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Hydrofoil River Power system

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ABSTRACT

With growing calls for alternative energy solutions, the Hydrofoil River Power System aims to verify theoretical analysis, simulation, and laboratory experiments predicting the potential of power harvesting from a river using a submerged airfoil. Based on the results obtained by Senior Design Teams P12462 and P12463 and the computer simulation developed by graduate student Kelsey McConnaghy, the team built a full-scale model system that will generate and measure power from the Genesee River flow. Additionally, the team identified and developed procedures for quantifying possible environmental impacts of the system on the local river. Based on the team's design parameters, the computer simulation predicts an average power output of 0.02 Watts. The test data indicates this was an under-prediction being that once the system was installed in the river, it produced an average of 0.09 Watts with peak values over 0.5 Watts in a river flow of 0.3 m/s.

INTRODUCTION

Traditional hydro-power systems, such as, dams, stream diversion, spillways, etc., are in abundance and produce great amounts of electricity. However, these systems can be detrimental to the environment by altering the flow of the river thus negatively affecting river ecology. Additionally, most of the rivers where dams are applied have already been exploited. The Hydrofoil River Power System, on the other hand, runs solely on the flow of the river which results in minimal flow disturbance and minimal lasting impact on the environment. It can be placed in any sufficiently flowing stream and generate electricity.

The Hydrofoil River Power System operates by the lift and drag forces created by water flow across a submerged airfoil. The forces are then transferred to a structure on the side of the river and used to turn a generator. The design objective was to create a light weight, durable system that could generate and measure power while withstanding the outside conditions it would encounter once installed at a river. The power output of the system must be capable of producing

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an average of at least 50 Watts of power in a 1 m/s river flow. The historical context for this project consisted of two previous Senior Design Teams, P12462 and P12463, the Tow-Tank Team and the Small-Scale Model Team, respectively. The objectives for these two teams were to take the theoretical knowledge gained from a computer simulation created by Kelsey McConnaghy, a graduate student at RIT, and prove it on a small-scale in a tank of water. The small-scale version was designed to be highly adjustable for experimental analysis and data collection in order to observe how different parameters effect the power production. Their work proved the feasibility of the concept and laid the groundwork to develop a full-scale model to implement in the Genesee River.

The other aspect of the project is to identify potential environmental impacts the system will have on the river and create assessment plans to quantify these impacts. Building a system for real operating conditions also provides valuable information by identifying design problems that laboratory-based systems do not encounter.

PROCESS

The driving theoretical support of this project is the production of hydrodynamic lift and drag forces on a structure in flowing water.

$$F_{drag} = \frac{1}{2}\rho A C_{drag}\left|V_{app}\right|^2 \quad (1)$$

$$F_{lift} = \frac{1}{2}\rho A C_{lift}\left|V_{app}\right|^2 \quad (2)$$

ρ is the density of the fluid, A is the area of the surface, and V_{app} is the apparent fluid velocity. These are the forces generated on any structure as a fluid passes over it. The lift and drag coefficients (C_{drag} and C_{lift}) are functions of the angle of attack and tabulated for a wide range of different shapes. The vectors of the lift and drag forces are perpendicular to and parallel to V_{app}, respectively. The shape of the structure greatly effects the lift and drag forces. The hydrofoil used throughout this project was the standardized NACA 0015 (National Advisory Committee on Aeronautics). The forces generated on the hydrofoil, if oriented correctly generate a moment about the base that is used to turn a generator in a ratcheting motion.

Customer Specifications

An initial list of customer needs was presented to the team at the start of the project and has undergone some revision through discussion with the customer. Some of the more driving needs are listed below.

- Measurements should be of high quality and made with appropriate sample rates and resolution.
- The model must be portable, easy to setup and use.
- The model must be safe for the operator and those around them.
- The model must be able to be setup, deployed, and removed without a single person entering the water.
- System must be cost-effective.
- Possible environmental impacts must be identified and plans for quantifiably measuring the system's impact must be developed.

In addition to the customer needs, engineering specifications were provided to the team. A number of the most important specifications are shown on the next page in Table 1.

Specification	Marginal Value	Ideal Value	Validation Method
Max. Transport Dimension	40 in.	≤35 in.	Tape measure
Weight	300 lbs.	≤150 lbs.	Machine Shop Scale
Hydrofoil Angle Resolution	2 degrees	≤1 degree	Microcontroller and DAQ
Aspect Ratio of Hydrofoil	4	10 in/in	Ruler
Data Sample Rate	TBD.	50,000 Hz	DAQ spec sheet
Data Resolution	16 bits	16 bits	DAQ spec sheet
Time Data Resolution	.01 s	.001 s	DAQ spec sheet
Setup Time	20 min	< 15 min	Stop Watch
Removal Time	20 min	< 10 min	Stop Watch
Run time per setup	2 hours	5 hours	~
Environmental impact (water: chemical)	1 test plan	2 test plans	~
Environmental impact (water: organisms)	1 test plan	2 test plans	~
Environmental impact (land)	2 test plans	3 test plans	~
Environmental impact (air)	1 test plan	2 test plans	~
Number of cycles with data at a given river speed	400 cycles	# = to > 2 hours of run time	Analyze data files
Hydrofoil Shape	0018	0015	Create a gauge

Table 1: Engineering Specifications

Design

The design of the system took on many shapes before defining a final design. The team brainstormed a plethora of ideas to satisfy the customer needs and engineering specifications. The general design was constrained to correlate to the computer simulation and the work done by the previous two teams. It consisted of a base, boom arm, end cap, hydrofoil and generator. Morphological charts, Pugh Charts, and knowledge from the small scale team were used to generate concepts and select a feasible design to proceed with.

For the base, a few different materials were suggested, as well as its structural shape. The desire for adjustability of the base legs to fit different riverbank profiles directed the material choices toward telescoping tubing. Initial design and analysis were completed using stock tubing sizes and wall thicknesses. The base geometry was triangulated where possible and analyzed. The design was later altered to allow for better placement on the riverbank.

The boom is the critical connection between the driveshaft on the base and the hydrofoil which generates hydrodynamic forces to create motion. The model predicted that a short boom produces more power than longer ones, but due to the river location and bank profile, a long boom was required to reach sufficient depth for the hydrofoil. This length provides a large moment arm for the hydrodynamic forces, and consequently high bending stress. Multi-piece booms were avoided due to the stress concentrations created by connection techniques.

The design of the end cap was driven by two major parameters; applied forces and weight. Being that the end cap is attached to the boom, the material selected needed to be based on minimizing weight with additional material being added to high stress areas. The major function of the end cap is to house and protect the electrical components that control the hydrofoil system. In order to rotate the foil shaft, a tension wire system was chosen over gears to avoid issues with mating.

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The hydrofoil design was determined based on engineering specifications, previous hydrofoil designs, the computer model and ease of manufacturing. The design chosen, shown in Figure 1, incorporates foam for the main body of the hydrofoil. This was chosen because of its light weight and access to a CNC hot wire cutter. A steel spar or rod supporting this foam body which goes down the length of the hydrofoil was also incorporated. Large bending moments occur from the hydrodynamic forces which are handled by the spar. The spar was also designed to be square in profile due to the torsion from the servo motor. The square profile helps to assure the spar transfers the torsion effectively and does not separate from the body of the hydrofoil. Wooden ribs were also included to provide more structure for torque and hydro forces. In addition, the hydrofoil was designed to be wrapped in fiberglass to seal the hydrofoil and reduce deflection.

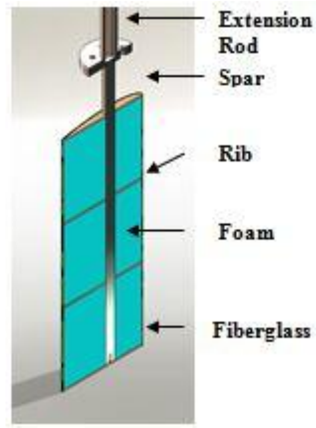

Figure 1: Hydrofoil section view

The heart of any power generation system is the generator. The resistive torque of the generator (also known as the "k-factor"), the voltage and current requirements, overall size and availability were the main factors considered. After researching many different applications of low speed generators, such as vertical wind turbines, a Brushed DC gear motor was selected. Even though a brushless motor would have had a higher energy conversion efficency, in the interest of costs savings it was avoided. An in-depth analysis was performed to determine the "k-factor" of the chosen generator before a gear ratio was chosen for the final drive.

Analysis

Base: The base was analyzed using ANSYS finite element analysis software for strength and stiffness. The CAD solid model was imported into ANSYS and the base was constrained in all degrees of freedom at each foot, as the metal stakes would on the riverbank. Figure 2 shows that the base stress was highest in the expected areas but well within the limits of the material. Most of the high stress points are artifacts of the model - at points in the end of tubing - and therefore should not exist in the actual base. The final result of the FEA analysis was confirmation in the ability of the stock tubing size that was selected to resist the operating loads of the system.

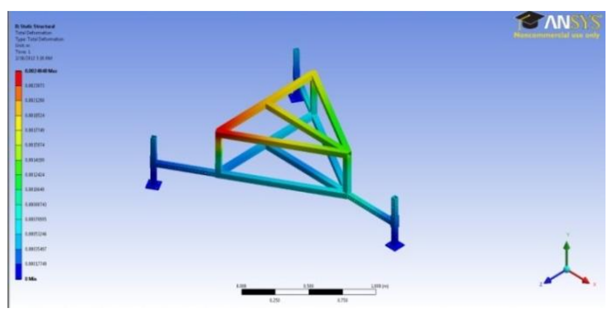

Figure 2: Base Deflection

Boom: Theoretical and ANSYS finite element analyses were conducted on the boom to determine the magnitude of the stresses that the boom would encounter based on loading cases from the simulation. A safety factor of two was used to double all of the loads. Deflection analysis, shown in Figure 3, was also completed to determine if a supporting superstructure would be needed. The analytical and ANSYS values for the von Mises stress agreed within 2%, independently verifying the solution.

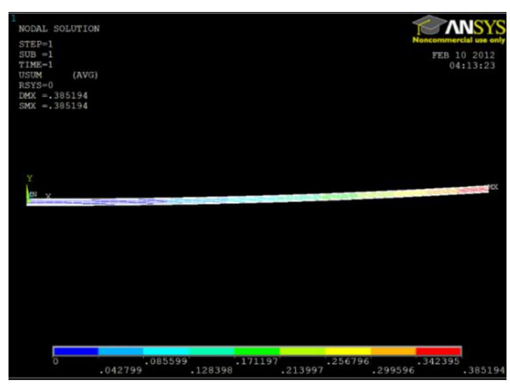

Figure 3: Boom Deflection Analysis

Hydrofoil: Theoretical calculations were performed in a spreadsheet to estimate the maximum stresses. The main structural component of the design was then checked in ANSYS (See Figure 4). The design used a factor of safety of two with respect to the hydro forces from a river moving at 0.5 [m/s]. The design focused on robustness over optimization due to the fact that the main goal is to collect data.

An extension rod was also designed to bridge the gap between the end of the boom and the surface of the water. This component was designed in a similar fashion as the spar.

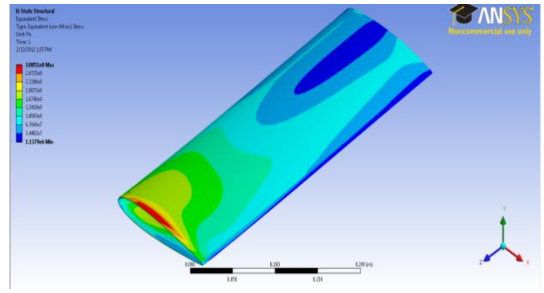

Figure 4: Hydrofoil fiberglass layer in ANSYS

End Cap: The design of the end cap box, used to house the servo for hydrofoil positioning, was analyzed using Solidworks 3D models imported into ANSYS Workbench. As predicted, worse case forces and moments were applied to bearing mount locations. All degrees of freedom where constrained in the location of the mounting bolt holes. The results from this analysis (See Figure 5) were used in selecting the material used, aluminum alloy 6061.

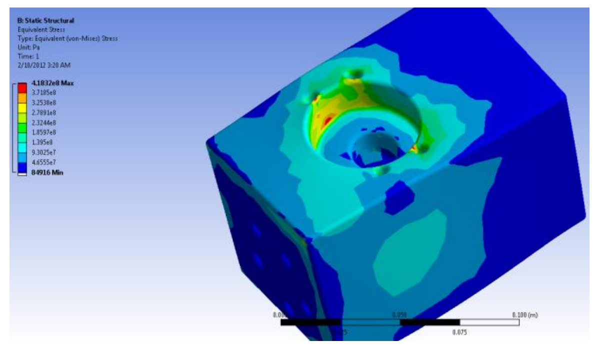

Figure 5: End Cap Stress Analysis

Generator: In order to ensure the generator had the desired k-factor, a set of tests were performed on it once it was received. These tests involved creating a constant torque on the shaft while maintaining a known load resistance. The torque was applied by hanging measured weights from rope tied to a pulley attached to the generator shaft. While letting the weights free fall and thus turning the generator, the output voltage and RPM were measured. The k-factor is the slope of the line when torque is plotted against RPM.

Testing

LabVIEW was used to create a program to measure and record the power production. Power by itself is of little value without the context of when and at what positions it was produced. Output voltage and current as well as angular position of the boom and angle of the hydrofoil relative to the boom are simultaneously measured and recorded by the program. A secondary Matlab processing program was written to compute power production, average power, and cycle power for comparison with the simulation.

In order to test most effectively, the simulation model was used to pinpoint certain hydrofoil and boom angle parameters to be deployed during testing. These angles gave the team the best shot at producing power during river testing.

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Environmental Assessments

An important aspect of this project was to design a system for which the environmental impacts of the device could be assessed and quantified. Historic river data presented in the primary literature associated with the Genesee River, and sources provided by the New York Department of Conservation were analyzed. The team then studied all possible environmental concerns, and rated them according to level of concern (highest to lowest) and ease of assessment (easiest and quickest to hardest and longest). Ultimately, the team predicted the level of impact of the device for each concern, and developed assessment plans for each.

Results and Discussion

The final CAD model and physical system are shown below in Figure 6.

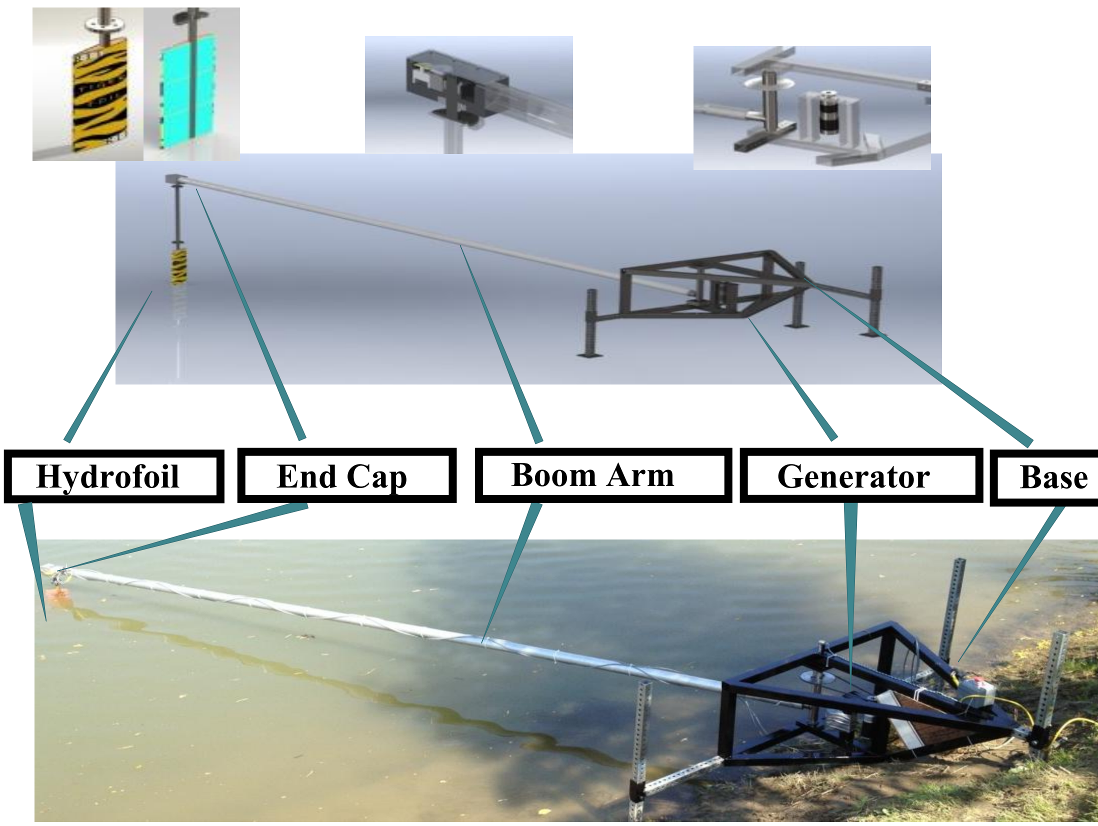

Figure 6: CAD Drawing and Full-Scale System

The final base design is an equilateral triangular shape made out of steel square tubing with three extendable/adjustable legs. Each side of the base is 42" in length weighs approximately 105 pounds with the legs attached.

The boom's stress analysis showed that a two inch schedule 40 aluminum pipe was the closest pre-made material available that could withstand the large bending moments generated by the hydrodynamic forces on the hydrofoil. To connect the boom to the driveshaft without compromising its structural strength a step-down sleeve was machined and connected to the boom with structural adhesive, increasing the wall thickness. Two pins connect the thickened portion to the driveshaft while a five-hole bolt pattern was used to connect the end cap to the boom. The mounting piece was machined, drilled, and tapped, then welded onto the end of the boom. The finished boom weighs 22.5 pounds.

The final end cap design consists of a digital servo, a tension cable drive system, and a rotary potentiometer for position reporting enclosed in a rugged and weather proof construction housing. The overall size was minimized, weighing a total of 4.5 lbs. The compact, internal compartment houses a high torque servo, bearing blocks, foil mounting shaft and a potentiometer (See Figure 7). The system is used for angular foil position control and measurement. The position control, in degrees, ranges from 45 to 360 with a step size of 1.70 degrees. An Arduino Bare Bones Board micro-controller handles all system controls based on predefined input parameters.

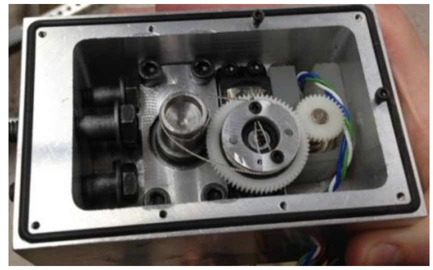

Figure 7: Final End Cap Design

Figure 8: Final Hydrofoil Design

The hydrofoil's final design (See Figure 8) is comprised of foam, a spar, an extension rod, two ribs, and enclosed in four layers of fiber glass. The total weight of the hydrofoil is five pounds.

The final generator design (See Figure 9) is a 46:1 DC brushed gear motor, an ANSI #25 steel roller chain, (20 tooth) and (60 tooth) steel sprockets and variable load resistor to simulate a battery in differing stages of charge. The total weight of the generator is roughly three pounds.

Figure 9: Final Generator Design

The power output of the system once installed in the river, produced an average of 0.09 Watts with peak values over 0.5 Watts in a river flow of 0.3 m/s. The initial goal of 50 Watts of power was deemed unattainable once the realization set in that the river velocity would be significantly less than the desired 1.0 m/s due to the calm winter. The objective then changed to being able to produce as much power as possible from any flow rate. The final design of the system satisfies the customer needs and engineering specifications to the best of the team's ability.

Environmental Assessment

The environmental assessment plans that were developed will provide adequate knowledge into handling the effects the full-scale system will have on the river ecology. The environmental concerns along with their respective assessment plans are shown on the next page in Table 2.

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Environmental Concerns	Assessment Plan
Physical harm to migratory sturgeons	⅄ On site, field samples of fish at three points- adjacent to the device and 15 meters upstream and downstream
Chemical pollution due to zinc and aluminum	⅄ Take initial samples of the river during peak summer time from three points- adjacent to the device and 15 meters upstream and downstream ⅄ Take samples periodically (every week) after the device is installed from the same points
Sediment stir-up and effects on water clarity	⅄ Take water samples from three points- adjacent to the device and 15 meters upstream and downstream to test for suspended soil particles. ⅄ Use long term, high resolution, hyper-spatial data to test for water clarity

Table 2: Environmental Assessment Plans

CONCLUSIONS AND RECOMMENDATIONS

The project, in general, was successful. The team was able to develop a full-scale river model system capable of generating power from a river. The primary need of the customer was a rugged system that can be used repeatedly to generate power and record data for future analysis. The power that was generated, however, was less than the initial goal of an average of 50 Watts for the project. The river was an issue the team had to deal with as well. Since the winter this year was milder than usual, the water level was low, and the velocity of the river was not as fast as originally expected. The team tested the system at a river speed of roughly 0.3 m/s rather than the anticipated 1.0 m/s river flow that would have been ideal, resulting in reduced power generation. The large structural size of the components also limited power production by increasing inertial losses.

Considering that the team was creating a full-scale version for the first time, there is significant room for future Senior Design teams to optimize and redesign the system. Also, collecting more data will improve simulation accuracy and in turn help to improve future system designs. Future work should include determining how much power is consumed by flipping the hydrofoil and create/test methods for doing that flip passively, exploring the use of flywheels for increasing the system efficiency, beginning execution of some environmental assessment plans to quantify the environmental impact of our device, exploring the use of curved plates for foil in place of more costly hydrodynamic shapes and lastly, replacing the rigid boom with a tether system in order to increase efficiency, lower cost and weight, and generate more power.

ACKNOWLEDGMENTS

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