall torque testing.

Tests of no load speed and stall torque were both conducted at a speed of 15 mph. Since winds in any direction add to the wind velocity driving a vertical axis wind turbine, tests were conducted in a partially closed parking garage to avoid cross winds, and an anemometer was used to determine the speed rather than the vehicle speedometer. No load speed and stall torque were both approximations since, the bearing surfaces applied some additional load to the system in both cases. The no load speed was measured using a non-contact, optical tachometer. The data in fig. 13 reflects the average of ten runs for each rotor. Stall torque was measured by fixing the shaft of the model rotors to a torque and gauge with a maximum capacity of 24 in-oz of torque and 1 in-oz gradations. While the stall torque varies according to the angle of the rotor with respect to the wind, the results in fig. 13 are an average of three measurements at each of three different orientations for each rotor.

4.3. Results

The results of the direct comparison test were inconclusive. With all rotor combinations, the torque difference was two small for rotations to start in either direction. The torque was so evenly matched that pushing the rotors in one direction or the other usually just induced oscillations in both directions. If rotation in one direction could be induced at all, it died out within two or three full rotations.

Performance data taken on Savonius rotors in wind tunnel tests show that the middle range of the torque v. speed measurements for Savonius rotors in a linear relationship. Fig. 13 approximates the performance of each of the three rotors. In reality, there is a friction load at the tested no load

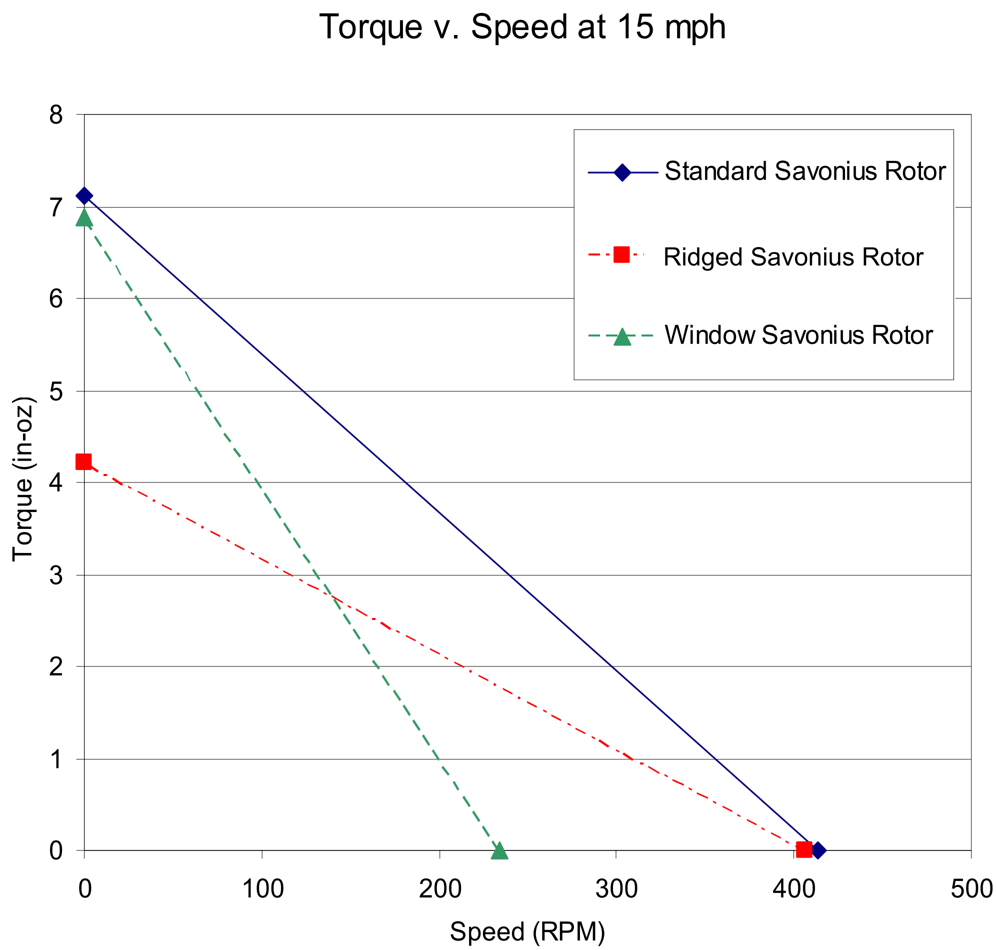


Figure 13: Torque v. speed for the three rotor models at 15 mph approximated as a straight line between the no load speed and the stall torque.

point that decreases the speed. Similary bearing friction is not accounted for in the stall torque measurement. These changes would shift each of the torque v. speed curves upwards towards a higher performance rotor.

Power is the product of torque and speed, so the window Savonius rotor has more power than the ridged Savonius initially but peaks earlier. The Standard Savonius rotor has the best performance over the entire range. Non-dimensionalizing the torque v. speed curve yield a graph of torque coefficient,

$$C_T = \frac{T}{\frac{1}{2\rho V^2 Sd}}$$

where, T is the shaft torque, ρ is the density of air, V is the wind speed, s is the projected area of the rotor, and d is the rotor diameter, versus the tip speed ratio, μ.

$$\mu = \frac{\pi d}{60}\frac{N}{V},$$

where N is the shaft speed. Comparing the performance of the tested standard Savonius rotor model with wind tunnel data, (Simonds 1964) as in fig. 14, shows that performance of the model rotors is well below ideal.

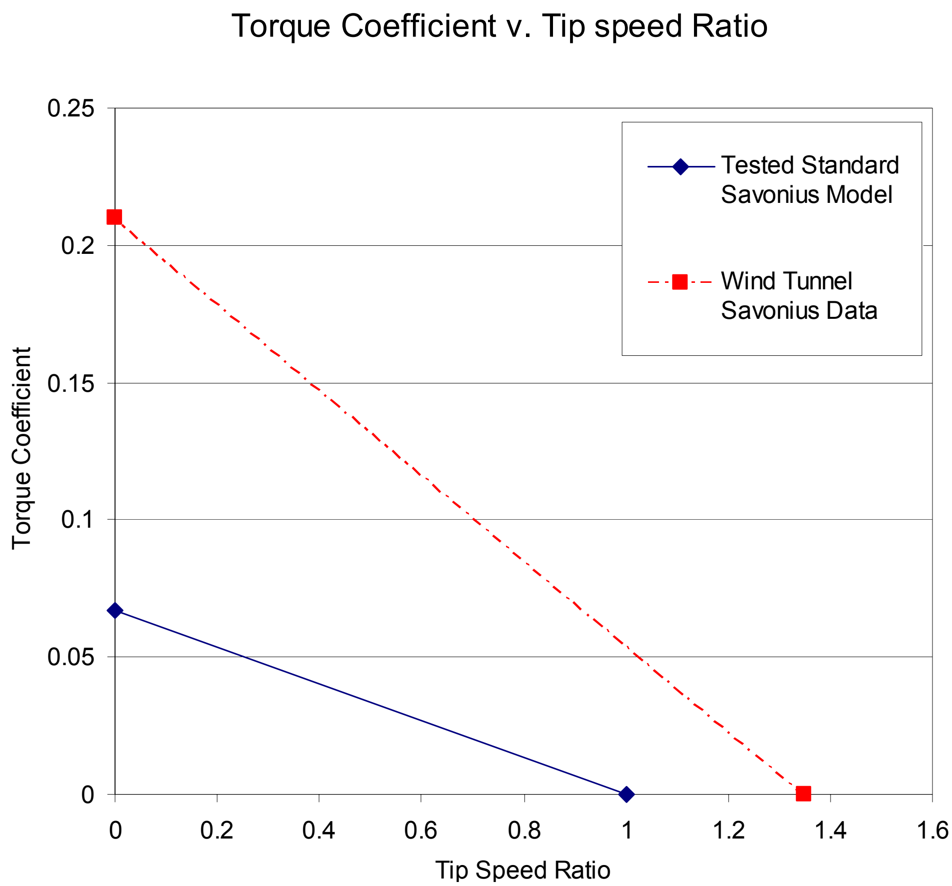


Figure 14: Non-dimensional torque v. speed curve for the best performing model, the standard Savonius rotor and for a wind tunnel tested rotor.

If the friction load in the bearings of the model is accounted for, both the torque coefficient and tip speed ration would be higher. This brings the results closer to the wind tunnel data. Also, performance is approximated from only the no load speed and stall torque which are the extremes of the data. This approximation ignores edge effects in the rotor behavior.

5. Future Work

Future work focuses on two aspects of this project. It is possible to make to make some adjustments to the aerodynamic design of the rotor, but most of the changes made from the standard Savonius rotor did not seem to have a positive impact in the small scale testing. Full scale testing of a single rotor stage is possible in the MIT wind tunnel and should provide cleaner data. If the window Savonius rotor is going to be explored further, the next models should be constructed in larger scale with several smaller windows. Also, there should be an overlapping edge backing on each flap that closes the windows. This would stop possible leaks around the edges of the windows that likely reduce the performance of that rotor. The performance of Savonius rotors has been extensively documented and the rotors installed in Honduras meet the physical specifications for good performance. Therefore it is more important to focus on mechanical changes and understanding the wind conditions in the area around the current windmill.

5.1. Honduras Summer 2007

Marta Fernandez, Victor Grau, and Patricia Pina, trip leaders for the D-Lab team during IAP, have developed a low cost anemometer, tachometer, and data logger. They have MIT IDEAS Competition funding to continue the project, and at the beginning of the summer they will install their anemometer on the tower of the windmill to measure wind speed in the vicinity and also install the tachometer on the rotor shaft to measure the rotational speed of the turbine. Currently the windmill is about 30 meters away from a group of trees because that is where the existing well was located. To understand the impact of this close proximity to the trees, whoever travels to Honduras will also install an anemometer on top of the house about 100m to 150m away. Data will be time stamped and if higher wind speeds are measured by the house, it implies that the trees are having a detrimental effect by interrupting the flow around the windmill. Characterizing the winds in the area provides important information about the power available to the windmill as seen in fig. 15 (Wegley 1978).

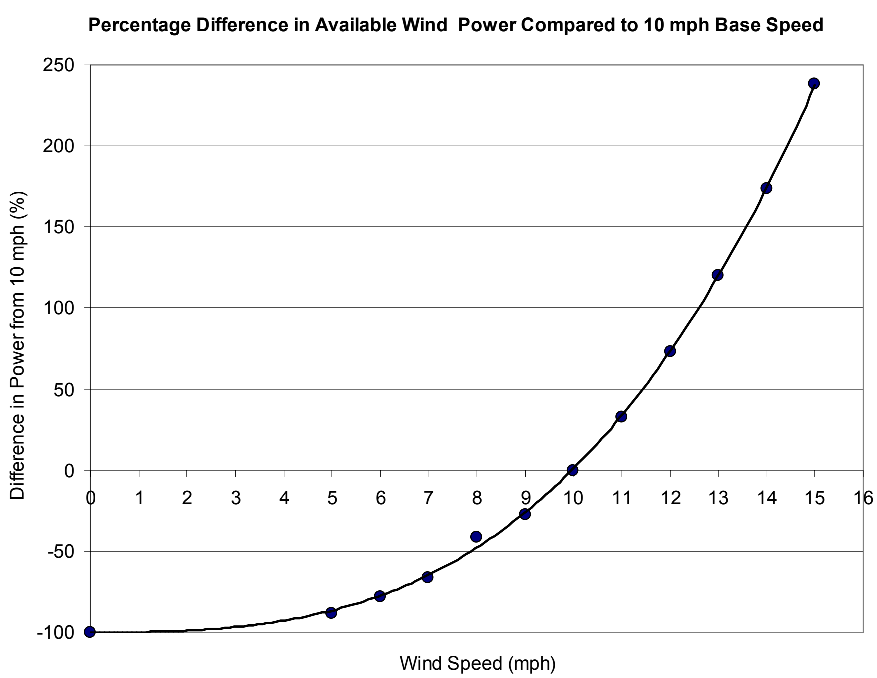


Figure 15: Percentage difference in available wind power from a base speed of 10 mph with a third order fit line.

If the wind measurements over time show a large discrepancy with lower winds by the windmill and higher winds by the house, the MCA residents have suggested that they would cut down the trees close to the windmill. Since even a small increase of a couple miles per hour in wind speed results in much higher available wind power this may be beneficial, but wind speeds will be confirmed with data before taking such an action. Those on the trip this summer will also take measurements of flow rate of the pump when hand pumping the system and make the suggested mechanical changes to the system to reduce the load that the rotor must overcome in order to allow wind pumping.

6. Conclusion

Mechanism based changes to reduce load on the rotor are the most promising. There are a variety of weight reducing and friction reducing measures to be taken with the current system. These will hopefully allow the Savonius rotor to power the rope and washer pump on its own. If aerodynamic tests on the rotors are going to be continued, they should be done at full scale in the wind tunnel with a dynamometer to characterize the system behavior. The window Savonius rotor does not seem like a promising solution, but future tests of that style should use a rotor made with greater precision that will avoid any leaks through the rotor blades. Wind measurement in Honduras will be taken this summer and improvements will be made that should allow the wind-powered water pump to function as originally designed.

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