DALHOUSIE UNIVERSITY
DEPARTMENT OF MECHANICAL ENGINEERING

DESIGN PROJECT - MECH 4020

SELF-STARTING DARRIEUS WIND TURBINE

DESIGN GROUP #7

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Client
Dalhousie University

Executive Summary

With a growing focus on renewable energy, interest in the design of wind turbines has also been expanding. In today's market, the horizontal axis (windmill) turbine is the most common type in use, but vertical axis (Darrieus) turbines have certain advantages. Darrieus turbines, which are lift-driven, have a higher power potential than the horizontal, or drag-driven turbines. The main flaw with their design is their inability to self-start. Darrieus turbines require an external energy source to bring the device to a minimum rotational speed. This report describes the design, construction, and testing of a Darrieus turbine which will start solely from the energy of the wind.

Initially, the ideas proposed consisted of mounting a separate drag device (Savonius type turbine) inside an existing Darrieus turbine. This would have a shape that would create enough drag force from the wind that it would spin the turbine fast enough for the Darrieus blades to create enough lift to spin on their own, at which point the starter would decouple. However, an idea evolved which would not need the existing Darrieus blades to produce lift. The idea proposed was to have large blades that would create sufficient drag, and then transform into an airfoil shape that generates lift. Several small models were built to test the idea in a rotational test as well as in a wind tunnel. The results from these tests were encouraging: through the drag forces created on the expanded blades, the model rotated at a high speed and the blades were observed to start their transformation into airfoils. The blades didn't fully close due to the inherent high friction existing in the models, but the idea behind the design was shown to be successful.

Over the last 4 months of the project, a 3.5 m tall prototype was constructed and tested. This design proved difficult to fabricate on the limited budget that was supplied. As a result, the finished prototype had some critical flaws. The design functioned almost the same as the models, in that the blades would induce rotation due to drag, and then close. Insufficient lift was produced, however, and the turbine would not reach optimum speeds. This does not mean that the design is flawed; rather, it proves that with a sufficient budget, the goal could easily be accomplished. The specific details of the current design, as well as the aspects that must be improved to accomplish the goals, are contained in the body of this document.

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1.0 Introduction

1.1 Group Mission

Darrieus turbines are a breed of vertical axis wind turbines which are driven by lift. Designed by George Darrieus in the 1920's, they are capable of producing much more power than most typical wind turbines. Increasing power output from renewable sources such as wind is becoming more important due to the increase in the publics awareness of the negative effects of relying on the finite supply of fossil fuels. Darrieus wind turbines would be much more common today, except for one major drawback: since lift forces drive them, they must be brought to a minimum speed before the forces generated are sufficient to propel the turbine.

Existing Darrieus turbines commonly use electricity to bring them up to the required starting speed. Though this method works, it is undesirable for several reasons. The turbine must then be hooked into a power grid, thereby greatly increasing the complexity of the design and limiting the use in remote areas such as offshore. Second, the power from wind turbines is totally renewable, so combining it with electricity from burning fossil fuel is somewhat self-defeating.

The Spin Doctors, a group of senior mechanical engineering students, are attempting to solve this problem, thereby increasing the value of this often overlooked breed of wind turbines. The group is comprised of Dylan White, Josh DeCoste, Daniel Berkvens, Aaron Smith, and Jody Crawford. The supervisors for this project are Drs. Murat Koksal and Alan Fung, and the client is Dalhousie University. This project is being continued from a group in last year's design class.

The goal of this project is to design an effective way to use wind energy to reliably start a Darrieus turbine.

1.2 How Darrieus Wind Turbines Work

The term Darrieus describes a class of Vertical Axis Wind Turbines (VAWT) that is powered by the phenomenon of lift. This class consists of two types of turbines, “eggbeater-type” and “H-type” (see Figure 1).

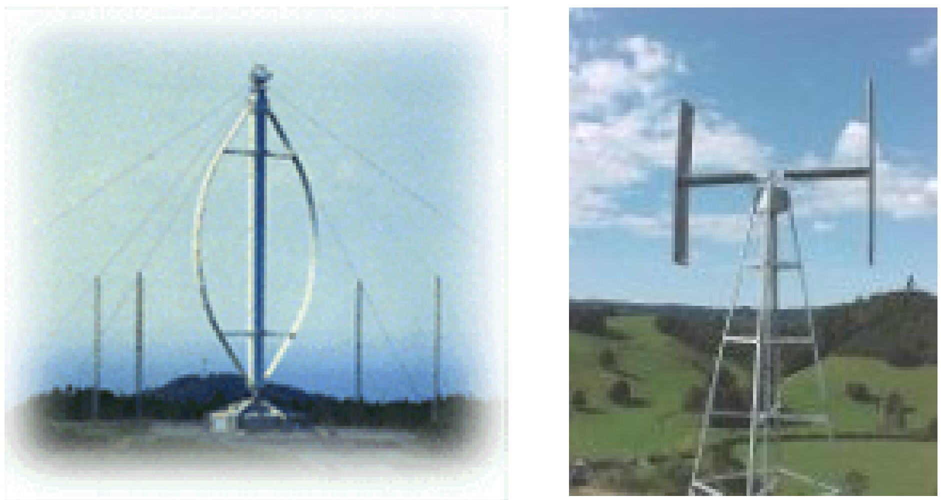
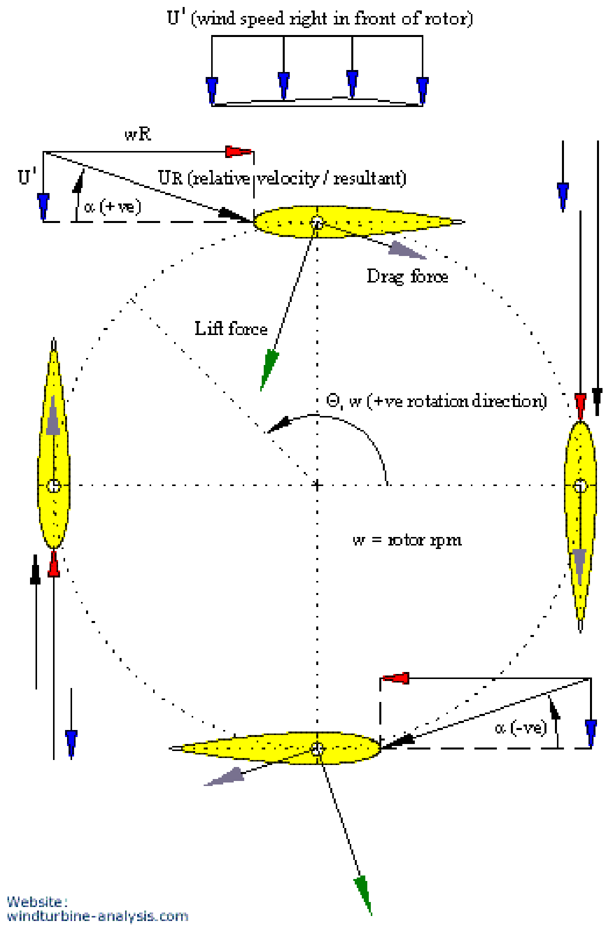


Figure 1: Eggbeater-type Darrieus versus H-type Darrieus

This lift is created because of the airfoil shape of the turbines blades. These blades cut through the air with an angle of attack to the wind causing a pressure differential. The resulting pressure differentials cause a force called lift, which propels the blade forward. In order to propel the turbine, the net torque caused by lift forces must be greater than the net torque caused by drag forces.



Legend:

Blue arrow - air velocity relative to the ground

Red arrow – velocity of the ground relative to the airfoil

Black arrow – resultant air velocity relative to the airfoil

Green arrow – lift force

Grey arrow – drag force

Figure 2: Top view of forces on a Darrieus blade throughout 360° of rotation

The forces driving Darrieus turbines can be described in more detail with the help of Figure 2. There are two important velocity components. There is the velocity of the airfoil relative to the shaft, which is at all times parallel to the chord, having a magnitude equal to the rotational speed multiplied by the radius. There is also the velocity of the wind, which is approximated as a constant velocity in one direction. The resultant of these two velocities is the velocity of the air relative to the airfoil. The angle between this resultant velocity and the chord of the airfoil is called the angle of attack.

Lift is created by a pressure differential, which occurs whenever there is an angle of attack, α, not equal to zero. In the 0° position (far right) and the 180° position (far left), α = 0°. At this point, only a drag force exists. Lift begins to be created as the blades rotate out of these two positions and α increases. This lift force is perpendicular to the resultant wind direction but, more importantly, it always induces counterclockwise rotation of the turbine. This lift force is strong enough to power the wind turbine whenever the blade is rotating at least 1.5 times as fast as the wind; that is, the blade has a tip speed ratio, tsr, of 1.5 or greater.

2.0 Design Constraints

2.1 Initial Requirements

Size/Geometry/Weight

The final design should be no larger in diameter than about 3m, and should not be so tall as to be unstable. It should be as light as possible, resulting in a low moment of inertia. This is important, as a large moment will add to the needed starting torque. The self-starter should be purely mechanical, in that it will not rely on electronics. It must be solely wind-powered, not run off any other source of energy.

Output/Input

The turbine will be expected to produce between 100 and 1000 Watts of power, while operating at wind speeds ranging between 5 and 7 m/s.

Ergonomics/Human Factors/Safety

No human interaction should be required during normal operation. A braking mechanism must be installed, however, to shut down the turbine if wind speeds are too high or so that maintenance can take place. Guy wires should be installed for added stability.

Expected Annual Usage

The turbine should run continuously, as much as the wind permits. However, it will have to be shut down on a regular basis for preventative maintenance. This should enable the turbine to last 20 years, and potentially longer.

Quality/Durability/Serviceability

The turbine must be able to withstand the weather over a long period, including wind speeds up to 12 m/s and all forms of precipitation and temperatures ranging from -20°C to +35°C. The whole assembly should be easy to work on, due to its compact size and relative simplicity. However, it should not be necessary to replace the blades or shaft. All other parts should be reasonably easy to replace, and even easier to inspect.

Appearance

The turbine must be aesthetically pleasing, and as quiet as possible. It's expected that a generator would add to the noise created, but it should still be tolerable, especially considering that the turbine will not be located near many people.

Materials

The main materials that will be used will include carbon fiber, aluminum and balsa wood, to ensure high strength to weight ratios, as well as durability.

Intellectual Property

The rights to the intellectual property surrounding the design of the self-starter will be shared as it was for last years design group. All the members of the group, as well as the advisor and client, will all share equal rights to the intellectual property.

2.2 Scope

To solve this problem, it was initially planned to design a self-starting mechanism that was going to be attached to last year's turbine. After brainstorming, various options were presented, many of which had the potential to work. The chosen design was would work on its own rather than working as a de-coupling mechanism for the previous year's turbine. Last year's design was thus abandoned and it was decided to construct an entirely new turbine. The existing turbine is still a useful learning tool, so no parts will be taken from it. It was decided to use the same base as last year's turbine to cut down on costs. The base would also be modified so as to allow it to fit through a standard sized doorway.

In the first stages of this project it was suggested that a generator coupling and a braking system should be designed. Though these components would be beneficial to the final product, it is thought that time constraints will limit it to the design and fabrication of the airfoils and the mounting system. It should be noted that last year's Darrieus team ran into similar time constraints and were only able to design the blades, shaft, and base for their turbine. The team members and supervisors have all agreed that this is the best course of action.

3.0 Preliminary Design

3.1 Idea Generation

As stated previously, last year's group was able to construct a Darrieus turbine, but was unable to achieve the desired lift to start the device. The goal was to come up with a mechanism that would enable the turbine to start on its own. Brainstorming was started by looking at the previous year's preliminary attempts at designing self-starters. Their designs consisted of material placed close to the shaft that would operate as a drag device, hopefully generating enough of force to rotate the Darrieus at the required rate. Once the Darrieus was rotating faster than the self-starter, the mechanism would decouple and the shaft would turn by the efforts of the Darrieus as opposed to the self-starter.

Last year's self-starter design was essentially four slightly curved plates that were offset by 90°. This did not create enough force to spin the blades fast enough. The original idea was to come up with a better drag driven device to mount inside the blades. The plates they had used were not very aerodynamic, and a substantial drag was created when the back of the plate was facing the wind, thus limiting the net force created. It was thought that if a drag device that was shaped more like a cup instead of a plate it would greatly reduce this effect. Also, it was decided to implement a three cup design, so the overall drag would again be substantially increased. A small demonstration model of this design was built out of tin.

This design was believed to have potential, but would require a decoupling mechanism for when the shaft reached an appropriate rotational speed. An attempt was made to come up with a design that would enable the turbine to avoid the problem of decoupling. One suggestion was to enable each of the blades of the self-starter to transform from a drag device into an airfoil after there was sufficient lift to drive the blades. By doing this, the self-starter would not impede the operation of the Darrieus at high speeds. To achieve this goal, a hinge could run along the whole span, near the front tip of a straight (as opposed to eggbeater shaped) airfoil, allowing the airfoil to fold open, to form an open-ended triangle. By mounting two (or more) of these on a shaft, there will be a net torque, due to the sharp nose.

It was decided that this idea would be used for the overall design rather than attaching it inside the blades of the existing turbine. This would allow the construction of the drag device to be much larger than initially planned, enabling the turbine to more easily reach the desired speed.

3.2 Model Construction

The final design was difficult to explain so several models were constructed to help visualize the idea. The first model was constructed solely for this purpose. A second model was built to show the general arrangement of the whole turbine during a class presentation. Finally, the third model was built for wind tunnel testing and as a visual guide for design refinement.

The first model was built using tin, coat hangers and duct tape, and was used only one day to explain the idea to the supervisors. The second model was built using tin, coat hangers, copper pipe, duct tape and rivets. The turbine blades were made from tin and incorporated the two hinge design. A small piece of tin was folded to make the leading edge of the airfoil while two larger, straight pieces were cut for the sides; all three pieces were then duct taped at the hinged portion to create the entire airfoil. Each airfoil used two coat hangers, one running up and down the inside of each half.

The hanger mounted on the half closer to the shaft acted as a pin, which slid back and forth in the rail, while the other hanger was a stationary pivot point on the end of the rail. The four rails were constructed of tin, which was folded over to make a U-shape in which the coat hangers rode. The clamps were used for shaft attachments to which the rails could then be riveted; the clamps were semi-circular and riveted together to form around the shaft. This model proved to be suitable for demonstrations, but its stability and strength was an issue and therefore could not be used in the wind tunnel.

	Starting (Open) Position	Full Speed (Closed) Position
Side View		
Top View		

Figure 3: Wind Tunnel Model

For the wind tunnel model it was believed that by using balsa as the material for the blades and carbon fiber for the rails that stability would be increased over previous models. The rails were constructed from two lengths of carbon fiber which ran the width of the turbine (see Figure 3 – Side View). Spacers were glued between the lengths in order to provide adequate space for the sliders to run within the rail. The airfoil blades were made from three pieces of balsa and constructed in a fashion similar to the tin design. The leading edge was sanded into an aerodynamic shape. The other two pieces of the airfoil were made from straight pieces of balsa and sanded to the appropriate profile. All three pieces were then connected by small plastic hinges that were inserted into the balsa. The sliders were made from carbon fiber that was sanded down to minimize friction. The blades were attached to the sliders by means of coat hangers that were inserted into the top and bottom edges of the balsa. One blade was attached to the slider while the other remained stationary acting as a pivot point for the airfoil.

3.3 Model Testing

After building the model, a few minor tests were completed to ensure that it functioned properly. All parts seemed to move as desired, albeit with a bit more resistance than originally hoped. The final prototype would be built with much more precision and better components, so this resistance decreased greatly in the full-size model. A very crude test was performed in which the shaft was coupled to the end of a cordless drill and spun rapidly. This test was done very quickly, without any real measurement, but had very encouraging results. The model held together and the centrifugal forces clearly closed the airfoil, even with the relatively high friction. (see video on web page)

Since the model design was deemed acceptable, the test was taken one step further. The model was mounted on a proper axle and stand, and a better drill was used with a tachometer. The model was coupled to the drill and the rotational speed slowly increased. The airfoils were observed to start closing in the range of 130 to 170 rpm. This number could be fine-tuned by adding weights to the inside of the airfoil to increase centrifugal forces, or by using a spring to hold the blades open. The model was rotated up to 400 rpm to verify that it was capable of spinning this fast without falling apart.

The final test performed on this model was done in the wind tunnel at Dalhousie. The airfoils were placed in the open position and dropped into the wind tunnel. When the wind started the model initially stalled, oriented with the rails nearly parallel to the wind. Eventually the wind caught it and it started spinning. Once it started it picked up a lot of speed very quickly. After only a few seconds the model was spinning at about 130 rpm, which is the minimum speed at which the airfoils closed in the previous test. While it was spinning it was difficult to tell whether or not the airfoils had closed. Once it stopped spinning after the test ended it could be seen that foils had closed considerably, although not completely.

It appeared as though 130 rpm was as fast as the model would go with a measured wind-speed of about 10 m/s. The original plan was to test the model at various different wind speeds in both the open and closed position. However, after spinning steadily for about a minute, a part failed.

The wind tunnel was turned off to inspect the model. One of the hinges had pulled out of the balsa, leading to high forces on the pin in the slider. This caused the slider to pull out of its rail and shoot down the tunnel and one half of an airfoil to hang limp.

Despite this failure, the overall results were encouraging. The blades functioned as drag devices and got the model up to a speed which could very possibly be high enough to produce lift. Due to the high friction and the lack of weights on the model, the airfoils were not expected to close all the way. Even if they had, the airfoils were somewhat crudely shaped and it would have been a pleasant surprise if they produced any lift. As such, these results are as good as expected.

4.0 Calculations

4.1 Aerodynamic Calculations

There are many variables within the design of a Darrieus wind turbine including the radius, r of the blade's arms, the height, h of the blades and the cord length, c of the blade (see Figure 4). One of the major factors which will determine each of these parameters is the "cut in" speed of the turbine, which is the speed in which the turbine will initiate rotation in its drag position. Another factor is the air velocity required to allow the turbine to rotate on its own in the Darrieus position.

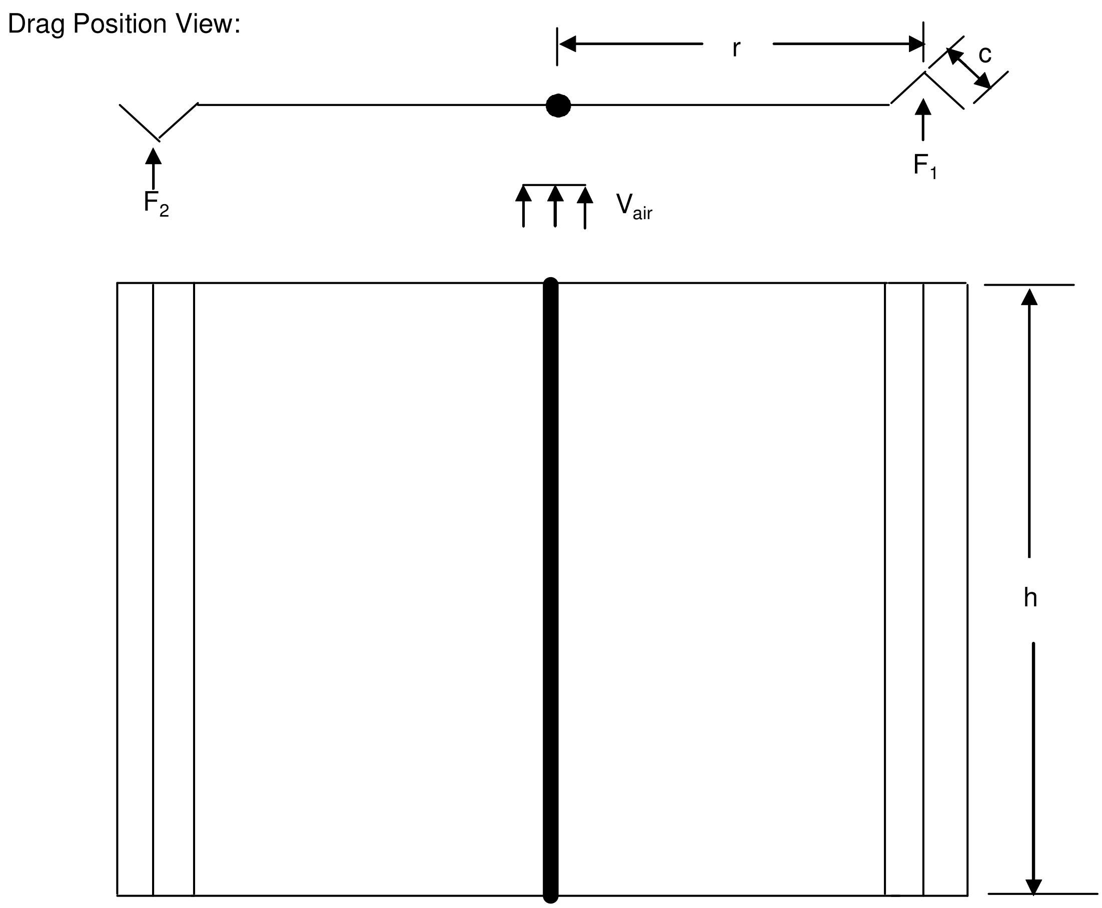


Figure 4 - The Darrieus Turbine in its Drag position

Calculations have been completed to determine the torque produced over various wind speeds in both the drag and Darrieus positions while varying the turbines radius, height and cord length.

The torque produced while in the drag position was determined by the use of basic fluid mechanics calculations. Two coefficients of drag were determined for the blades in their drag position, one for air blowing against the front of the blade and one for air blowing against the back. These were used to calculate the force on the front of the blade, F_1 and the force on the back of the blade, F_2.

$$F = c_D(1/2 \text{ x } r \text{ x } V^2 \text{ x } Ass) \qquad [1]$$

The net torque by the turbine was determined with the use of the turbine's radius.

$$T_{ss} = (F_1 \text{ x } r) - (F_2 \text{ x } r) \qquad [2]$$

To determine the torque produced in the Darrieus Position, the power produced by the turbine was calculated by the use of the following calculation:

$$P_{dar} = c_P(1/2 \text{ x } r \text{ x } V^3 \text{ x } A_{swept}) \qquad [3]$$

The coefficient of power is determined from Figure 7 with the solidity of the turbine being calculated as follows:

$$\text{Solitity} = Nc/D \qquad [4]$$

N represents the number of blades on the turbine; c is the cord length of the blades; and D is the diameter of the turbine. The rotational speed of the turbine can then be determined in [5].

$$w_{dar} = tsr \text{ x } V_{air} / r \text{ x } (60/2\pi) \qquad [5]$$

In [5] the tsr, tip speed to wind speed ratio of the turbine is assumed to be 2.5, i.e. the blades rotate at 2 and ½ times the speed of the wind. The torque produced by the turbine can then be determined from the power and rotational speed in [6].

$$T_{dar} = P_{dar}/w_{dar} \qquad [6]$$

The results of the calculations are in Appendix A. Average dimensions were chosen for the turbine of radius 1m, height 2m and chord length 0.2 m, then each of these parameters were varied. The torque produced by the turbine while in the drag position can be seen in the first three graphs and the net torque produced by the Darrieus can be seen in the next three graphs. For the turbine to initiate rotation, it must produce enough torque to overcome the frictional torque in the system. The frictional torque in the system was estimated to be less than 1 N-m in the design phase and measured to be 0.22 N-m after construction.

It can be seen that the main parameter in determining the torque from the self-starter (turbine in the drag position) is the length of the cord. The self-starter will produce enough torque in wind speeds of 0.5-1.5 m/s to overcome the frictional torque no matter what is varied.

The torque produced while in the Darrieus position also varied the most with the cord length. The main factor in determining the torque was the coefficient of power which varies with the solidity of the turbine, which can be seen in Figure 5.

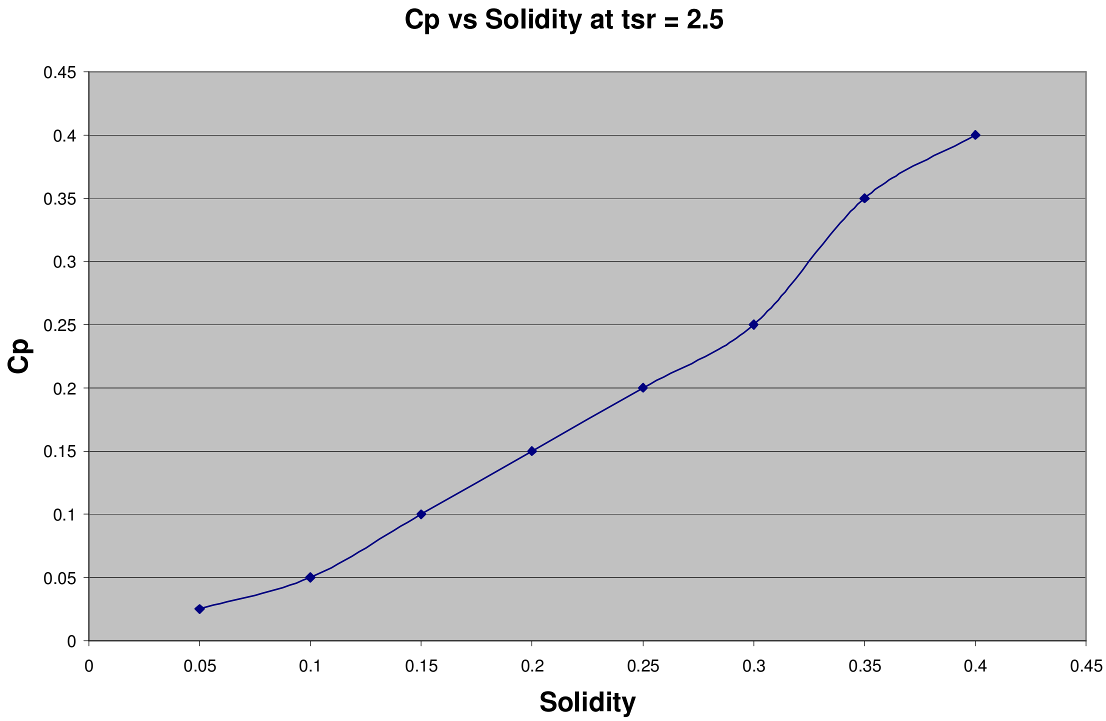


Figure 5 - Cp vs Solidity

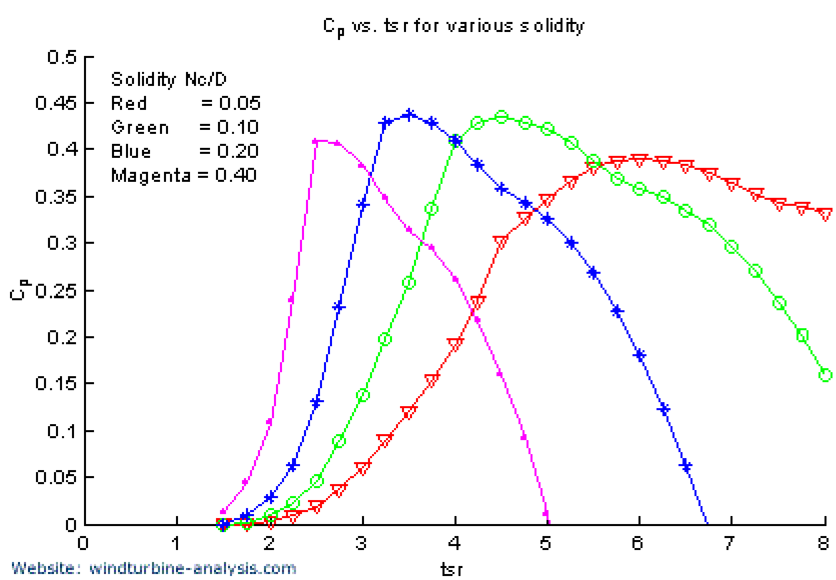


Figure 6: Cp vs. tsr for Darrieus Wind Turbines

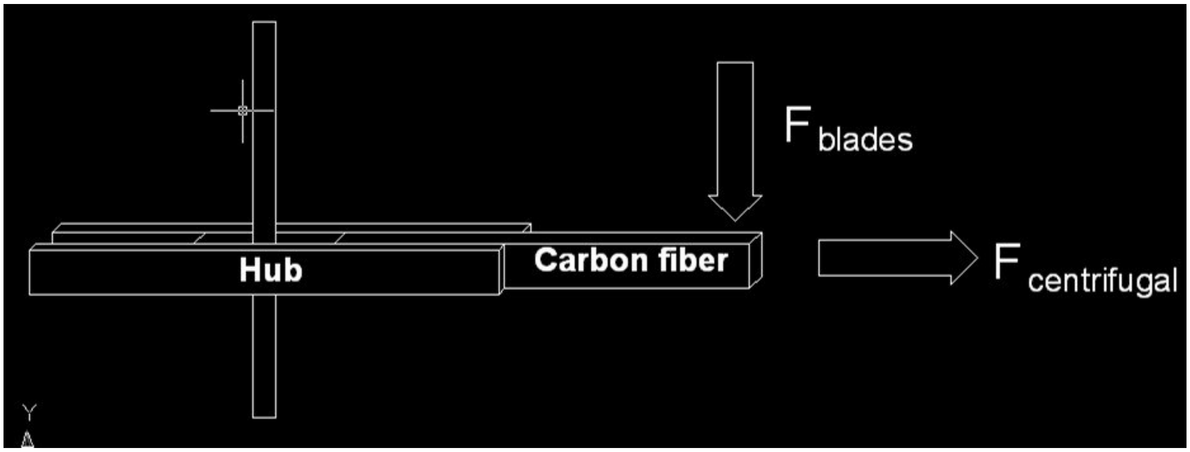
The higher the solidity, the higher the power produced and therefore the higher the torque produced. Therefore, it may be desirable to have the solidity as high as possible. For the turbine to rotate on its own while in the Darrieus position it must exceed the frictional torque in the system. If this is assumed to be 0.22 N-m again, the required wind speed varies from 2m/s to 7 m/s.

From speaking with many experts in the wind energy field from Sandia Laboratories and the Atlantic Wind Test Site, higher solidities have not been better with working prototypes. Rotors with higher solidities run at lower rotational speeds and require more expensive gear boxes. Therefore optimal solidities have been found to be in the range of 0.1 to 0.2. In conclusion, a solidity of 0.15 was chosen for the design.

4.2 Critical Speed Calculations

This turbine has two blades, a solidity of 0.15, and a diameter of 2m so, from [4], the cord length should be 0.15m, or approximately 6". From Figure 6, it can be seen that Darrieus turbines produce power at tip speed ratios of 1.5 and greater. If it is desired to have the turbine start in wind speeds of 5 m/s then the blades should be moving at 1.5 times the speed of the wind. The rotational speed, w_{dar} is found to be 71 rpm from [5], using a tsr of 1.5, radius of 1m.

4.3 Strengths Calculations



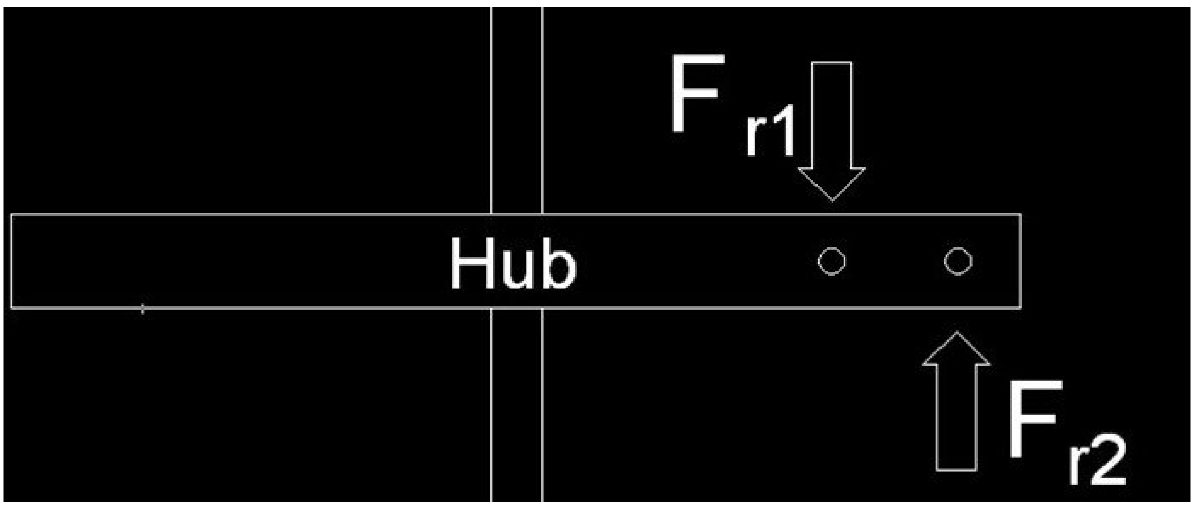


Figure 2 : Internal Forces on Arms/Hubs

The critical area of this design will be the area between the shaft and the airfoils. Before the materials were selected and fabrication started, several calculations were performed to ensure that materials of suitable size and strength were chosen. The first calculations were based on the weight of the blades and arms (F_{blades} in Figure 7). Since the exact construction method was unknown at this point, the exact weight could not be known, so a rough estimate of 200 N per blade was assumed. Using this number in the calculations, it was observed that there would be a large factor of safety, in every component, so fabrication was allowed to continue. It was believed that 200 N was a very conservative estimate for the weight of the blades and, after construction, this proved correct; the final weight was under 30 N. The effect of this weight would have the largest effect on the narrow area of the hub which is closest to the shaft, and on the bolts which hold the arm to the hub. Using the more accurate figure of 30 N, the results of these stresses are as follows:

Bending of Hub due to weight of wing

$\sigma_{bend,max} = Mc/I = 4.0$ MPa

Bolt Shearing, due to weight of wing

$\sigma_{shear,max} = Fr1/\pi r^2 = 18.5$ MPa

The next stresses are a result of centrifugal force. Using the more accurate number for the weight of the blades, a maximum centrifugal force of 5263 N was calculated. Two of the critical areas affected by this force are the same as above, where the bolts attach the arms to the hub, and where the hub is narrowest, by the shaft. A third critical area is where the aluminum mounting rod will sit in the bushings. The centrifugal force will try to shear this rod where it sits in the bushing. The resulting stresses are as follows:

Bolt Shearing due to centrifugal force

$\sigma_{cent,max} = F_{centrifugal}/A_{bolt} = 20.8$ MPa

Tension in Hub due to centrifugal force

$\sigma_{hub,cent} = F_{centrifugal}/A_{hub.min} = 8.8$ MPa

Shearing of mounting rod due to centrifugal force

$\sigma_{shear,rod} = F_{centrifugal}/A_{rod} = 46.7$ MPa

Note that all stresses calculated are well below the yield strength of aluminum (~300 MPa), which is the weakest material in use.

4.4 Centrifugal Force and Spring Rate

As stated above, the blades were weighed after fabrication was complete, and they had a mass of 3 kg. Since the mass of the blades was known, the centrifugal forces which would be acting on the blades could be worked out. This force had to be counteracted by springs, at least until the critical speed of 71 rpm was attained. The centrifugal force acting on the whole blade was found to be 118 N at a speed of 71 rpm. Since the plan was to use a spring at the top and another at the bottom, it was expected that each spring must exert a force greater than 59 N when the blades were partially closed. If this were the case, then the blades would stay open until this speed was reached.

Springs were selected, and fine tuned during testing with the use of turnbuckles. This fine-tuning was done to ensure that the blades were closing at the desired speed. After testing, the spring rates were measured and found to be approximately 500 N/m. The springs were stretched by 14.2 cm at peak extension, and the resulting force was found to be 69 N. This force is marginally higher than the calculated requirement of 59 N. This shows that the calculations were verified by the field testing which was performed. As well, this is proof that the springs could be fine-tuned to enable the blades to close at whatever rotational speed is critical, dependant on the wind conditions.

5.0 Prototype General Arrangement

Figure 3: Fully Assembled Turbine

5.1 Components

Base

The base will be a truncated pyramid, just less than 1 m tall. This base was fabricated last year, but it was too wide to be easily transportable. As a result, it was shortened so that it fits through a standard doorway. It has 3 levels, one at ground level, one about 1/3 of the way up and one at the top. There is a bearing mounted in the center of both the top and the middle levels.

Shaft

Sitting in these bearings will be the shaft. The shaft is a 3.6 m tall length of steel mechanical tubing, with initial dimensions of 1½" OD, 1" ID. To allow the shaft to sit on top of the bearing, thereby taking some of the weight off of the set screws, a technician milled a section at each end down to an OD of 1⅜", leaving a shoulder of 1/16".

Hubs/Arms

Attached to the shaft by set screws are 2 blocks of aluminum which, each of which are shaped like a horizontal “H”. These were fabricated by the technicians at Dalhousie. Bolted inside each open ends the each hubs is a lightweight arm that was fabricated by the group. These arms are made of two strips of carbon fiber which are attached over a piece of high-density foam, using epoxy. These materials were selected for their high strength to weight ratio. (see Appendix C for a detailed drawing)

Blade Mounting

At the furthest extremity of each arm there is a bushing. This bushing is made of ultra high molecular weight (UHMW) polyethylene, and they contain a small ball bearing. Beside these bushings, a drawer slide is bolted to the arm. Mounted on the slide, just next to the outer end, is another bushing. This bushing will seat one end of a mounting rod from an airfoil, while the bushing on the arm next to the drawer slide will seat the mounting rod from the other half of the airfoil. The arrangement of this mounting hardware is shown in Figure 9.

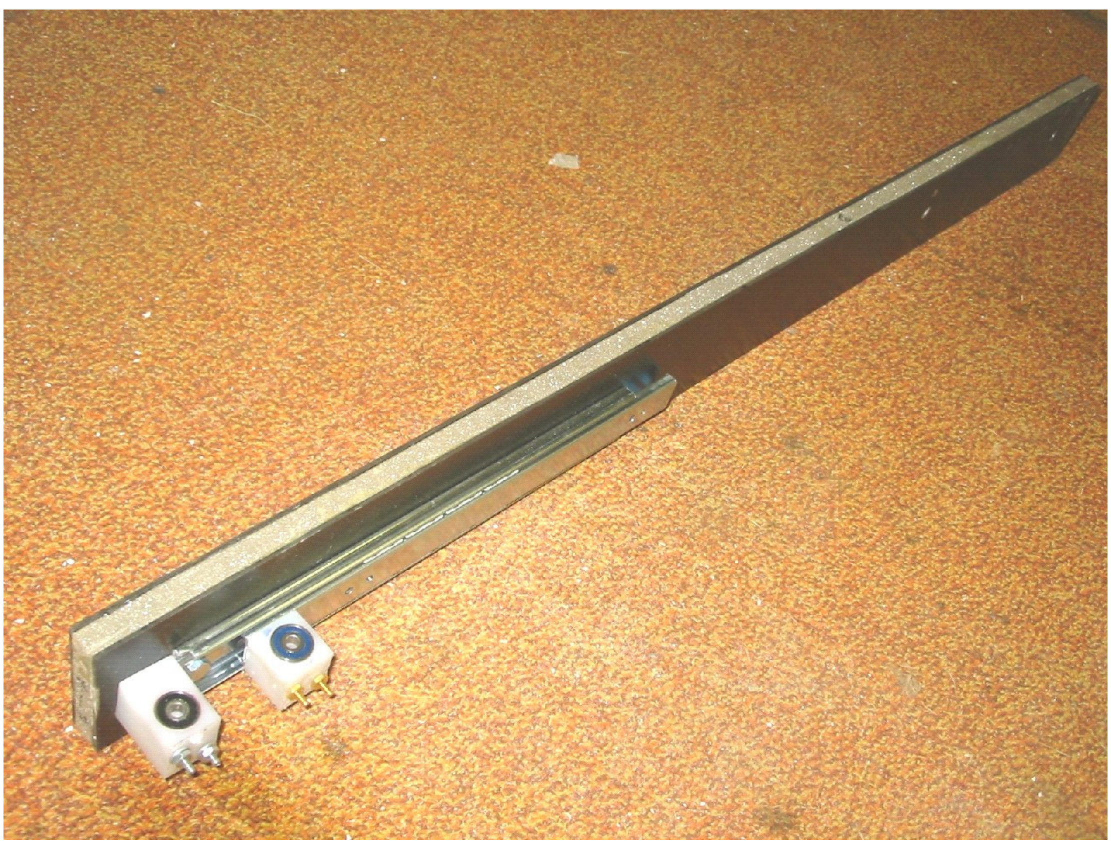


Figure 4 : Arm/mounting hardware

Airfoils

The airfoils have been designed to make the turbine function as a drag devices as well as a lift driven device. To accomplish this, the airfoils will fold between an open (drag) and closed (lift) position. To enable such a fold a straight airfoil must be used, to which a hinge can be attached. This is why the design will appear similar to the H-type Darrieus rather than the eggbeater type. These airfoils were shaped to resemble the NACA 0015 standard airfoil. This shape was suggested by experts from Sandia University.

Each half-blade profile is shaped out of extruded polystyrene, which was sanded using a specially constructed sanding block. When an appropriate profile was complete, a long strip of carbon fiber was attached to the inside and a long aluminum rod was attached to the outside periphery, using epoxy. The purpose of the carbon fiber is for mounting the hinge, and the purpose of the aluminum rod is for mounting the blades. When all these steps were completed, a layer of epoxy resin and matting were applied to give the blades their strength. A completed half-blade cross-section can be seen in Figure 10.

Figure 5 : Completed Half-blade

When construction of 4 half-blades was completed, two half-blades were attached together via a piano hinge which runs along the leading edge of the airfoil to produce a completed folding blade. The final step was to paint the blades and assemble the turbine.

Opening Mechanism

Since the blades will have to be kept open at low speeds, there is a spring and turnbuckle attached to each drawer slide to apply an adjustable force to the blades. This setup will be stretched between the drawer slide and one of the bolts used to hold the arms to the hubs. There was also a bolt added beside the sliders which would operate as a stopping mechanism, preventing the blades from opening to an angle greater than 90°. This arrangement can be seen in Figure 11.

Figure 6 : Spring/Turnbuckle Arrangement

5.2 How will this prototype function?

When the Darrieus is not moving, or the wind speed is low, there will be insufficient lift to propel the turbine. Therefore, the airfoils must function in the drag driven mode. They will be held open by the spring/turnbuckle system mentioned in the previous section. The wind will be caught by one of the open blades, and diverted around the other. This will result in a net torque which will drive the open airfoils around the shaft. This will induce rotation of the turbine, which will lead to centrifugal forces.

The rotational speed will increase until a critical point at which the turbine is moving fast enough to be driven by lift forces. At this point, the tip speed ratio will be approximately 1.5. The opening/closing mechanism will be designed such that the centrifugal forces will overcome the inertial forces and spring forces at exactly this critical speed. This will lead to a translation of the drawer slide, which will result in the airfoil being closed, to function in the lift driven mode, as a standard Darrieus would.

6.0 Budget

The most expensive parts of this design, in terms of material cost, were the hubs. Labour costs are not included, as it was provided free of cost by Dalhousie University. The aluminum required for the hub fabrication cost approximately $200. $100 each was spent on fasteners (including epoxy) and the shaft. The project was able to be completed without exceeding the original budget of $780. In order to achieve this, however, the blades were not able to be made using a CNC machine and were shaped manually. Also, the carbon fiber used was donated by an outside source, which helped reduce the overall cost. A more detailed budget is included in Appendix B.

7.0 Testing

On March 28, 2004, testing was done on the prototype at two locations: Lawrencetown Beach and Citadel Hill. At Lawrencetown the turbine was set up on top of a cliff with average wind speeds upwards of 9 m/s and gusts of up to 15 m/s. These wind speeds were well above the design range, but it was decided to try it anyway. As expected, the winds proved to be too much and the drawer slides separated, leaving the blade flapping loosely. From this short test, it was also found that the stops should have been substantially larger, to prevent overriding. It was decided that for the safety of the turbine, it should be moved to a new location.

Figure 7 : Testing on Citadel Hill

The second test was performed at Citadel Hill where wind speeds measured between 4 and 6 m/s, with gusts up to 9 m/s. These conditions were exactly for what it was designed, so several different tests were done here. The first was just to let the turbine do what it was designed to do, open the blades and let the wind propel itself, then see if enough lift was being produced when the blades closed. It seemed as though the turbine would slow down too much in the regions where lift isn't produced thus the blades kept opening up just to allow rotation.

Next the blades were clamped open to check the maximum attainable rotational speed in the drag position. In this position it was observed that there was plenty of windswept area to rotate the turbine. A rotational speed of 75 rpm was achieved, where it was calculated to only need to reach a speed of 71 rpm to self-start in those winds. This essentially proves the design is capable of inducing rotation up to a speed where the lift forces should be capable of propelling the turbine.

Lastly, the blades were clamped shut and a wire was wrapped around the shaft. The wire was then pulled, resulting in an applied torque, which brought the turbine up to speeds in excess of 100 rpm. The turbine was observed to slow down considerably once applied torque was stopped. Insufficient amounts of lift were being produced, and this led to the belief that the blades were not exactly NACA 0015 airfoils once they were closed. This theory was upheld by Carl Brothers, the head of the Atlantic Wind Test Site. He said that given the rotational speed achieved, in those wind conditions, the Darrieus should have had no problem sustaining rotation. He was sure the main factor contributing to its failure was the poorly shaped blades.

7.0 Future Work

7.1 Design Improvements

While the prototype did not perform as well as initially hoped, with a few changes to the design this should improve greatly. The most important area of improvement is the blade construction. Currently the profile, while close to the desired NACA 0015 shape, is not exact. Having the precise shape is essential to generate sufficient lift. This could be accomplished by using a CNC mold as opposed to manual shaping. This was the preferred fabrication method but, however, the budget was much too small to allow for this. Also, the current hinge placement (with a large part protruding from the leading edge) disrupts the flow around the airfoil. Mounting the hinge in such a way that retains a true leading edge would drastically increase the lift generating capabilities of the airfoil. This could easily be accomplished by covering the whole blade with a smooth material which would cover the hinge tip.

Another change that would improve the performance is altering the design of the arms. They are creating a large drag force, hindering the rotation of the blades. By making them an aerodynamic shape as opposed to simply flat plates, it would greatly reduce the overall drag on the device. Another option would be to simply mount the arms in a manner rotated 90° from their current position, which would reduce the total area facing the wind.

There are several simple improvements that could be made on this design. Some of these improvements would be to purchase better bearings, install better stops, and add weatherproofing. A better bearing (possibly a linear bearing) would enable the turbine to turn more freely, reducing the starting torque and making everything work much more smoothly. The bolts used to prevent the sliders from opening the blades wider than 90° were simply not long enough and the slider slid over top of it, resulting in a blade shape that was highly unproductive. Using a longer bolt would eliminate this problem. Since the turbine is designed to be used outside for a long period of time, some measure to weatherproof the device must be taken. Parts such as the hinges, sliders, and springs should be covered to prevent ice/rust buildup and ensure smooth operation even after extended periods in inclement weather conditions.

7.2 Additional Considerations

In order for this design to be most useful there are several additional items that must be considered. These items were deemed to be out of the scope of the project given the time and monetary constraints; however, they must be addressed if this project is to prove its true value. Once the arms have been redesigned and the blades have been fabricated to the exact specifications, this turbine will be capable of spinning at extremely high rotational speeds. As a result, the centrifugal forces will be very high, and the turbine could be damaged. To keep the turbine from reaching these dangerous speeds a braking mechanism should be designed. This mechanism should not require human intervention; rather, it should engage only when the speeds are high, and disengage automatically when these speeds decrease.

To fully understand the potential of this design, a generator must be coupled to it. This will allow the users to gauge the output in various wind speeds. Since the torque produced in the open blade position is relatively low a clutch mechanism may be required, which will allow the turbine to get up to speed before engaging the generator. This will allow the turbine to produce sufficient torque before the load is applied.

8.0 Conclusion

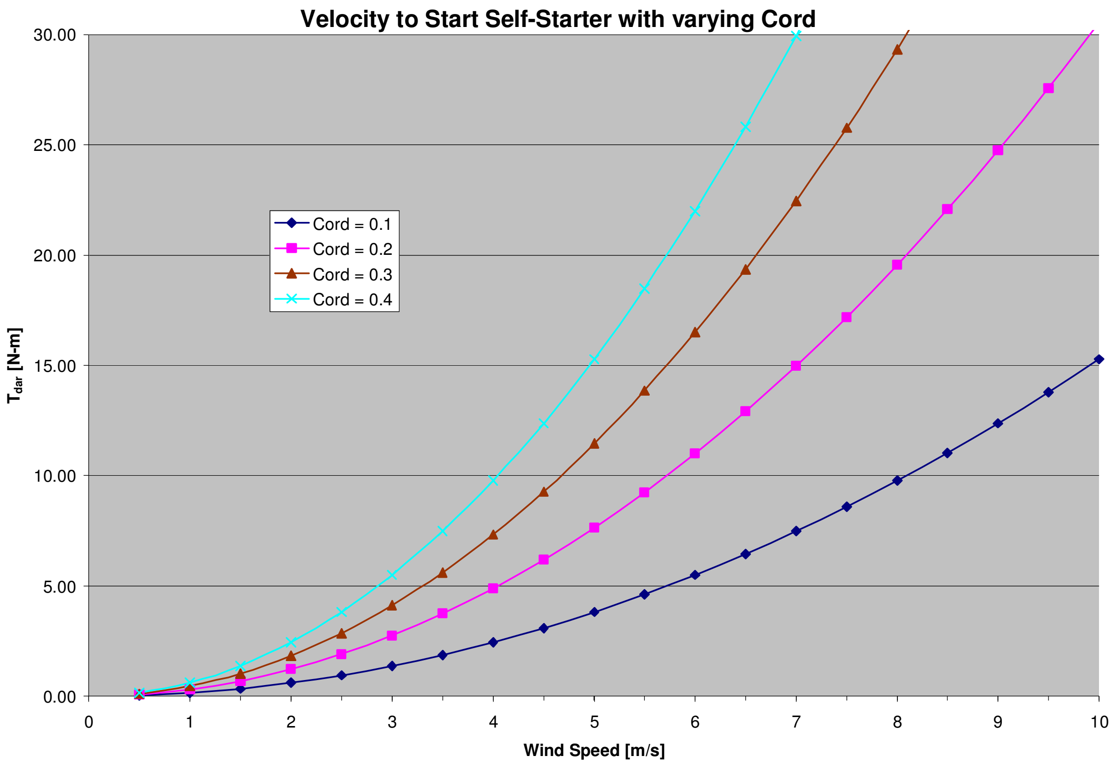
The initial goal of this project was to come up with a self-starting mechanism for a typical Darrieus wind turbine. However, the solution attempted was anything but typical, resulting in a totally new breed of Darrieus turbine. One could argue that the goal was not accomplished, as this solution is not designed to start a typical Darrieus. On the other hand, this new breed that was developed probably has more potential than a device which attaches to a typical Darrieus. This potential has not yet been realized, but the concept has been proven to function as a self starter. This design fills the functions required of a starting mechanism; it is mainly the inaccuracy of the blade profiles in the closed position that led to less than desirable results during testing.

Most of the tough design problems have been resolved, so another group could easily concentrate on fabricating quality blades and improving the overall design. With a sufficient budget, this design could easily be developed to capitalize on the potential which has been discovered. While it is disappointing that the design this year has not proven to be successful, much has been learned, and the concept that has been proposed has much room for future development.

References

1. http://www.solwind.co.nz/, October 15, 2003.
2. http://www.epelectric.com , November 28, 2003.
3. http://www.windturbine-analysis.com, January 29, 2004.

Appendix A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Cord = 0.2
Cord = 0.3
Cord = 0.4
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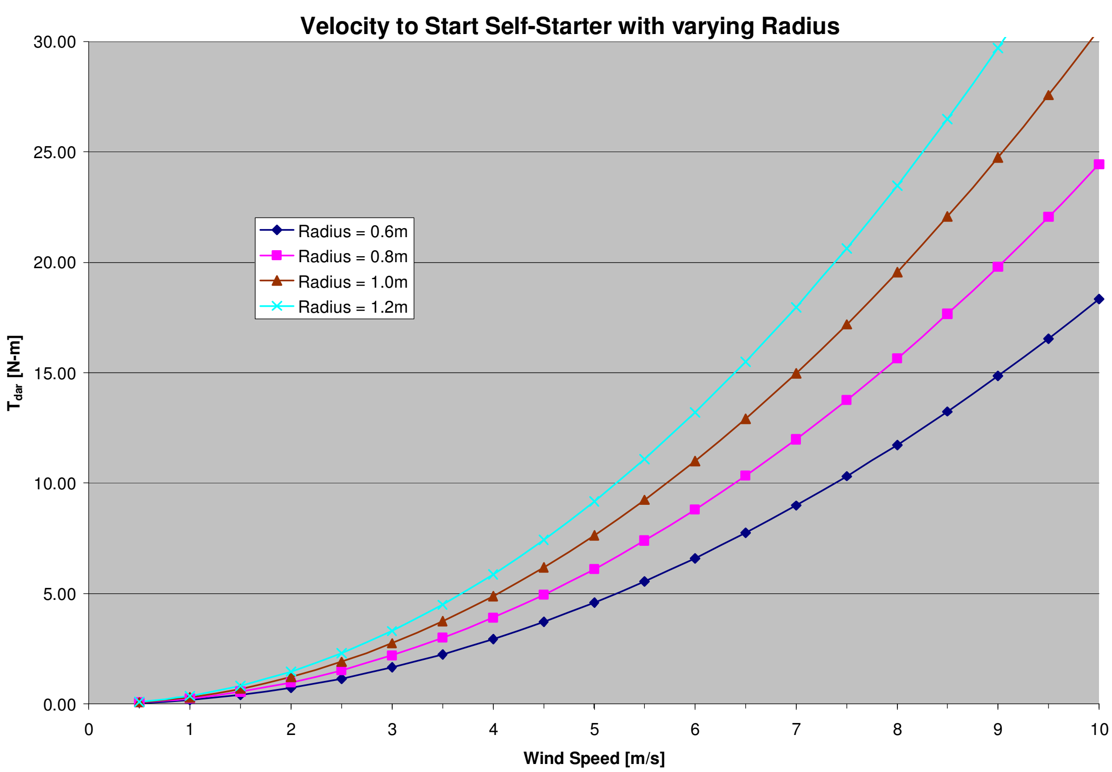
Wind Speed [m/s]
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
1
2
3
4
5
6
7
8
9
10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Radius = 0.8m
Radius = 1.0m
Radius = 1.2m
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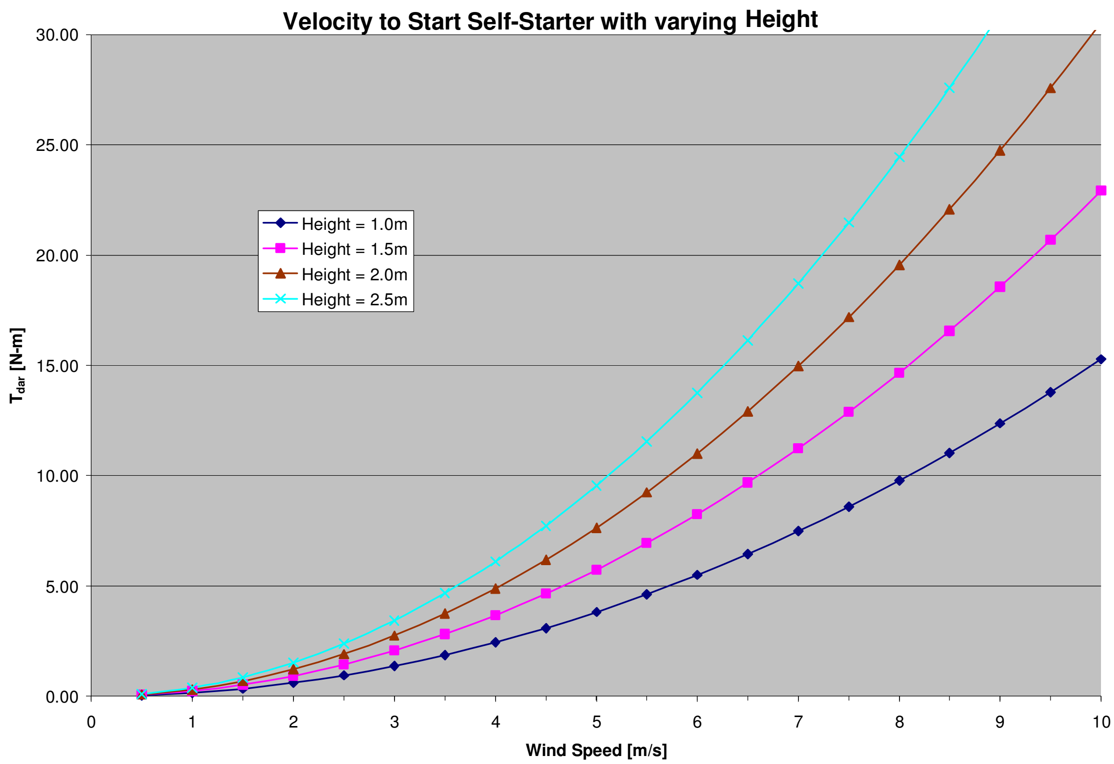
Wind Speed [m/s]
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
1
2
3
4
5
6
7
8
9
10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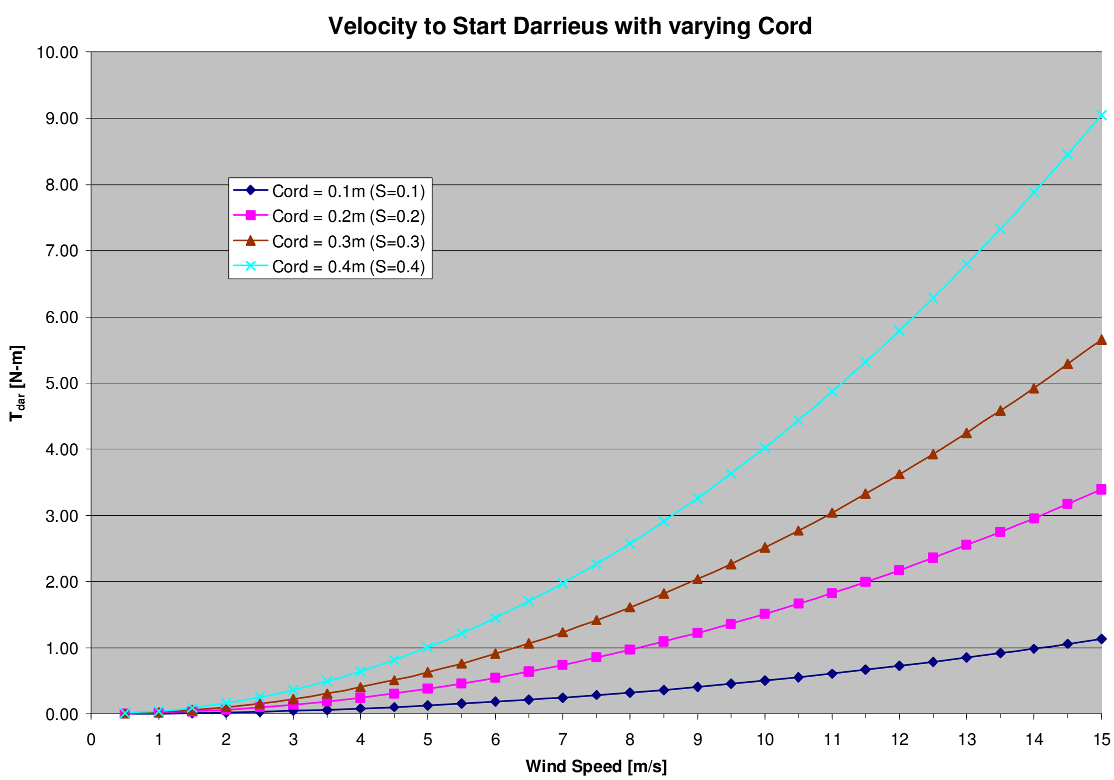
Height = 1.5m
Height = 2.0m
Height = 2.5m
T_{dar} [N-m]
Wind Speed [m/s]


Velocity to Start Darrieus with varying Cord
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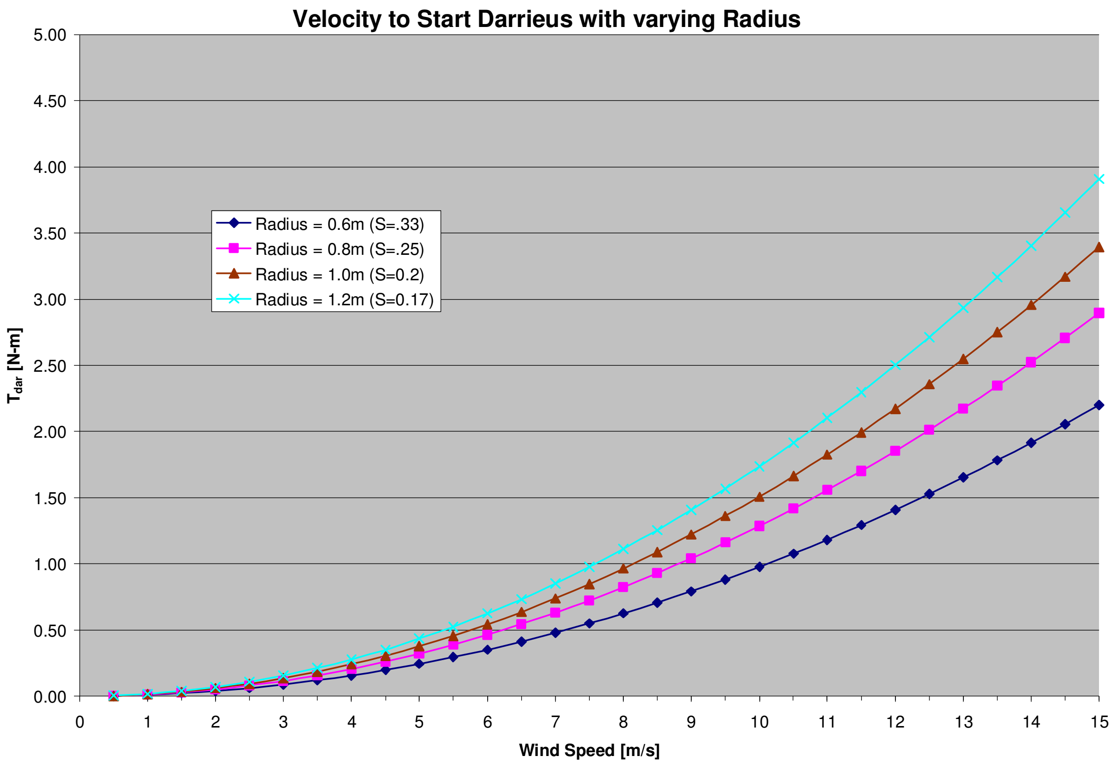
Cord = 0.2m (S=0.2)
Cord = 0.3m (S=0.3)
Cord = 0.4m (S=0.4)
T_{dar} [N-m]
Wind Speed [m/s]


Velocity to Start Darrieus with varying Radius
Radius = 0.6m (S=.33)
Radius = 0.8m (S=.25)
Radius = 1.0m (S=0.2)
Radius = 1.2m (S=0.17)
T_{dar} [N-m]
Wind Speed [m/s]
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
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11
12
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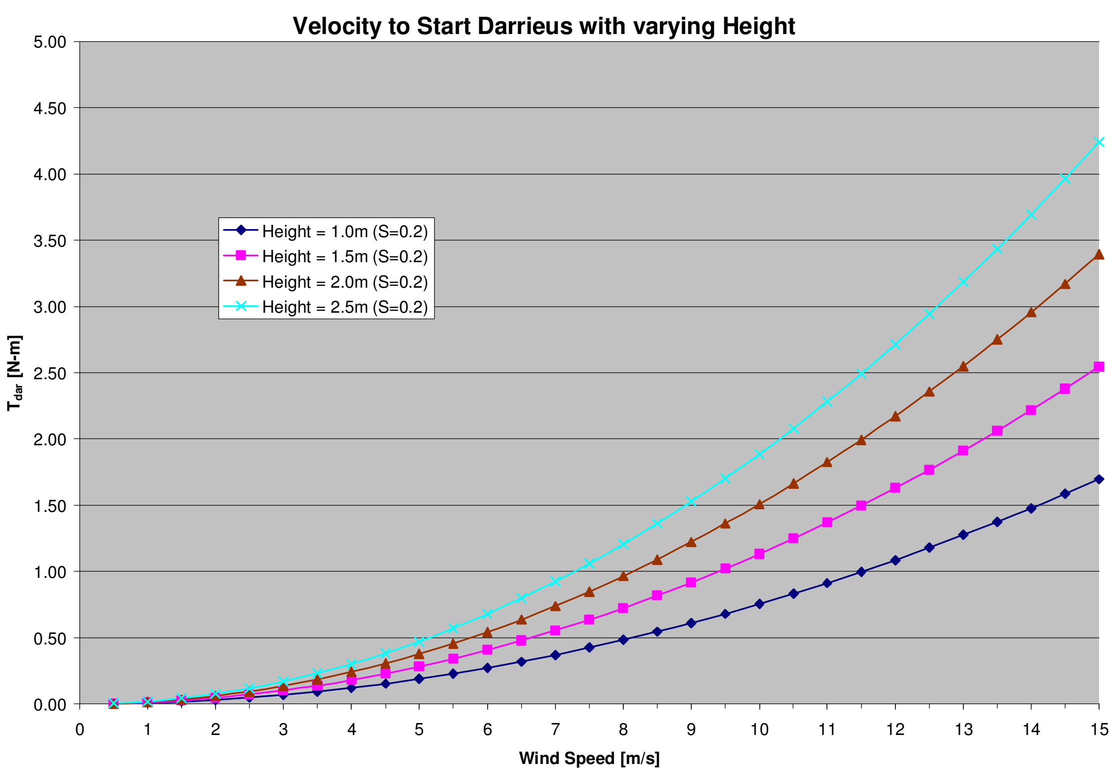
14
15


Velocity to Start Darrieus with varying Height
Height = 1.0m (S=0.2)
Height = 1.5m (S=0.2)
Height = 2.0m (S=0.2)
Height = 2.5m (S=0.2)
T_{dar} [N-m]
Wind Speed [m/s]
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Appendix B

BUDGET

Design Group #7

7-Apr-04

INCOME				
Department Model Money				$50
Money left from Last Years Group				$430
Departmental Money				$300
			TOTAL	**$780**

EXPENSES		**Cost/part**	**Quantity**	**Cost**
Small Scale Models:				
Preliminary model for presentation (built)		$30	1	$30
Wind Tunnel Model (built)		$40	1	$40
Full Scale Model:				
Blades				
	Carbon Fiber	$0	0	$0
	Aluminum Stability Rod	$3	4	$12
	Hinge	$12	2	$30
	Extruded Polystyrene	$10	1	$10
	Hinge Cover	$0	2	$0
	Fiberglass	$20	1	$20
Support Arms				
	Carbon fiber	$0	0	$0
	Slider Mechanism	$16	2	$42
	Springs	$10	2	$20
	Honeycomb	$75	1	$75
Hubs		$100	2	$200
Shaft		$100	1	$100
Bushings		$7	8	$56
Fasteners etc…		$100	1	$100
			TOTAL	**$735**
			NET	**$45**

Appendix C