The Creation of a Fully Submersible Geared Water Turbine for Alternative Energy Production

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Introduction

Alternative energy production is an important part of our future energy resources. Every effort to optimize efficiency is needed to meet the goal set by the President Obama during the 2011 State of the Union Address of nationally consuming 80% clean energy by 2035. Hydroelectricity is an important energy source needed to meet this goal.

Most hydro-turbines today use static (not dynamic) wheels that hold fins in a fixed way for capturing energy from water flow. The spinning of these wheels can be used to generate electricity with a generator. The biggest difficulty with this standard turbine design is that if a turbine is completely submerged in flowing water, the fins themselves must be designed to have high drag when the fin goes with the current, and low drag when the fin goes against the current. Turbines like this cannot use the design of a fin with maximum resistance or a fin with absolute minimum resistance but often require a trade-off with a cleverly shaped fin that works somewhat well for both.

Widely-used, traditional turbines try to get around this trade-off by requiring targeted streams of water at one side of a rotating turbine created by either using a dam or placement at the upper barrier between a stream and the open air. A fully submersed water turbine eliminates the need for large, expensive dams and allows for power to be generated throughout the depths of a river instead of being restricted to water flow from the top.

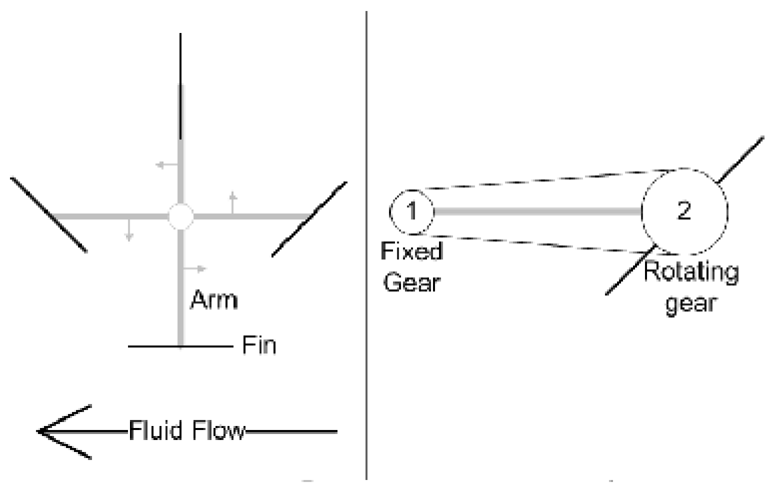
The purpose of this research is to evaluate an innovative design for a fully submerged water turbine with articulating fins, specifically with an arm to fin gear ratio of 2:1 and compare the advantages of this design to a traditional water wheel.

The hypothesis is that the power output of a fully submersed water turbine with proportionately articulating fins would be greater than the power output of a traditional partially submersed water wheel turbine with fixed fins of equal size.

Theory of Operation

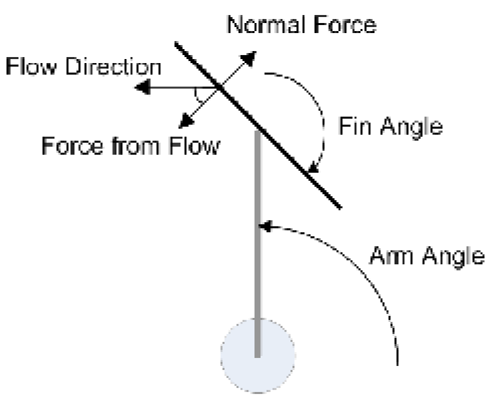
During a private brainstorming session with a notepad about 4 months ago, I contemplated the efficiency of electricity generators that harvested energy from the water. I considered that one of the most effective energy capture methods is a “fin” with a large area perpendicular to the flow of water. A fin alone, however, cannot generate rotational torque required to spin an electrical generator. I considered that if this fin were to be attached to an axel on the bottom side, so that it could be pushed around and down, it would not be able to return to its original position. This conseqeunce is because of the immense drag it would have as it rotated down and back, perpendicular again to the flow of water but going against the current. So, I went back to the drawing board. I thought that as the fin was coming back, if it was parallel to the flow of water then there would be no drag. This idea of having a fin upright on one side of a rotating axel and flat on the other side was very interesting to me because I wanted to know if it could also be made to work at every other angle.

I knew which way I wanted the fin to tilt at the top when it is rotating with the flow of water and at the bottom when it is against the flow, but I wasn’t sure about when the fin was half way between the two. I estimated that a 45 degree angle of a fin would be appropriate to generate the best torque when it is halfway between the top of the axel and the bottom. When I analyzed this diagram of angles at different positions around an axel, I noticed a pattern. As a fin moved around 90 degrees around the axel, its tilt always rotated 45 degrees in the same direction. This meant that if the fin rotation and the axel rotation were connected by a gear ratio, than fins would be tilted exactly as I had estimated the maximum torque to be! I was very excited and built a crude model with small gears to prove the concept.



Now, at this point I was extremely curious. I knew that the angle of the fin at the top of the axel and the bottom of the axel (the two extremes) were definitely correct, but I couldn't be positive about the angle of the fin at other points around the axel unless I did some calculations. I decided to start from scratch to determine again what the optimum angle of a fin was at any position around an axel with a constant flow direction algorithmically. By graphing the torques produced at all angles of a fin at any point, I could pick the fin angles with maximum torque and determine the absolutely correct design.

I created an equation for the torque of a fin on an imaginary arm (just the radius from the axel) produces by using my knowledge of mechanical physics from my college physics classes. To calculate torque, two angles need to be considered. When a fin is hit by water at an angle, the force acting on the fin is only the component of the force from the fluid in the direction of the vector normal to the surface of the fin. This component depends on the difference in angle between the fin surface normal vector and the angle of the placement of the fin around the axel which determines whether the flow is going against or with the movement of the fin or somewhere in between. Torque is calculated by multiplying the radius by the component of the force on the fin (calculated earlier) in the direction perpendicular to the arm. This is only dependent on the angle of the fin around the axel. I defined the zero positions of the two angles (fin and axel) and used the stated physics to logically come up with the formula as described in next figure.



Torque = Force component perpendicular to the radius x radius length

Force component perpendicular to the radius = Force from Flow x cos(Fin Angle)

Force from Flow = Max Force x sin(Angle between Flow Direction and the normal vector from the Fin Surface)

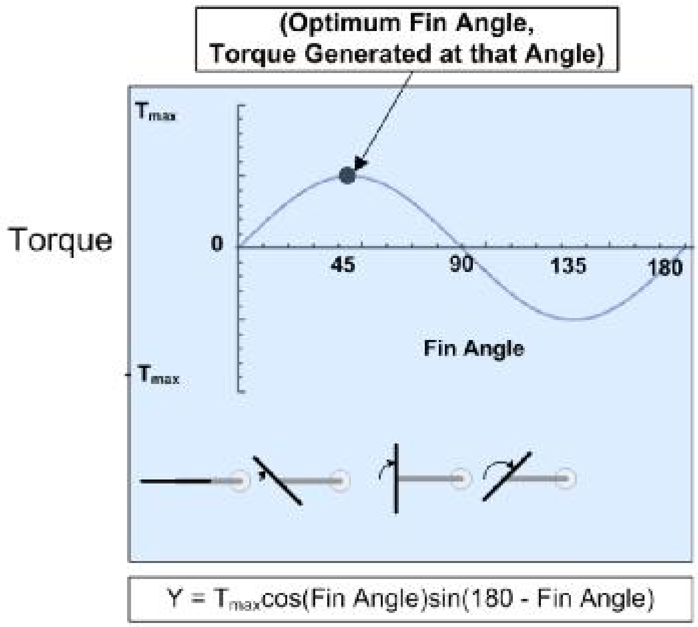
Angle between Flow Direction and the normal vector from the Fin Surface = Arm Angle – Fin Angle

Therefore:

Torque = Max Torque x cos(Fin Angle) x sin(Arm Angle – Fin Angle)

The design of the turbine revolves around a spinning fin that experiences drag held at a distance away from the central axis by an arm that experiences no drag. Power is generated from a motor attached to the axis of the arm. In reality, the arm is merely the radius of a large disk gearbox but for torque calculations, this simplified model works well. Through a lot of sketching and a Lego model I discovered that a 2:1 gear ratio optimizes torque in all positions of the arm, which I later proved mathematically.

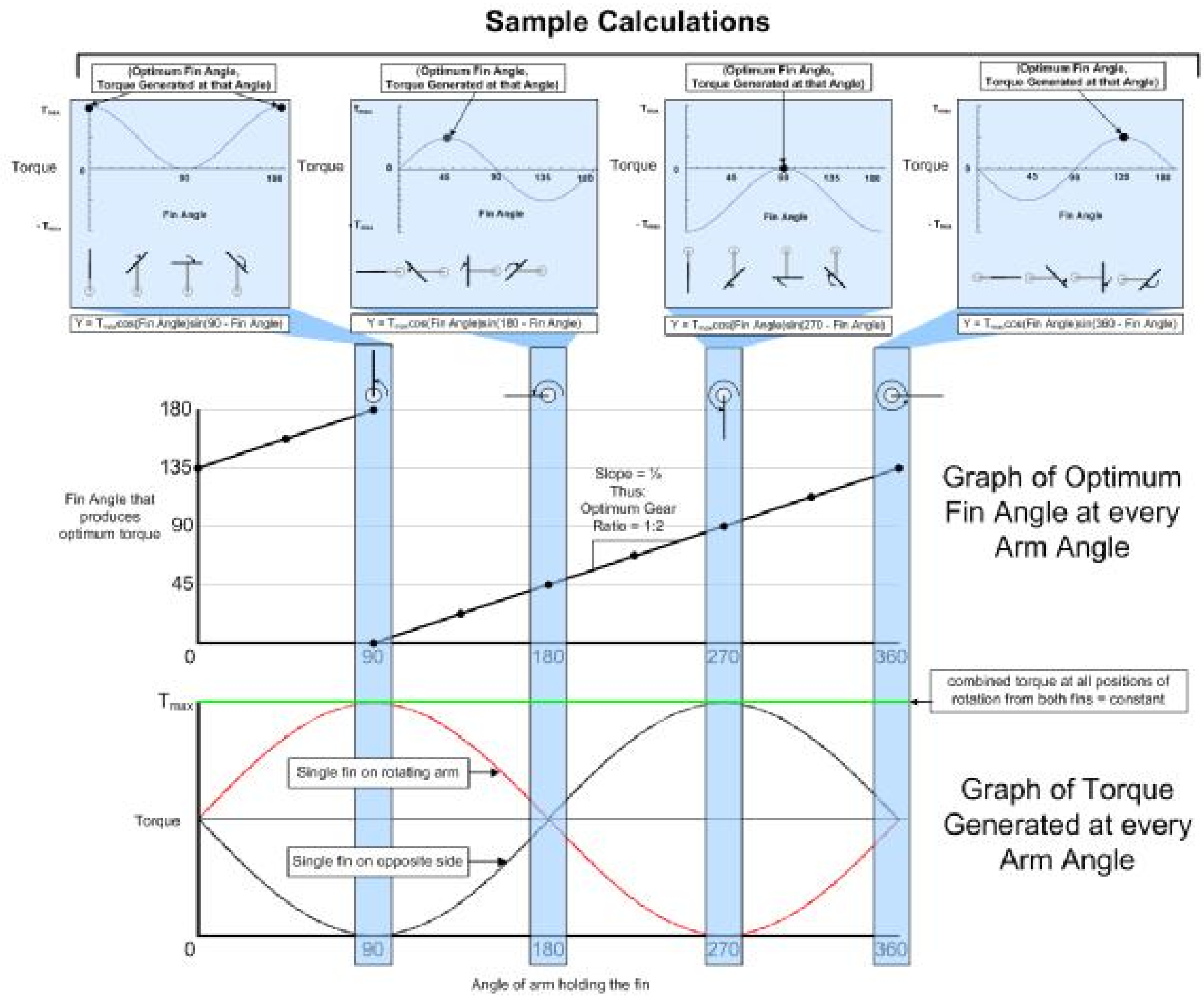
I used this formula to test for the fin angle that would produce the most torque when the Arm Angle was 180 degrees. By plugging 180 into Arm Angle, I plotted the formula of Torque over a range of 180 degrees of Fin Angle and got Graph 1. When a fin is rotated 180 degrees it becomes the same shape as it was originally and thus has the same torque.



From Graph 1 it is clear to see that the highest torque for a fin attached to an arm at an arm angle of 180 degrees occurs when the fin is tilted 45 degrees exactly. After determining that at a 180 arm angle the best fin angle is 45 degrees, I determined the best fin angles for every other arm angle by testing many other arm angles and plotted the best arm angles on a new graph (middle of Diagram 1). These optimum fin angles that I was measuring didn't necessarily achieve the same highest torque across different arm angles but at their angle they were the best. I also plotted the specific high torques at every optimum angle on another graph (bottom of Diagram 1) out of curiosity.

These two compound graphs (one of torque depending on the arm angle, and one of fin angle depending on arm angle) were extremely surprising to me. In the first one, "Graph of Optimum Fin Angle at every Arm Angle," it is immediately striking how linear the plot is. From an equation as complex as the formula for torque at any arm angle or fin angle, it is amazing that a linear equation emerges from the maximums of the equations using arm values between 0 and 360. Because of this linearity, excitingly, the slope of the line is the quantifiably optimum gear ratio between a gear mounted to the fin and a gear mounted to the axel! While this does match the ratio that I had guessed on paper originally, this ratio was developed completely from the ground up from physics equations of force and torque.

In the second graph, "Graph of Torque Generated at every Arm Angle," the curve in red is the actual torques of the angles in the first graph. This curve is clearly sinusoidal but interestingly fluctuates between its maximum torque (the perpendicular sail straight above the axel) and its absolute minimum torque of zero. The torque for this design amazingly never goes below zero at any time, even though the fins move both with the current and against the current at different times. I added a black second curve with a 180 degree phase shift to the second graph to show the additional torque that would be received from a fin 180 degrees around the axel. The addition of this fin has the interesting effect of causing the torque to be a positive constant at all times, which is a big benefit for efficient energy production.



A common question that is asked of this design is, "Why don't you curve the fins?" There are two reasons that the fins are flat. One reason is that at the lowest position when the sail is moving against the flow of water, a curved sail would have drag. Another reason is that because the fins turn at half the speed of the main rotation so that after every turn of the turbine, the sails have flipped 180 degrees and any curve would suddenly be curved the other way half of the time. This flipping effect is predictably useful to stop the possible material warping that could happen when such a turbine is being used heavily underwater. This would be stopped because a fin would be equally pressured in both directions.

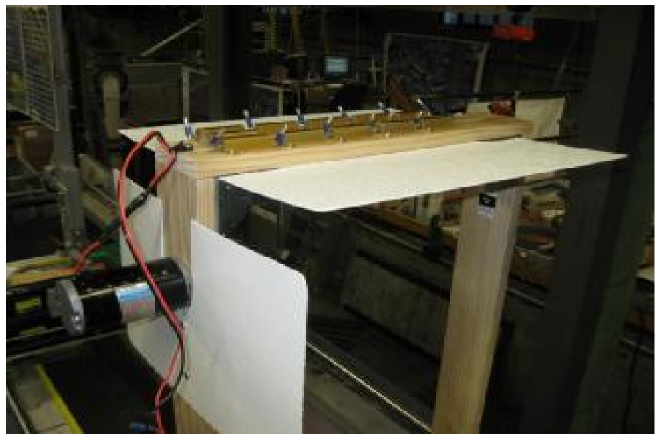
In summary, the design of this alternative hydroelectric generator utilizes two fins that actively generator a steady combined torque. Both fins are designed to be at their optimum angle for producing torques at all angles of rotation.

Materials and Methods

To test if the water turbine design was really feasible, I needed to build a scale model. I ended up using PVC pipe, a store bought cutting board, plastic gears, chain and a metal axel from a robot kit, regolith, wood and screws. I built the turbine with power tools at home under adult supervision.

I decided to build a turbine with only two fins to make my gearing simpler. These fins could have been held away from a central axel by a beam, but I reasoned that as the beam spun around the axel underwater it would incur some drag and reduce efficiency. Instead, I made the two sails attach on the sides of large discs of cutting board which would not drag as they spun. The two discs (one for each side of the fins) also conveniently operate as semi-closed gear boxes that connect gears on each fin to gears attached to the core axel that runs through a PVC pipe to the other disc. The two gears have a 2 to 1 ratio with the smaller gear on the axel. Interestingly, because the gears are supposed to turn the fins as the whole turbine turns, I needed to fix the center gear to not turn. This way, when the whole gearbox turns, from its perspective it is not the gear box that turns but rather the center gear.

I attached the two gear boxes and two sails together. I then made a supporting brace to let the turbine spin. After I was able to put together the turbine to prove that it could function, I wanted to test the mechanical power that it could produce. To do this, I attached an electric motor through a chain to the turbine so that the motor was out of the water. By attaching a resistive load between the terminals of the motor and measuring the voltage, I was able to measure the electric power (V^2/R) which equals the mechanical power of the turbine.



As a control to compare the power output of this experiment, I created another turbine with a traditional fixed fin design. This wheel was made out of wood and had the same sized fins and the same radius as the new turbine, but the traditional turbine had four fins instead of two because with less than four the turbine would not be able to spin continuously. The traditional design is not able to operate completely submerged because of its fixed fins. The power output of the traditional turbine was measured using the same motor/resistor set up.

Test Procedure

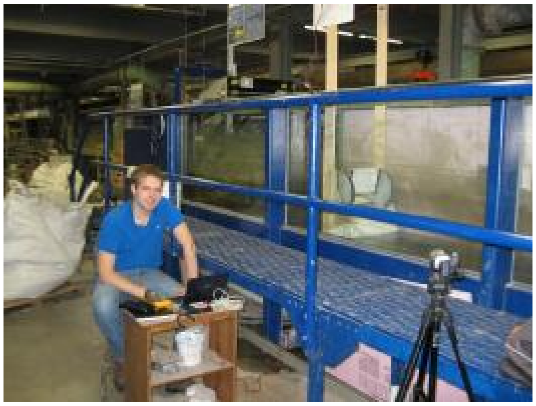
I was very lucky to get connected with Ms. Sara Johnson at the University of Minnesota-St. Anthony Falls Laboratory (SAFL) to test my turbine models in the 20 inch water flume housed there.

While at SAFL, I had two water speeds (slow and fast) and two turbine models (traditional and new) which I tested in all four possible combinations. For each combination, I measured the voltage range and average voltage multiple times with a series of progressively smaller resistances. I did this so that I would be able to find the peak power output which requires just the right resistance to match the load. I varied resistance by screwing 3 lines of resistors of 1, .5, and .1 Ohms which could be combined to form a wide range of resistances.

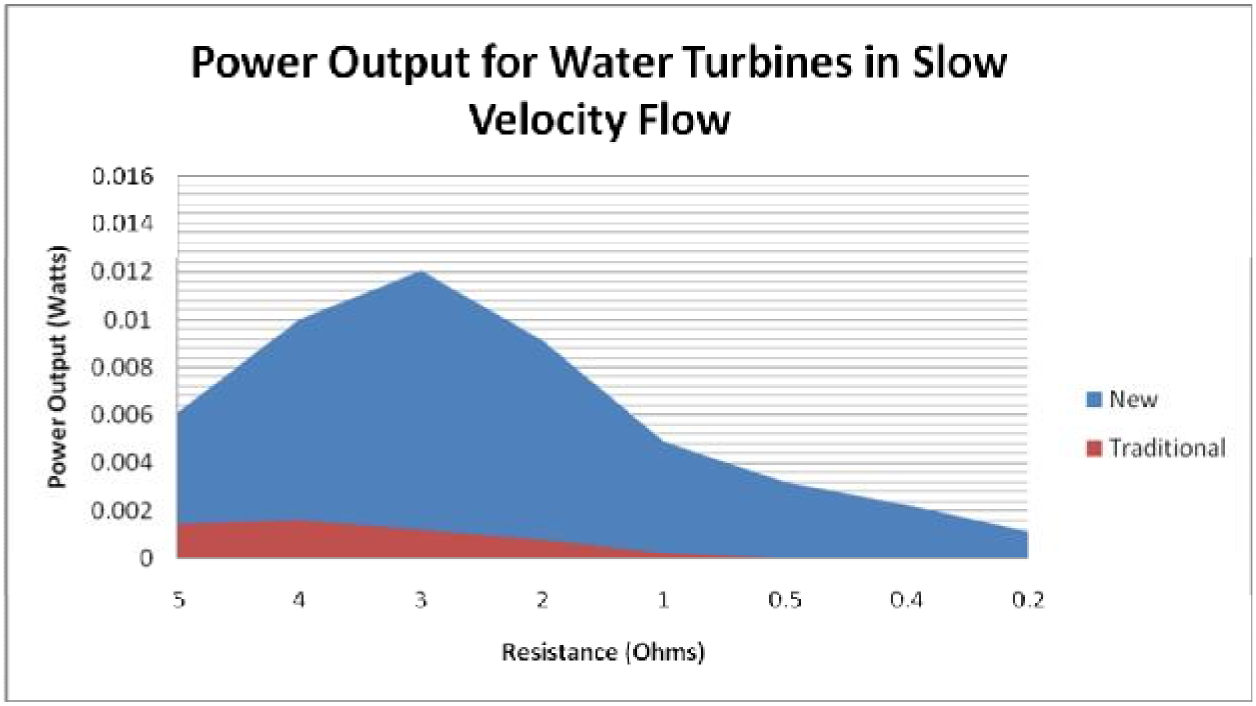
There were a lot of challenges to testing my turbines at the flume which were unexpected. Immediately I discovered that while it is a 20" flume, there is a metal lip over the top edge of the flume that made it impossible to fit my turbine as it had been designed. I fortunately managed to get it in the flume opening by detaching one of the wooden beams temporarily and then clamping it on tightly after it was in.

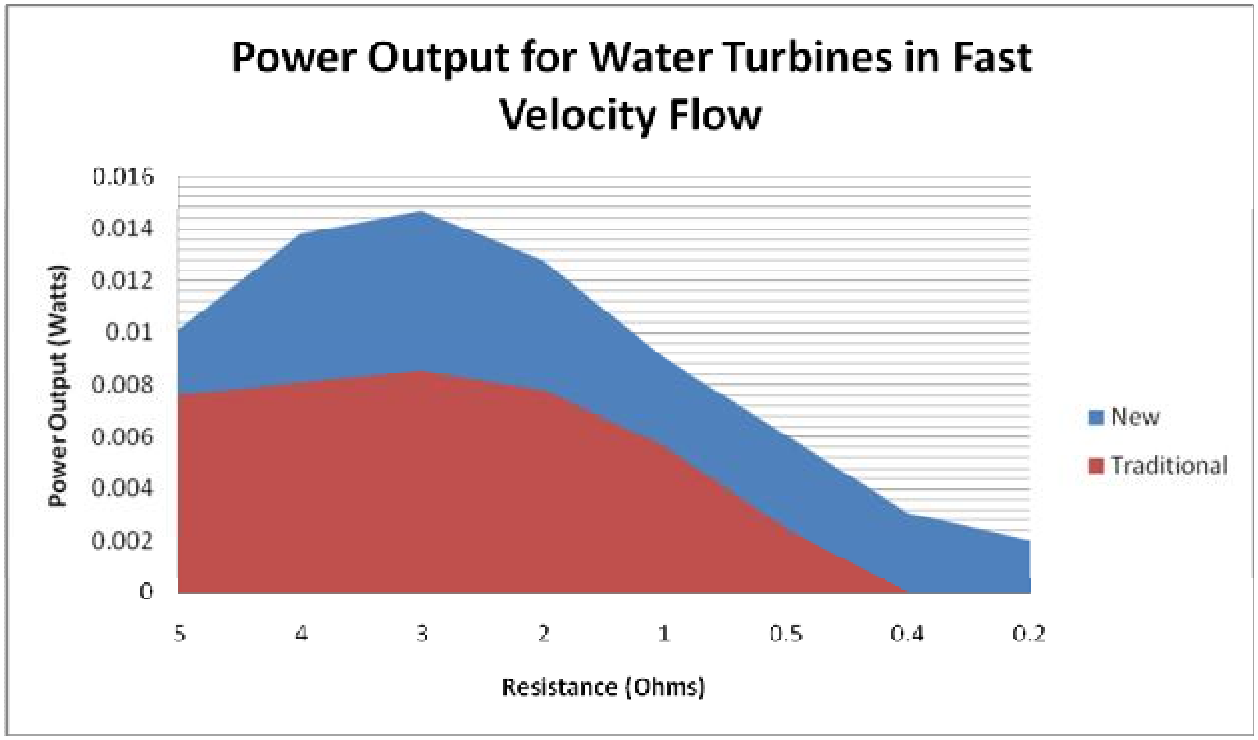
A second challenge was the whole process of controlling the flume speed and depth. There was a delay in the responsiveness of the lever that controlled the water speed of the freezing Mississippi River water and it was easy to overshoot the input volume/minute. Additionally, there was a second gate on the other end of the flume that had to let out just as much water as was coming in or the water height would increase or decrease.

Unfortunately, because of the inner chain and gears of the new turbine being made out of plastic, it was unable to handle the third higher velocity when positioned at 45degrees. While setting the flume at this very high rate, the chain broke inside. I will be replacing the plastic chain and sprockets with a metal chain for future testing.



Results


Power Output for Water Turbines in Slow Velocity Flow
Power Output (Watts)
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
5
4
3
2
1
0.5
0.4
0.2
Resistance (Ohms)
New
Traditional


Power Output for Water Turbines in Fast Velocity Flow
Power Output (Watts)
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
5
4
3
2
1
0.5
0.4
0.2
Resistance (Ohms)
New
Traditional

The data measured for both turbines in both speeds share some pretty distinct results. I was fortunate to get test results since my model was built as a proof of concept and not one aimed at testing. I was extremely happy that testing the design proved functionality and started a baseline of understanding its performance capabilities.

As was predicted, each combination of turbine (new or traditional) had a resistance that maximized the power output of the turbine for that water flow velocity. This is largely due to an inherent property of the motor I used for measuring both turbines. Please keep in mind that the power measured is at very slow water flow speed; It is approximately 1ft/sec at the slowest velocity and twice this speed at the higher velocity.

In both velocity situations, the turbine with the new design produced more power over all resistances. If we compare the peak power outputs for both turbines in both velocities, at the low velocity the new design was 7.5 times more productive than the traditional design, and at the high velocity the new design was 1.7 times more productive than the traditional design. This strongly supports my hypothesis.

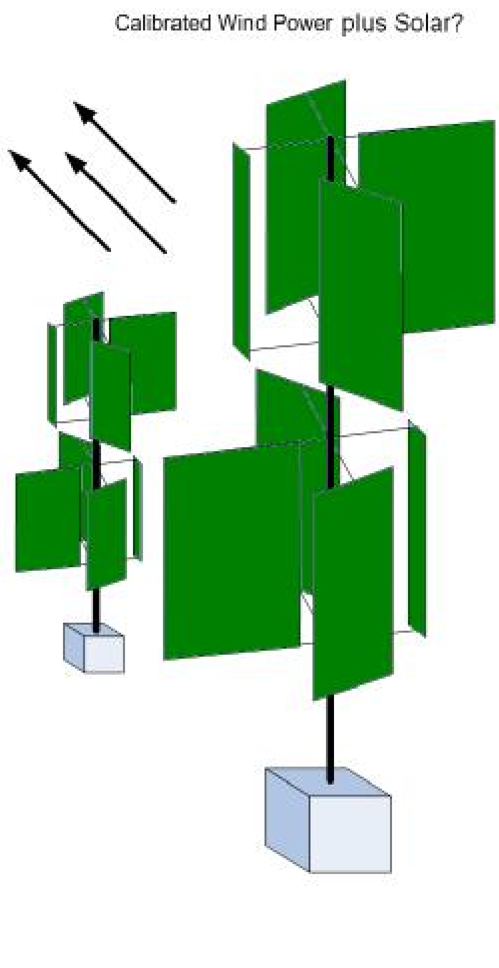
Some interesting observations were made when the traditional design was being tested. Because the traditional design can only have one side of it touching the water, it was much more difficult to set up because the power was highly dependent on the water height being optimum. If it was too low, the power would not be maximized, and if it was too high, the wheel would have a lot of resistance from water pushing the wrong way on the wheel. With the new design, the height of the water did not affect the turbine because it operates best when completely submersed. Also, the traditional design was noticeably scooping up water as the fins came out of the water, which clearly slowed it down. The traditional turbine also required far more water speed to move at a good pace as can be seen from the data from the low velocity.

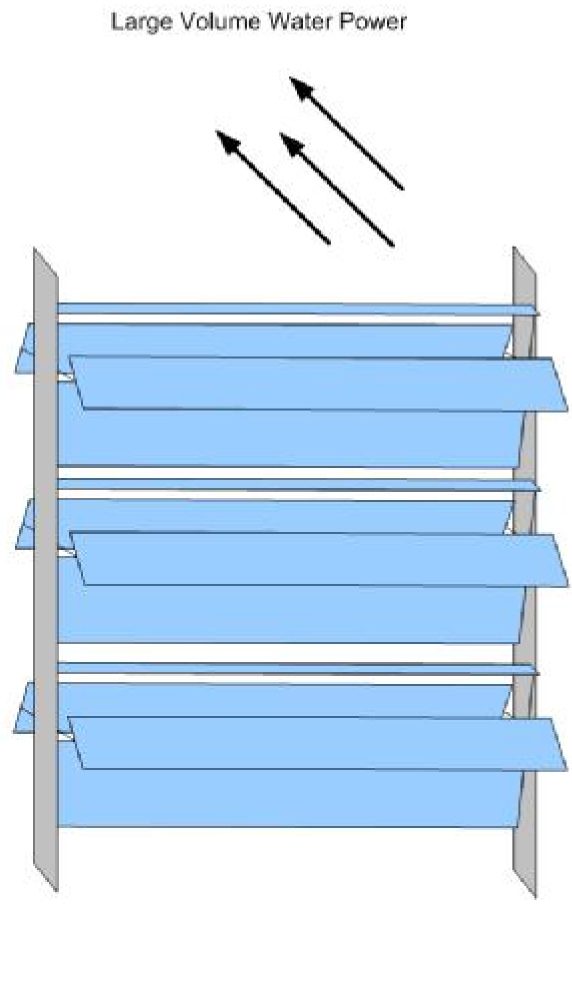
Conclusion

In conclusion, after thorough physical calculations and building a working model, I was able to produce a design that systematically optimized the drag of a turbine to maximize torque. The two to one ratio of the main motor-connected wheel to the fins was surprisingly found to tilt the fins at the ideal angles needed to generate optimum torque at all times. This allows the generator to be placed in the middle of a fluid stream completely submerged. Testing supported the hypothesis that the new design could produce more power from the same sized turbine as a traditional water wheel design. While the torque was not completely constant as was predicted, this was likely due to when one fin goes in front of the other while spinning which decreases efficiency. I hope that this approach to fluid power harvesting can inspire engineers to think outside the box to maximize efficiency.

Future Possibilities

The design of this device can be used in multiple other ways for energy generation. One way is for wind energy harvesting. As can be seen from the below left picture, the design of the turbine can fit four fins and be tilted vertically. By rotating the inside fixed gear, the direction that the wind turbines would be set to capture could be easily changed. Also, because these fins would have plentiful access to sunlight and would not need to be curved, they would be perfect places to mount solar panels. On the right is a large scale mockup of layered turbines for use in deep waters. Previously, this was impossible because half of a turbine had to be outside of the water





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