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Using the Moment of Inertia as a Means of Better Controlling the Speed of Wind Turbines

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USING THE MOMENT OF INERTIA AS A MEANS OF BETTER CONTROLLING THE SPEED OF WIND TURBINES

By

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Scholarship Project Advisor (printed)	Signature	Date
Honors Council Chair (printed)	Signature	Date
Honors Council Member (printed)	Signature	Date

To my future wife and best friend, Abigail Allen, who has supported me throughout my entire college career; and to my parents, who have worked hard to give my siblings and I the opportunity to pursue higher education and supported us our entire lives.

ACKNOLWEDGEMENTS

I would like to thank my mentor and professor, Dr. Schroeder, for guiding me and encouraging me through this research process and my entire academic career.

I would also like to thank the honors department for making this opportunity possible and for the funding provided for this project.

I would like to thank the Walker School of Engineering for providing sensors and instrumentation as well as the 3D printer and materials for fabricating the turbine.

I would like to thank Dr. Armstrong of the chemistry department for providing me with some acetone and a safe environment to work in while melting my turbine together and for encouraging me in my research as well.

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ABSTRACT

In the following document, the possibility of using the moment of inertia as a means of speed control for a wind turbine is explored. This document gives an introduction to wind energy and current speed control methods. This information was obtained through databases found at Benner Library. Also, an experiment was used to collect data and determine the relationship between the moment of inertia and angular velocity of a turbine. A model turbine was fabricated and powered by a fan while a Logger Pro program was used to record the angular velocity of the turbine. The moment of inertia of the turbine was modified by sliding weights along the arms of the turbine. The data collected showed a 56% decrease in variability of the angular velocity of the turbine when using the moment of inertia as a speed control method. These results showed that this could be a viable option for controlling the speed of a turbine, and further research should be done to see if this is true for a wider variety of wind speeds as well as for a dynamic version of this speed control method

INTRODUCTION

Over the course of one day, two and a half million dollars’ worth of modern technology literally came crashing to the ground. On September 28, 2008, Typhoon Jangmi hit the coast of Taiwan and caused the entire wind turbine industry to take a step back and reconsider the way it manufactures and monitors wind turbines everywhere. When wind turbine number two on the shore in Taichung Harbor was found bashed into three pieces on the coast the next day, the Taiwan Tech research team was asked to analyze the situation (Chou & Tu, 2011). While this was one of the first wake up calls that the wind turbine sector of the alternative energy industry received, it was not the first incident of its kind caused by excessive wind speeds. Of the many potential causes of wind turbine destruction, turbine speed control failure is a major contender. At the time of this accident, more than eighty wind turbines of similar size were being built (Chou & Tu, 2011). This caused the industry to begin to look for ways to prevent future turbine failures due to high wind speed. Since then, many efforts have been made to improve the condition monitoring systems, structural integrity, and speed control systems of a wind turbine. This paper will present a new method of speed control that could be implemented in wind turbines. It uses masses that slide along the arms of the turbine to control the angular velocity of the turbine by changing the moment of inertia. In light of the many problems a lack of reliable speed control can cause a wind turbine, there must be a way to improve traditional speed control methods in a cost-effective, safe, and consistent manner.

REVIEW OF LITERATURE

Before one can begin to create a solution to various wind turbine problems, one must first understand the impact of wind energy on the alternative energy industry as well as learn of the shortcomings of this relatively new technology. In a time where gasoline has previously reached an upwards of four dollars a gallon and other sources of energy such as coal are destructive to the environment, any form of clean, renewable energy is welcome. One of the fastest growing renewable energy source industries is the wind power industry. With government funding and the public support, wind energy has developed much over the past decade. The government is not the only organization that supports wind energy, though. Private corporations and even the public in general express growing support for this form of alternative energy. In Sweden, a power company gave its consumers an opportunity to choose between using wind energy and using energy produced by traditional sources such as coal and nuclear power plants. Surprisingly, more of the Swedish people chose to use this “green” energy over regular electricity. In fact in the course of two years, consumption of electricity produced by wind turbines had doubled (Ek, 2005). This electricity was no different from electricity coming from other sources; however, consumers preferred it anyway, partially due to the fact that it is an environmentally friendly energy source.

Shortcomings

Obviously, there is plenty of support for the wind energy industry. One thing that could hold it back is the shortcomings of modern turbines. Turbines are great at converting wind energy into electricity, but currently they cost more to build and maintain than they are worth.

Cost and revenue

As mentioned earlier, one wind turbine can cost an upwards of two and a half million dollars to produce. However, this initial cost is not the total cost. There are also maintenance costs that come along with running a turbine. Operation and maintenance costs account for between seventy-five and ninety percent of the total costs of a wind turbine (Garcia Marquez, Tobias, Pinar, & Papaelias, 2012). This means the largest cost of wind turbines comes from maintenance. Replacing a gearbox alone costs 250,000 dollars (Van Rensselar, 2010).

Turbine failure

Despite all of the costs that come along with putting up a wind turbine, they typically pay for themselves after about fifteen years. The problem is the average life expectancy of a turbine is twenty years (Chou & Tu, 2011). With such a short lifespan, there is no room for turbine failure, yet turbine failure still occurs after years of research and development. If these turbines fail before fifteen years, then the company experiences a loss as opposed to a profit produced by that turbine. Because of this simple truth, efforts must be made to prevent the wear and tear that eventually leads to turbine failure. Also, in moments of extreme weather, preventative measures must be taken to prevent the total destruction of a turbine like the one in Taiwan mentioned earlier. Since mechanical brakes are used to stop wind turbines in extreme wind and are also often susceptible to eventual harmful wear and tear, a new form of braking could be very beneficial for wind turbines and make wind energy even more appealing to the public. As one can see, wind energy is a very promising field, but it has its limitations due to maintenance costs and failure. A new method of braking may make wind energy a more plausible alternative.

A Look at Current Speed Control Methods

Although one could begin to create a new way of braking a wind turbine without looking at anything else, it would be better to first examine the current control methods and take away ideas from them. Braking methods are used for more than just stopping a turbine from destroying itself; constant speed control is necessary for wind turbines to be as energy efficient as possible. Despite what many think, when wind speed increases, wind turbine energy production only increases up to a certain speed; high wind speed actually causes no increase in energy production.Wind turbines ideally run at speeds of about twenty-five miles per hour (Van Rensselar, 2010). Since wind rarely if ever blows at a constant wind speed of twenty-five miles an hour, continuous monitoring and adjustment must be made by a turbine to keep it running at maximum efficiency. Through the process of reverse engineering, one can look at a current mechanism used to achieve the desired goal, break it down to its fundamental parts, and then use similar structures in the new design if they work well (Dym & Little, 2009). This means that looking at the speed control methods used now can help one create better mechanisms in the future.

Methods Used

Traditional horizontal axis wind turbines use three main methods of speed control. These methods are pitch adjustment, yaw adjustment, and mechanical braking. Throughout a turbine's lifetime, all three of these methods are likely to be used; however, pitch and yaw adjustments are used much more often than mechanical braking.

Pitch adjustment

Pitch adjustment is continually used to control wind turbine speed. Simply stated, pitch control is the control of the angle of the blades on the wind turbine. The larger the angle of the blades, the less wind energy a turbine receives (Melício, Mendes, & Catalão, 2011). So, whenever turbine speed needs to be reduced, some energy is used to rotate the blades so that they will actually catch less wind, causing the turbine to slow down. The same method can be used to increase turbine speed when wind speeds are lower, but it can only do this to a certain extent. Pitch control cannot cause a turbine to go faster than the wind that is blowing it. While pitch control has many advantages, there are also some disadvantages that come along with this form of speed control.

As it is, pitch control is generally a great way to control turbine speed. It almost instantly adjusts blade angle as needed, causing turbine speed to remain fairly constant. In times of dangerous wind speeds, it can adjust the blades so that they capture the least amount of wind as possible, potentially preventing a major turbine breakdown. It is a very effective way to control wind speed. However, there are some disadvantages to this method of turbine speed control. In research done by Melício, et al. (2011), researchers intentionally caused a pitch control malfunction to see what the effect would be on the turbine. When the malfunction happened, the blades became locked at a fifty-five degree angle and the power production dropped by almost nine hundred kilowatts. Pitch control is too vital to a turbine's function to be able to break down, but malfunctions will happen regardless. Though it can instantly adjust to changes in wind, it is not effective at instantly stopping a turbine when problems arise. For example, if some part of a turbine were to malfunction, pitch control could by no means instantly stop a turbine's motion, allowing further harm to be done to the turbine before coming to a complete stop. Also, some energy would be required to use pitch control, taking away from the overall energy production of a turbine.

Yaw adjustment

While pitch control does a great job of controlling turbine speed, it could not be successful without other forms of controlling the amount of wind a turbine catches. Yaw adjustment is another method of controlling wind turbine speed that focuses on adjusting the turbine to either increase or decrease the amount of wind a turbine receives. This adjustment system causes the whole rotor system to rotate around the main pole of the turbine, causing rotors to either face or not face the wind (Garcia Marquez, et al., 2012). This is an effective form of control that allows the turbine to receive wind from any direction. If a turbine is spinning too quickly, yaw adjustment allows the turbine to simply rotate until the rotors are not catching the wind anymore. In this way, potentially destructive situations can be avoided using this method of speed control.

Although yaw adjustment does a fairly good job at helping control the speed of a wind turbine, it has both advantages and disadvantages that one must weigh when considering a method of speed control on a wind turbine. Like pitch adjustment, yaw adjustment is great in the sense that it does not cause wear and tear on the turbine, reducing the amount of maintenance that has to be done on a wind turbine. It also is necessary to turbine function because without it, the rotors would not be able to be oriented to the wind to capture energy. However, it also requires energy to change the direction of the rotors, and this takes away from the overall power production. Another disadvantage to yaw adjustment is the fact that it takes time to rotate the whole rotor system. This means that in moments of drastic wind speed change, the yaw adjustment would not be quick enough to prevent the high wind speed from affecting the turbine. As one can see, yaw adjustment effectively controls turbine speed, but it cannot be expected to do this without the help of other mechanisms.

Mechanical braking

When looking at pitch and yaw adjustment, it is clear that these mechanisms do not actively brake the turbine, so they cannot be trusted to quickly stop turbines in cases of emergency. This is why all turbines have mechanical brakes that do this exact job. Mechanical braking is achieved by a steel brake disc on the high-speed shaft coming into contact with a caliper. Friction does the rest after this. The brakes are generally applied only after other speed control methods have been used to slow the turbine down. However, in cases of emergency, these brakes are applied right away to bring the turbine to a halt. (Entezami, Hillmansen, Weston, & Papaelias, 2012). Obviously, mechanical braking is the most reliable, yet least used form of speed control in a wind turbine.

Before deciding to settle on a mechanical braking system for turbines, one must first examine both the desirable characteristics and the shortcomings of this system. Mechanical braking is by far the fastest-acting speed control system on the turbine, making it the most effective at stopping a wind turbine in emergencies. On the other hand, it still takes some mechanical brakes an initial ten seconds before the brakes actually kick in (Rajambal, Umamaheswari, & Chellamuthu, 2005). In the amount of time it takes for these brakes to kick in, a wind turbine could have already spun out of control and destroyed itself. Even when the brakes do work quickly enough to prevent too much acceleration, the amount of stress these brakes undergo causes much wear and tear that eventually requires maintenance or a replacement of components. According to Entezami, et al. (2012), “Wind turbine brakes experience extreme stresses, so special alloys are used in brake disc manufacture, capable of withstanding temperatures up to 700 °C” (p. 175). Even this is not enough to prevent the rapid breakdown of parts. To avoid these problems, one must look for a new method of cost-effective speed control to solve this problem.

Current Possible Solutions

As mentioned earlier, current speed control methods are usually effective in carrying out their purposes. However, some methods simply are not effective without the help of other control systems, while others cause continual maintenance or replacement to be implemented. Looking for other speed control mechanisms could be well worth the search because it would end up saving costs in the long run. Of the current possible solutions to this speed-control problem, the two most popular are electrodynamic braking and an improvement of condition monitoring methods.

Electrodynamic Braking

Electrodynamic Braking is a developing form of braking for turbines that is looking fairly promising. In the process of electrodynamic braking, a switch connects a large capacitor to the generator of the turbine, allowing a large charge to be built up using the power produced by the wind turbine. As a result, a large current is distributed throughout the generator and rotors, causing an electromagnetic torque to be produced in the opposite direction of rotation. This causes a braking effect to occur on the turbine (Rajambal, et al., 2005). While this method can be somewhat confusing, it has characteristic that make it a very plausible candidate for a new form of speed control.

Just as the current speed control methods have both positive and negative aspects, electrodynamic braking has both appealing and unappealing characteristics. The best trait of this system is the fact that no physical contact is required to stop the turbine. This means there would be no wearing down of parts and, therefore, no need for replacing parts or constant maintenance of the wind turbine. Another great aspect of this method is the braking can be effectively applied at higher speeds than mechanical braking. In fact, in their research, Rajambal, et al. (2005) found that electrodynamic braking can be applied at speeds that are about 250 rotations per minute higher than the speeds that mechanical braking is applied at. This means that braking can be applied sooner with this system. One disadvantage of this system is it still requires other forms of speed control to work in collaboration with it. It can only reduce the speed of a turbine to about sixty percent of its initial high speed (Rajambal, et al., 2005). Also, this form of speed control can only cause a turbine to slow down. It cannot promote an increase in velocity like pitch and yaw adjustments can. Regardless of its disadvantages, electrodynamic braking still seems like it could be a very welcome addition to a wind turbine’s speed control system.

Improvement of Monitoring Methods

While replacing the current braking mechanism could be a viable option for improving speed control, improving the condition monitoring systems of turbines could be another way to solve this problem. Condition monitoring is a very viable way to control the speed of a wind turbine. It works exactly as the title states; the condition of the wind turbine is constantly monitored by a condition monitoring system. This causes the turbine to be able to instantly act to changes in wind speed and direction or a part breakdown by receiving this information and then relaying it to the appropriate area. So if wind speed picked up, the monitoring system would simply tell the turbine to change its blade pitch. If a part breaks down, the system would alert the maintenance department and the issue would be fixed as quickly as possible. This beats having scheduled maintenance checks because these are a waste of time and resources most of the time (Hameed, Ahn, & Cho, 2010). This concept is so simple, yet so innovative that it could easily be another solution to speed control problems as well.

Like other methods of speed control, condition monitoring systems have both positive and negative attributes that one must look at before he or she decides to implement the system. One benefit to condition monitoring systems is they have the ability to predict impending faults before they happen (Hameed, et al., 2010). Therefore, with condition monitoring, parts can be replaced before they break, preventing further damage to the machine. Another positive aspect of this mechanism is it can more accurately detect changes in wind speed and respond faster to outside influences on the turbine. While the system is excellent at predicting part failure, it does not do anything to prevent it. This is one downfall to condition monitoring systems. All they can do is tell one that a part is going to break, they cannot stop it. The same speed control mechanisms themselves still have to be used in conjunction with this system. Obviously, a condition monitoring system could be useful in the future, but it would not necessarily solve the speed control problem on its own.

Purpose and Proposal of Research

Purpose Statement

As renewable energy sources become more popular, the desire to make the systems that capture this energy more efficiently and through more economically viable means becomes greater. Wind energy is currently a popular source of alternative energy, but some improvements can be made on the way the turbine speed is controlled. The research explored the viability of using the moment of inertia as a means of better controlling the speed of wind turbines. This was a design project done through the creation of a model of a vertical axis wind turbine with attached sliding weights that increased and decreased the moment of inertia. Tests were run on this model in order to see if changing the moment of inertia on the wind turbine is an effective means of speed control.

Proposed Design

Important Concepts and Principles

A moment of inertia braking system could be a very viable option for controlling the speed of a wind turbine. The advantages to this form of speed control are numerous. It would provide instantaneous speed control, making it less likely for a turbine to spin out of control. It would not require any power to work because it is a purely physical principle. In order to understand how such a system would work, one must know about the moment of inertia and the conservation of energy principle.

The moment of inertia

The moment of inertia is a concept that can be summarized as follows: the farther out a mass is from its point of rotation, the more force it takes to move this mass around its axis (Serway, R. A., & Jewett, J. W., 2009). This means that if two identical turbines were different only by a mass added along the arms of one turbine, more force would have to act on the turbine with added mass to achieve the same velocity as the regular turbine. Using this principle, the speed of the rotors of a wind turbine could be adjusted by sliding masses farther outward or inward on the rotor. This mass could be solid or liquid, and it may be able to work on a horizontal axis turbine as well as a vertical axis turbine. However, to work on a horizontal axis turbine, some adjustments must be made to the design. Currently, there are no turbines on the market that have this type of speed control.

Conservation of energy principle

According to the first law of thermodynamics, energy can neither be created nor destroyed. An equation that represents this concept is shown here:

$$KE + PE + U = constant$$

where KE is kinetic energy, PE is potential energy, and U is internal energy (Cengel, et al, 2012). For this experiment, I assume U is constant because the temperature of the system and other internal energy sources will not change. I also assume PE is constant because both systems will remain at the same height and no other sources of potential energy are present. This means that between the two models, kinetic energy has to be the same in order for the conditions of the first law to be true. The equation for kinetic energy for a rotating body is shown here:

$$KE = \frac{1}{2} I \omega^2$$

where I is the moment of inertia that was previously mentioned, and ω is angular velocity (Serway, R. A., & Jewett, J. W., 2009). Since the kinetic energy of the first turbine must equal that of the same turbine with added mass, the angular of the second turbine must be lower than that of the first because the second has an increased moment of inertia.

Desired Results

As stated previously, the goal of changing the moment of inertia of a wind turbine would be better speed control. Keeping a turbine within an ideal range of angular velocity allows for the greatest amount of power generation possible. The different aspects of speed control are mentioned below.

Reduction of turbine rotation speed

The first function of the new system would be reduction of wind turbine speed in times where the turbine begins to rotate faster than the maximum optimal angular velocity. As a result of the principle of conservation of energy, by moving a mass to the farthest point along the turbine arm, the moment of inertia would be increased and the angular velocity of the turbine would decrease as a result. This would prevent the turbine from being damaged in high winds or operating out of its optimal range of angular velocity.

Perpetuation of rotation

The second function of the new system would be perpetuation of rotation in times of low wind or no wind. In a situation where wind speed suddenly drops and the angular velocity of the turbine begins dropping, moving a mass to a point closest to the axis of a turbine would decrease the moment of inertia. According to the conservation of energy principle, this would cause the angular velocity to increase, allowing the turbine to continue to operate in conditions in which the wind speed is less than ideal.

METHODS

Model Fabrication

In order to find out just how much changing the moment of inertia affect the rotational velocity of a wind turbine, some sort of wind turbine must be constructed for experimentation. The design and reasoning for the design decisions made are discussed below.

Model Choice

The model's intended purpose is to catch wind and be able to support weights that would move in and out along the arm of the turbine. The model that seemed best for this task was an H-Type Darrieus Vertical axis wind turbine. The turbine had to be a vertical axis turbine because if it was a horizontal axis turbine, the effect of gravity would make even distribution of the weights difficult. An H-Type Darrieus turbine was chosen because it was a turbine with geometry that was simple enough to both fabricate and allow the attachment of a weight-bearing mechanism.

Drawings

The turbine created was designed from scratch in Creo Parametric 2.0 software. It was based on type of vertical axis turbine mentioned above. However, it was not meant to be geometrically similar to any existing turbine, as it was only created to catch wind. A rendering of the creo model is seen in figure 1, and the fabricated turbine is seen in figure 2.

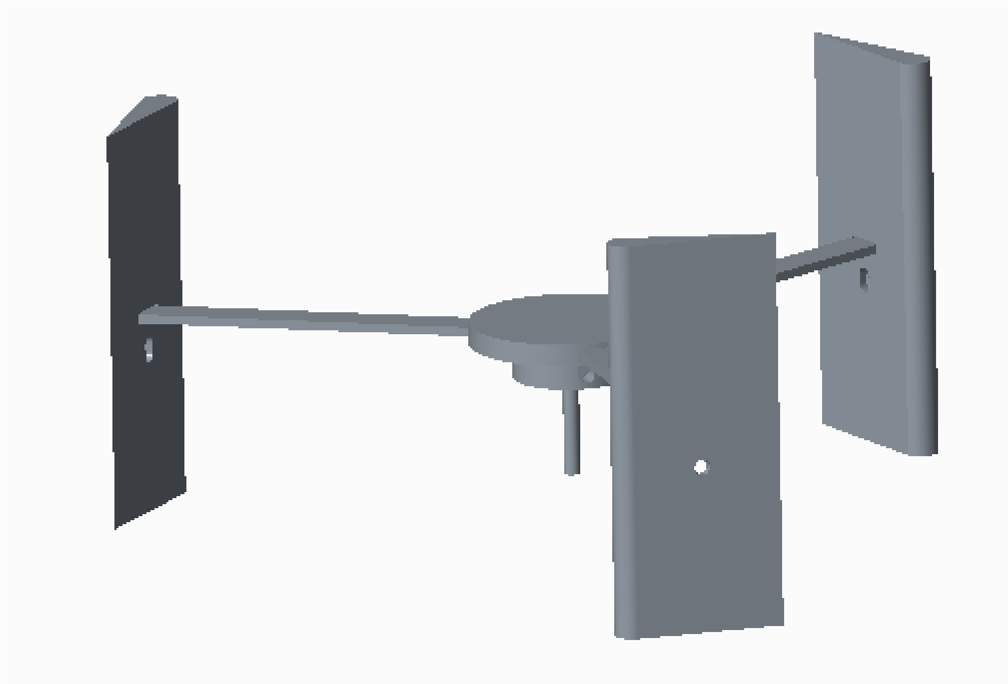


Figure 1 – Rendering of Creo Model

Figure 2 – Picture of Fabricated Model

The hub of the turbine specifically has an extra piece below it that will allow for the metal, weight-bearing rods to be inserted, and a corresponding hole can also be seen on the fins.

Fabrication Process

Once designed in Creo, the model could then be printed in the Makerbot 3D printer. The pieces were printed out of ABS plastic, as this seemed to work best in the 3D printer. It also provides reasonable strength while remaining lightweight. The printer fills the inside of the parts with a honeycomb pattern which saves plastic, time, and weight while maintaining structural integrity. This honeycomb pattern can be seen in Figure 3.

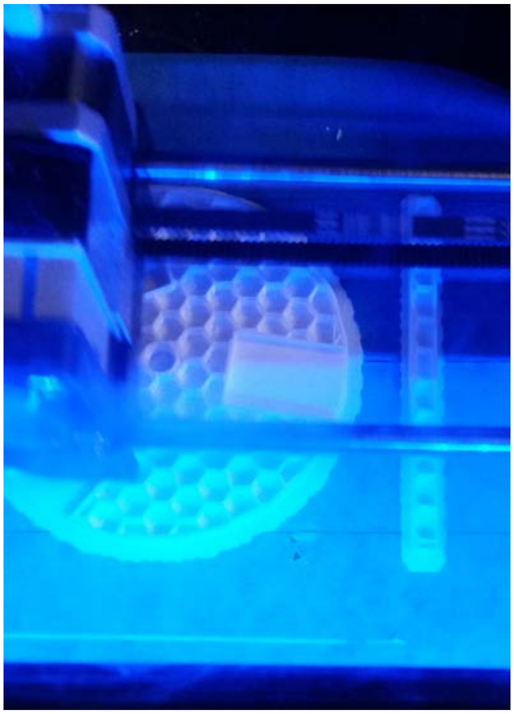


Figure 3 – Printing of the Hub of the Turbine

The fins, arms, and hubs were printed separately from each other due to restrictions of the small build volume of the printer. As a result, these pieces had to be joined together after printing. Fortunately, ABS plastic is known to be soluble in acetone. With the help of Dr. Armstrong of the chemistry department, acetone was obtained for this task, and it did a good job of welding the pieces together. An example of this process can be seen in Figure 4, and more photos can be found in Appendix 1.

Figure 4 – Welding Plastic Pieces Together with Acetone

Unfortunately, this process did not go completely as planned, as too much acetone was used to bond the arms of the turbine to the hub. This almost completely melted the hub seen in figure 5. Another hub was printed to replace this one, and less acetone was used the second time around.

Figure 5 – Melted Turbine Hub

After the plastic was fused together, three 8-milimeter metal rods were cut down to the length of the arms of the turbine. Unfortunately, when the original hub melted, some of the arm length was lost in the process, so the metal rods ended up being longer than the arms, but this was not an issue. The Hub of the turbine had a rod coming out of the bottom that was connected to a flange bearing. This was the axis about which the turbine rotated. This rod eventually broke off and was replaced by a piece of one of the metal rods.

The weights that were added to the turbine to increase the moment of inertia consisted of fishing weights that were put on a fishing line and wrapped around the metal rod. Duct tape was used to hold these weights in specified positions along the rod as well as hold the metal rods in place. The flange bearing was screwed into a wooden block found in the tech center. This fabrication resulted in a functional wind turbine that could catch wind and bear the added weight, as was the goal of fabrication.

Experimental Design

The experiment was designed to observe the relationship between two specific variables. The moment of inertia was the independent variable, and the angular velocity was the dependent variable. The angular velocity is also dependent on wind speed and the efficiency of the turbine, of course, but these were controlled so that they were consistent for each trial. The efficiency of the turbine is based on its geometry, which cannot change between trials, and the wind was produced by a fan with three settings.

Sensors and Instrumentation

In order to record the angular velocity of the turbine, the program Logger Pro was used. This program is used in many physics labs as well. This program receives information from an external module that receives information from various sensors connected to it. A diagram of this apparatus is found in figure 6 below

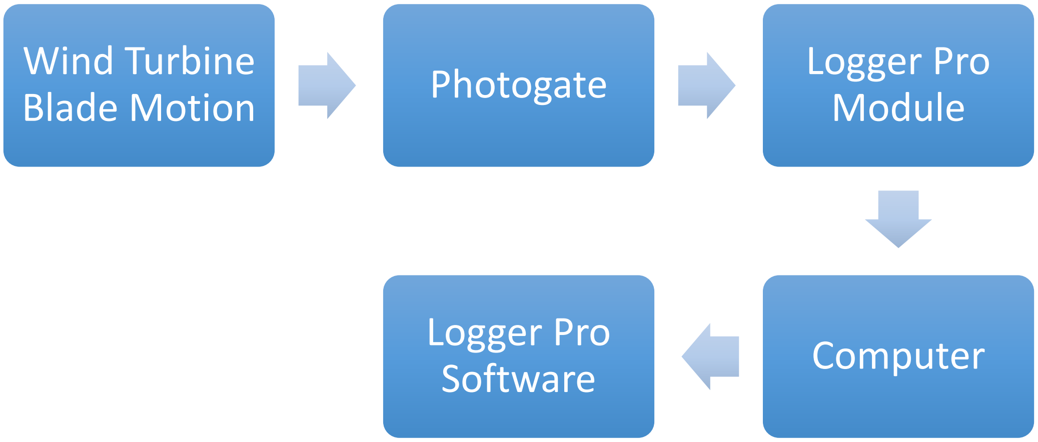


Figure 6 – Diagram of Sensor Set Up

For this experiment, only a photogate was used to record data. A photogate is a sensor in which there is an opening between a transmitter and receiver that are lined up with each other. When nothing is in this opening, the gate is considered unblocked. When something passes through the opening, the gate becomes blocked. When this information makes it back to the logger pro program, it can then be recorded and displayed in any way defined by the user.

Normally, the user can pick the way the data is displayed from a set of templates. However, since the photogate was being used to record angular velocity, a quantity that is normally measured with different sensors, a new program had to be written. After learning the syntax of logger pro, it was simple to create graphs in which angular velocity was displayed. To determine angular velocity, the program simply had to divide the number of times the photogate became blocked by the amount of time of the recording period. Since the turbine had 3 fins, dividing this number by three gave an output of revolutions per second. To convert this to revolutions per minute (RPM), this number was then multiplied by sixty. The equation turned out to be

$$RPM = \frac{\#\ of\ photogate\ obstructions}{Recording\ time} \div 3 \times 60$$

A hand-held anemometer was also used to record the wind speed produced by the fan in each of its three settings. The anemometer was held as close as possible to the front of the wind turbine in order to best determine the wind speed at the turbine. These readings were recorded in miles per hour.

Experimental Set Up

Experimental trials were run in the physics lab on the first floor of Reed Hall of Science. The set up of the experiment can be seen below in figure 7, and more photos of the set up can be found in appendix 1.

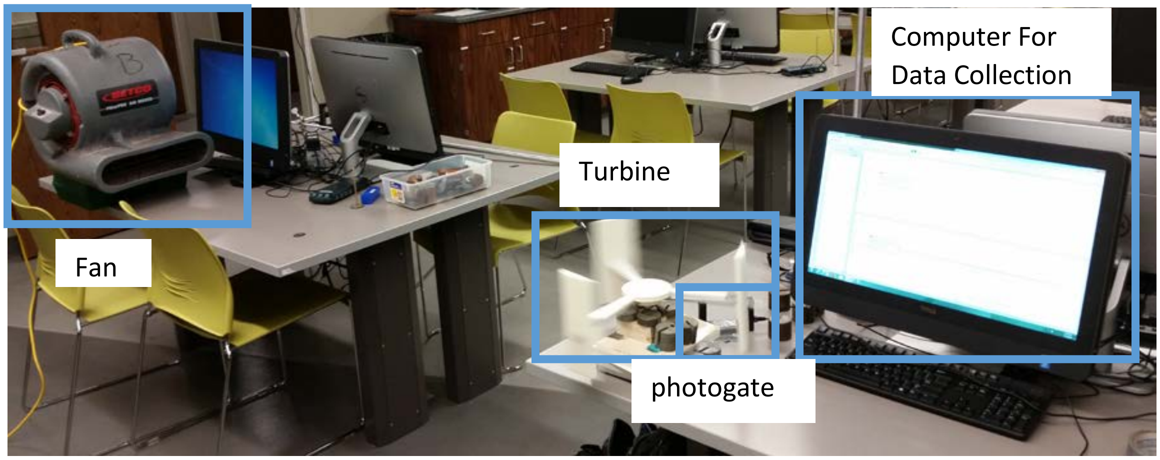


Figure 7 – Experimental Set Up

As can be seen in the photo, the turbine and photogate were placed on one table across from the fan, which was placed on another table. The turbine and fan remained about eight feet apart for the duration of the experiment. The photogate was taped onto a book so that it could be high enough to allow the fins to pass through it, and weights were placed on the wooden block and the book with the photogate on it in order to prevent both devices from moving in the wind. The photogate was plugged into the logger pro module, which sent data to the logger pro software on the computer through a usb cable.

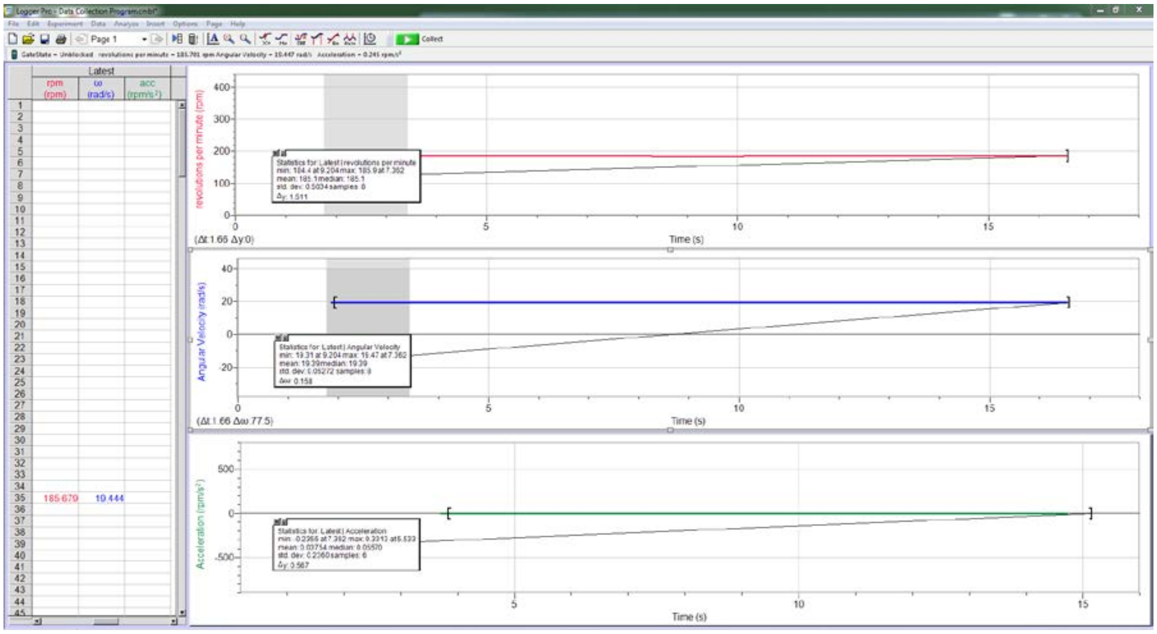
Data Collection

Data was collected over a total of sixty trials during experimentation. Five trials were for each of the twelve different variable combinations. Wind speed was adjusted between the three speeds of 15.5 miles per hour, 16.6 miles per hour, and 17.9 miles per hour. The control turbine for each wind speed was the one in which no weight was added. For all other set ups, a weight of 4.5 ounces was added to each fin of the original turbine. The distance of the weight from the center axis was varied between 0 inches, 3.25 inches, and 6.5 inches. The different combinations of these parameters produced twelve different alternatives that were tested in five trials each. A summary of these combinations is found in Table 1 below.

Number of Trials per Combination				
	Distance of Weights from Center			
Wind Speed (Mph)	No Weights	Weights at 0 in	Weights at 3,25 in	Weights at 6.5 in
15.5	5	5	5	5
16.6	5	5	5	5
17.9	5	5	5	5

Table 1 – Combination Matrix

Data was recorded with the logger pro sensors and software as mentioned earlier. A screen shot of the logger pro software can be seen in figure 8 below.



```
Statistics for: Latest | revolutions per minute
min: 184.4 at 9.204 max: 185.9 at 7.362
mean: 185.1 median: 185.1
std. dev: 0.5034 samples: 8
Δy: 1.511
```

```
Statistics for: Latest | Angular Velocity
min: 19.31 at 9.204 max: 19.47 at 7.362
mean: 19.39 median: 19.39
std. dev: 0.05272 samples: 8
Δω: 0.158
```

```
Statistics for: Latest | Acceleration
min: -0.2366 at 7.362 max: 0.3313 at 5.533
mean: 0.03754 median: 0.05570
std. dev: 0.2360 samples: 6
Δy: 0.567
```

Figure 8 – Screen Shot of Logger Pro Software

As one can see, the software prints out a graph of the angular velocity recordings over the fifteen second recording period. Also, the program can display various statistics about the graph, as seen in the pop up box. From this statistic box, the average angular velocity was recorded and placed in an excel spreadsheet. This was used later to perform some analysis of the data. This was done for each trial until all data points were recorded.

In order to control as much outside factors as possible, a couple of steps were taken to keep each trial consistent with the next. The first was to make sure the turbine was settled at its steady operating velocity at each wind speed. This was done by consistently running the program until the average velocity did not increase or decrease very much between each run. At this point, the data collection started for that specific combination of variables. Another step taken was checking to make sure the center rod of the turbine did not slowly drop through the flanged bearing before each trial. This assured that no frictional effects of the rod touching the wood would give false readings.

RESULTS

Data Collected

As stated earlier, all data was collected and compiled into excel spreadsheets. Tables of this data can be found in Appendix 2. Angular velocity was the data point of interest, as the goal of adding this mass was to help control the velocity of wind turbines in order to prevent the turbine from spinning outside its optimal range of power generation. It was collected in terms of revolutions per minute in order to make the quantities easier to grasp for the audience. In table 2, one can find a list of the average velocity readings for each option.

Average Angular Velocities					
	Angular Velocity (RPM)				
Wind Speed (Mph)	No Weights	Weights at 0 in	Weights at 3,25 in	Weights at 6.5 in	Ideal Turbine
15.5	186.34	174.62	167.56	155.12	174.62
16.6	208.68	197.44	187.98	173.52	187.98
17.9	227.86	222.12	206.82	192.8	192.8

Table 2 – Average Angular Velocities

It is important to note that this turbine was spinning much faster than large commercial wind turbines, but this is acceptable since the turbine was not meant to be exactly similar to other turbines because it was only being used to prove the concept of using moving mass to control the speed of a wind turbine. With the data already compiled into excel, it was easy to organize and plot on graphs in order to find important trends in the data. These trends will be displayed and discussed in the following sections.

Data Analysis

Effects of Changing the Moment of Inertia

Since the proposed speed control method uses weights to change the moment of inertia of the turbine, the effects of changing the moment of inertia on the angular velocity of the turbine will be examined here. To calculate the moment of inertia for the control turbine, I approximated it as a disc with mass, a rod with mass, and a point mass at the end of the rod. These calculations can be found in appendix 3. The moment of inertia of this turbine was found to be .0106 kg*m^2. The moment of inertia was calculated for each trial and angular velocity was plotted against the moment of inertia in Figure 9 below.

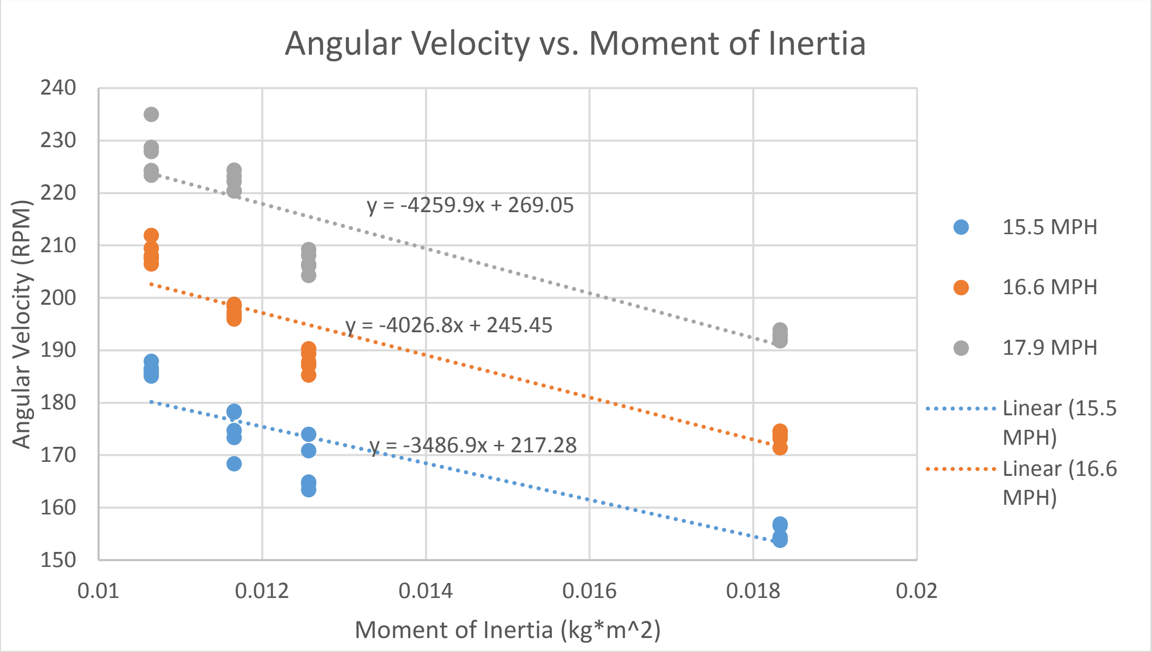


Figure 9 – Graph of Angular Velocity vs. Moment of Inertia

When looking at the graphs, it s important to note the slopes of the line of the approximated linear relationship. The angular velocity of the turbine decreases as the moment of inertia increases for each wind speed, and the rate at which the velocity decreases increases with wind speed. Now that the relationship between the moment of inertia and angular velocity is known, the behavior of the turbine in various wind speeds for these trials can be examined.

Comparison of Turbine Velocities

For most of the following analysis, average velocities from the five trials of each combination will be used, as it is easiest to compare these values with each other. Table 1 above will be used to start the conversation. As one can see, the average angular velocities generally decrease from left to right in the table, as adding weight and moving it farther along the radius increases the moment of inertia of the turbine, causing the velocity to decrease. This is mathematically expected, of course. However, what is of most interest is the velocities of the control turbine, which has no weights added, and the turbine that is labeled ‘Ideal Turbine,’ which is a combination of the values found in the trials in which weights were placed different distances from the center of rotation. Specifically, the ‘Ideal Turbine’ has the value of the turbine with weights farthest in for the lowest wind speed, the value of the turbine with the weights halfway out for the medium wind speed, and the value of the turbine with the weights all the way out for the highest wind speed. This is how speed control system that changes the moment of inertia of the wind turbine would work in practice.

When looking at the values of the control turbine as wind speed is increased, one can see that the angular velocity increases by about twenty rpm. When comparing the increase in angular velocity for the ideal turbine over the same wind speeds, it can be seen that the angular velocity only increases by about ten rpm. When looked at graphically, the difference becomes even more apparent, as can be seen in figure 10.

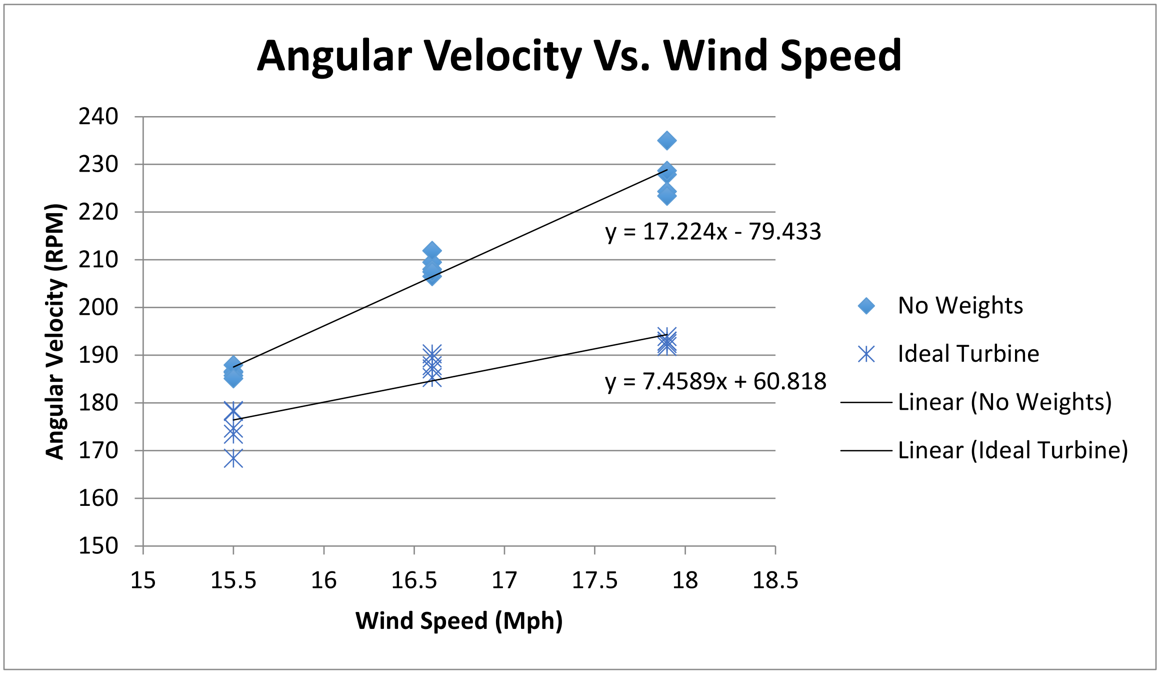


Figure 10 – Graph of Angular Velocity vs. Wind Speed

The equation for each line was placed on the graph so that the slopes could be compared. The slope in this case is the ratio of increase in angular velocity to the increase in wind speed. For example, for the control turbine, the slope was about 17, which means that for every 1 mph increase in wind speed, the angular velocity of the turbine increased by 17 rpm's. This slope represents the variability of the turbine's angular velocity, so the higher the slope, the more variable the wind turbine is. Obviously the 'Ideal Turbine' is less variable than the original. In fact, it is 56.7% less variable than the control turbine.

Another important factor to consider when talking about speed control is the range of angular velocities. As mentioned earlier, there is an optimal operating range for power generation in wind turbines, and maintaining angular velocity within this range is the goal of implementing a speed control system. Table 3 shows the minimum, maximum, and range of angular velocities for each turbine during this experiment.

Extreme Values of Angular Velocity					
	Angular Velocity (RPM)				
	No Weights	Weights at 0 in	Weights at 3,25 in	Weights at 6.5 in	Ideal Turbine
Maximum	227.86	222.12	206.82	192.8	192.8
Minimum	186.34	174.62	167.56	155.12	174.62
Range	41.52	47.5	39.26	37.68	18.18

Table 3 – Extreme Values of Angular Velocity

The range of the original turbine's angular velocity spans 41.52 rpm's, while the range of angular velocity of the ideal turbine spans 18.18 rpm's. This is a 56.2% decrease from the original turbine's range.

DISCUSSION

Significance of Findings

The data collected presents many interesting results. First of all, the data showed that as the moment of inertia increases, the angular velocity of the turbine decreases. This is expected, but the interesting part of this is that as wind speed increases, the rate of decrease of angular velocity increases as well. This means that the moment of inertia has more of an effect on the angular velocity of a wind turbine at higher speeds.

Another significant finding came from the behavior of the ‘ideal turbine’ when presented with changes in wind speed. Compared to the control turbine, the ideal turbine changed velocity at a rate 56.7% lower than the control. Also, the range of angular velocities experienced by the ideal turbine was 56.2% less than that of the control. This means the ideal turbine was able to operate within a range of velocities that is half as large as the control turbine. This is ideal for turbines, as they need to operate within a certain range of angular velocities in order to generate electricity at an optimal level. Also, a low rate of change in velocity of a turbine as found in the ideal turbine situation is desirable, as it prevents the turbine from experiencing high velocities and accelerations that could eventually damage the turbine. Since the rate of change is less than half of that of the control turbine, changing the moment of inertia of the turbine seems like it could be an effective form of speed control. However, more research should be done to support this idea.

Suggested Further Research

As can be seen from the findings, changing the moment of inertia of a wind turbine seems to be a viable method of speed control. However, more research must be done to confirm the viability of the prospective method. Unfortunately, due to time constraints, a weight system in which the weights would move back and forth along the fin with the aid of a spring could not be fabricated. Future research should incorporate this dynamic control system into testing, as it would give an insight on how the system would respond to the movement of weights along the arm during rotation. If this method of speed control still proved promising after this testing, then testing of a scale model that is completely similar to that of current wind turbines should be done. This would be the next step in determining if the system could be applied to current technology. After this, a prototype could be built and tested, but only if the method still proved viable, as this would be a costly endeavor.

Lessons Learned

As this project was the first self-guided research project for many of the honors students, it is important to take some time to note the lessons one has learned through this process. The first lesson learned came early on in the proposal process. The proposal for this project was eventually accepted after some rewriting. Even though the project was one spanning a few semesters, it was important to have as much detail as possible as well as a well thought-out plan to accomplish the research. This demonstrates that one not only has an idea for research but he or she also has the ability to accomplish this research.

Another lesson learned is one should always overestimate the time required to get something done, and then double or triple this time. This is something Dr. Schroeder had repeated throughout the research process, and it rang true as fabrication of the model took much longer than expected due to 3D printer problems, and the testing itself took a long time due to unforeseen issues.

The last learning point came from scheduling. As this was a one-on-one research project, the pace of research was left up to the student. It is important to stick to the pre-made schedule in these projects because since no one else is involved, it is easy to forgo the week’s work and get behind in the process, as did happen with this project a few times during the semester.

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APPENDIX 1 – EXCESS TABLES

Average RPM's			
Low	15.5 mph		
No Weights	weights at farthest in	weights at halfway	Weights at full length
186.4	178.4	163.4	154.4
186.6	178.2	164.6	153.8
185.7	168.4	164.9	156.9
187.9	173.4	170.9	153.9
185.1	174.7	174	156.6
average			
186.34	174.62	167.56	155.12
max Acceleration	rpm/s		
0.9737	0.2657	0.7606	0.4382
0.2047	0.07991	0.1866	0.4419
0.414	0.5497	0.3964	0.001515
0.3699	0.6199	0.2286	0.1777
0.3313	0.6733	0.649	0.2879
average			
0.45872	0.437702	0.44424	0.269443

Medium	16.6 mph		

Average RPM			
No Weights	weights at farthest in	weights at halfway	Weights at full length
206.5	196	187.1	173.2
209.5	197.3	189.4	174.5
208	198.8	190.3	173.9
207.5	196.7	187.8	171.4
211.9	198.4	185.3	174.6
average			
208.68	197.44	187.98	173.52
Acceleration			
0.8772	1.429	0.1155	0.07422
0.8009	0.7016	0.5313	0.1577
1.109	0.1235	0.1362	0.6777
0.429	0.4505	0.9715	0.05444
0.6269	1.153	0.1804	0.6013
average			
0.7686	0.77152	0.38698	0.313072

High	17.9 mph		

Average RPM's			
No Weights	weights at farthest in	weights at halfway	Weights at full length
227.9	222.2	206.4	192.4
235	220.4	204.3	192.9
224.3	224.4	208.1	193.9
223.4	220.4	206.1	191.8
228.7	223.2	209.2	193
average			
227.86	222.12	206.82	192.8
Acceleration			
0.4587	0.7245	0.5382	0.3468
0.8685	1.989	0.8252	0.4816
1.064	0.8164	0.3731	0.5567
0.3449	0.7578	0.5409	0.4423
1.062	0.125	0.0000292	0.3123
average			
0.75962	0.88254	0.45548584	0.42794

Table of Raw Collected Data

	15.5 MPH	**16.6 MPH**	**17.9 MPH**

Moment of Inertia (kg*m^2)	Angular Velocity (RPM)	Angular Velocity (RPM)	Angular Velocity (RPM)
0.0106456	186.4	206.5	227.9
0.0106456	186.6	209.5	235
0.0106456	185.7	208	224.3
0.0106456	187.9	207.5	223.4
0.0106456	185.1	211.9	228.7
0.0116548	178.4	196	222.2
0.0116548	178.2	197.3	220.4
0.0116548	168.4	198.8	224.4
0.0116548	173.4	196.7	220.4
0.0116548	174.7	198.4	223.2
0.0125656	163.4	187.1	206.4
0.0125656	164.6	189.4	204.3
0.0125656	164.9	190.3	208.1
0.0125656	170.9	187.8	206.1
0.0125656	174	185.3	209.2
0.0183256	154.4	173.2	192.4
0.0183256	153.8	174.5	192.9
0.0183256	156.9	173.9	193.9
0.0183256	153.9	171.4	191.8
0.0183256	156.6	174.6	193

Table of Calculated moment of inertias and corresponding velocities

APPENDIX 2 – SAMPLE CALCULATIONS

Calculating the Moment of Inertia of the original turbine:

$$I = 3\left(\frac{m_{rod} \times {r_{rod}}^2}{3} + m_{fin} \times {r_{fin}}^2 + \frac{m_{arm} \times {r_{arm}}^2}{3}\right) + \frac{1}{2} m_{hub} \times {r_{hub}}^2$$

$$= 3\left(\frac{.080 \times .1905^2}{3} + .092 \times .1615^2 + \frac{.02 \times .1615^2}{3}\right) + \frac{1}{2}(.064) \times .075^2$$

$$= .0106\, kg \times m^2$$

Calculating the Moment of Inertia with Added Weight

$$I = 3\left(\frac{m_{rod} \times {r_{rod}}^2}{3} + m_{fin} \times {r_{fin}}^2 + \frac{m_{arm} \times {r_{arm}}^2}{3}\right) + \frac{1}{2} m_{hub} \times {r_{hub}}^2 + 3m_{weight} \times r_{weight}^2$$

$$= 3\left(\frac{.080 \times .1905^2}{3} + .092 \times .1615^2 + \frac{.02 \times .1615^2}{3}\right) + \frac{1}{2}(.064) \times .075^2 + 3(.1).058$$

$$= .0117\, kg \times m^2$$

*All units are in kg and m

APPENDIX 3 – OFFSITE PRESENTATION

This work will be presented at the Associated Colleges of the Chicago Area (ACCA) Student Scholarship Symposium on April 16, 2016. More information on the conference can be found at the link below.

https://www.cuchicago.edu/acca