AC 2011-2297: LOW COST RIVER SIMULATOR FOR 100W HYDRO-KINETIC TURBINE TESTING

Edward Russell Forringer, LeTourneau University
Matthew G. Green, LeTourneau University

Dr. Matthew G. Green is an assistant professor of Mechanical Engineering at LeTourneau University, Longview. His objective is to practice and promote engineering as a serving profession. Focus areas include: remote power generation, design methods for frontier environments, enhanced engineering learning, and assistive devices for persons with disabilities. Contact: MatthewGreen@letu.edu.

Jesse J French, LeTourneau University
Paul R. Leiffer, LeTourneau University

PAUL R. LEIFFER, PhD, PE Paul R. Leiffer is a professor in the School of Engineering and Engineering Technology at LeTourneau University, where he has taught since 1979. He is currently co-developer of the program in BioMedical Engineering. He received his B.S.E.E. from the State University of New York at Buffalo and his M.S. and Ph.D. degrees from Drexel University. Prior to joining the faculty at LeTourneau, he was involved in cardiac cell research at the University of Kansas Medical Center. His professional interests include bioinstrumentation, digital signal processing, and engineering ethics. Email: paulleiffer@letu.edu

Low-Cost River Simulator for 100W Hydro-Kinetic Turbine Testing

Abstract

In a multi-year project our students are designing, prototyping, and testing hydro-kinetic devices intended to provide electrical power in remote regions by extracting energy from river currents. The low-cost submersible devices must not disturb surface use of waterways while producing between 20 and 100 watts of power for river currents between 1 and 3 m/s.

These hydro-kinetic power systems must be tested in a full range of water flow velocities. Local river testing does not readily provide a wide range of flow velocities and commercially available water tunnels are infeasible for this application, starting at $14,000 for a model with a maximum flow velocity of 0.3 m/s and a 70 in^2 test cross-section, much less than the 400 in^2 test cross-section needed.

This paper describes the conversion of a pre-existing 24 foot diameter 4 foot deep above-ground pool into a variable flow-rate "water tunnel" facility using $500 of additional equipment. Steady state flow rates of 0.89 m/s are achieved using an 80 pound thrust (rated) trolling motor powered by a pulse-width-modulated motor controller drawing approximately 970 W of electrical power. Calculations indicate that approximately 400 pounds of rated thrust will be required to reach our goal of 2.0 m/s flow rates near the outer edge of our pool river simulator.

1 Introduction and Motivation

1.1 Global Service Learning

Many engineering schools involve students in global service-learning projects[1,2,3]. The importance of integrating both global impacts and social impacts into the engineering curriculum is acknowledged by the ABET criteria[4], and human need is a clear priority of the engineering profession, as indicated in the NSPE creed[*,5]. The majority of North American engineering students, however, are not familiar with the contexts in which vast needs exist, such as those among the physically disabled or among the estimated 4 billion people living on less than $2 a day (purchasing power parity)[6]. Integration of hydro-kinetic energy projects into senior design and thermodynamics courses exposes students to the growing field of renewable energy, as well as supports the emphasis LeTourneau University places on global service due to the potential of small-scale hydro-kinetic technologies for use in remote areas.

1.2 The Need for a 100W Hydro-Kinetic Generator

Electric power is a major quality of life enabler through technologies such as lighting, communications, and digital electronics. From a global perspective, many remote areas have either unreliable electrical power or no power at all[7]. HCJB Global, an international humanitarian organization, requested a student team to design, prototype, and test a system to provide ~2.4kW-hr/day (before storage) of electrical power to remote areas, from a river with no dams or other significant elevation change. Creating a remote power module with minimal site

[*] "As a Professional Engineer, I dedicate my professional knowledge and skill to the advancement and betterment of human welfare …"

works (e.g. no dams) could empower HCJB Global to fulfill their humanitarian objectives in several capacities in remote areas.

Figure 1 shows a 100W *hydro-kinetic* device which harnesses the kinetic energy of flowing water, commercially available for ~$1200. Such technologies appear promising in certain remote contexts unfriendly to fossil fuel generators (due to fuel cost and maintenance), solar photovoltaic (due to low sunlight or trees), and potential-energy hydro (if dams and diversions are problematic, for example.) A low-power hydro-kinetic technology that is easily transported and installed is attractive for a number of the remote locations where HCJB global works. The feasibility is extremely sensitive to the available river velocity since power density (V^3/2 kW/m^2) is proportional to the cube of river velocity.

Figure 1: Sample 100W Hydro-kinetic Electricity Generator (Ampair UW100)*

1.3 Hydro-Kinetic Testing Alternatives and the Need for a Low-Cost "Water-Tunnel"

Feasibility evaluation of a low-power hydro-kinetic technology requires data for power produced in various river velocities. Several testing options considered were not pursued due to feasibility concerns: (1) a swimmer's treadmill (continuously flowing swimming pool) had too small of a flowing cross-section, (2) the cooling water outlet from a local power plant may have been too difficult to access due to post-9/11 security concerns and too turbulent, (3) inducing flow with an outboard motor in a large oval-shaped ditch of water was deemed to require too much land and power, and (4) a cursory search indicated commercially available water tunnels start at $14,000 for a model with a maximum flow velocity of 0.3 m/s and a 70 in^2 test cross-section, much slower and smaller than the 400 in^2 test cross-section needed.

Testing options which *were* used by students include pulling the hydro-kinetic device from a boat (in which the wake is a challenge), anchoring in a natural river as in Figure 2 (which offers no speed control but provided some good data from 0.7-0.9m/s), and pulling from land (which is limited to short tests but allows speed control). Testing anchored in a river provided the most realistic and long-term testing (including debris and flood stages) with the disadvantages of no control over flow speed and difficulty with site access and setup. Pulling from land proved conducive to rapidly testing multiple configurations across a variety of water speeds.

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* http://www.boost-energy.com/ampair/products_product5.asp

The river simulator is under development in hopes of obtaining a variable-speed velocity with long run time in a highly accessible and controlled environment.

Figure 2: River Testing

2 Prototype River Simulator and Sensor Systems

A hydro-kinetic testing setup requires relative velocity between water and the test device, and a calibrated velocity sensor. The prototype river simulator reported here is based on a 24 foot diameter, 4-foot deep above-ground swimming pool. Similar pools are available new for $1,000-$2,000. The entire body of water is caused to rotate using a Minn Kota 24V trolling motor assembly (Figure 3) rated at 80 pounds of thrust that was donated to the project by East Texas Sonar of Longview, Texas.

Figure 3: 24V Trolling Motor

2.2 Electrical Power Systems

Power to the trolling motor was supplied by a Mean Well SE-1000-24 regulated power supply rated at 24V and 41.7A and powered by 110V AC grid power. For some of the tests, the power supply was connected directly to the trolling motor. In these cases, the trolling motor drew more than 50 amps of current from the power supply, exceeding its rating, causing shutdown on a thermal overload.

Additional tests were run using a Kelly KDS36100 pulse width modulated motor controller, powered by the Mean Well described above. The motor controller is rated at 24-36V up to 100 amps. The final electrical system used is shown in Figure 4. An electrical schematic is shown in Figure 5 (in which the "battery" shown is replaced with the Mean Well supplied with 110V grid power.) It was observed that the power supply would shut down due to thermal overload after approximately one hour when run between 40 and 50 amps. The system may be able to run longer if less power is drawn from the supply.

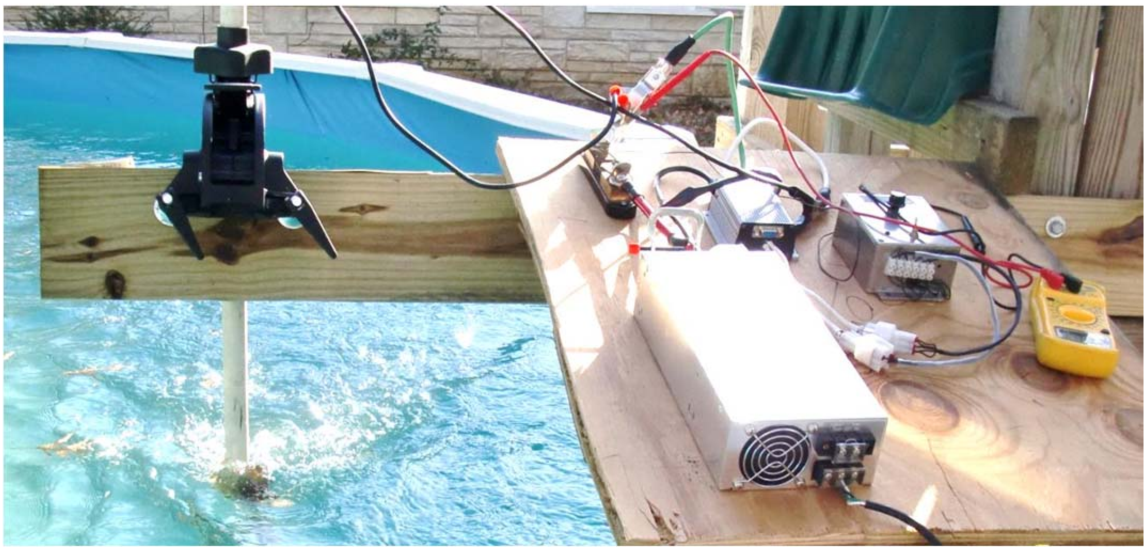

Figure 4: Trolling Motor and Kelly Power System

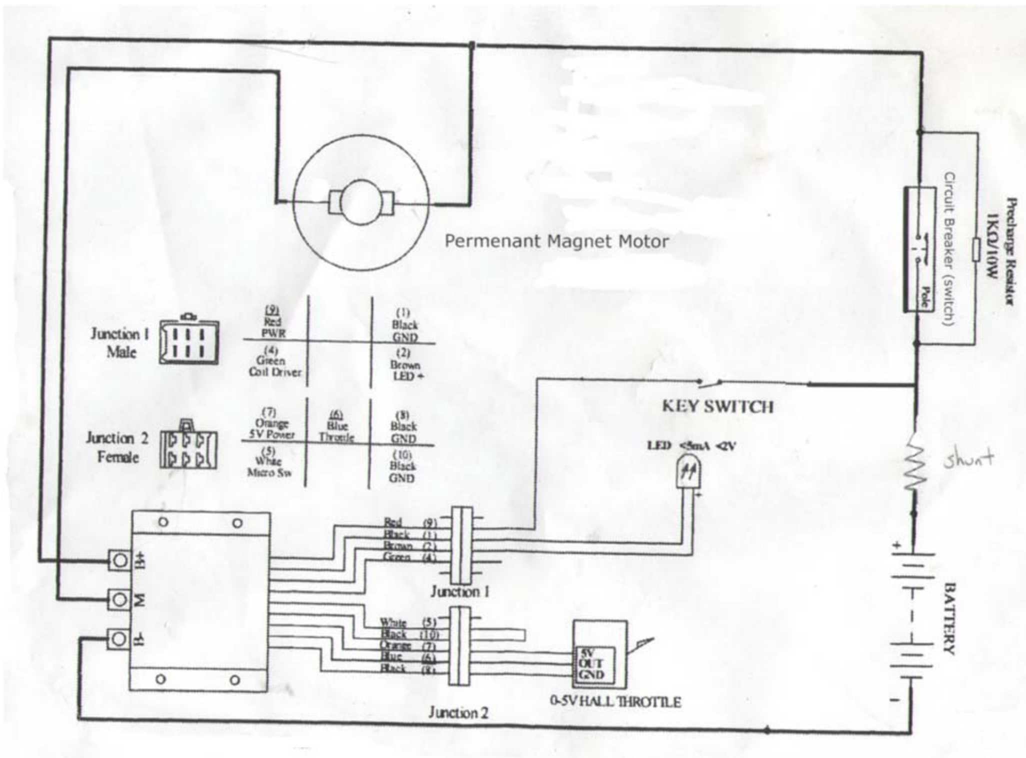

Figure 5: Schematic for Trolling Motor Power System
(the "battery" shown is replaced with the Mean Well power supply, supplied with 110V grid power)

2.3 Vortex Suppression

A 55 gallon barrel was placed in the center of the pool in hopes of reducing the potentially damaging (energy-draining) effects of vortex formation. Figure 6 shows the method for centering the barrel – not a trivial assignment on a cold December day.

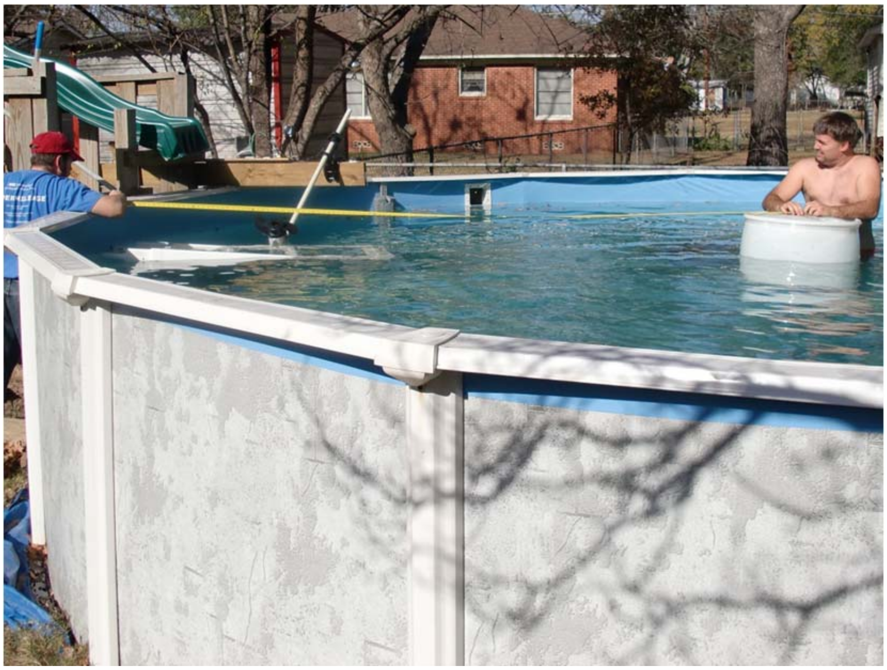

Figure 6: 24ft Pool and Vortex Suppression Barrel Being Centered

2.4 Velocity Sensor Positioning System

A sensor positioning system was designed to achieve both rigidity and accurate radial and vertical positioning as shown in Figure 7.

2.5 Velocity Sensors

Three types of velocity sensors were used to characterize the river simulator: a floating ball ($1), an educational-grade Vernier sensor ($129+$61) and a professional-grade Swoffer ($316) coupled with a custom-built logging circuit. Cost can be a major obstacle to student projects, so all three sensors are described here.

2.5.1 Timing a Floating Ball

Timing a floating ball circling the pool was used to estimate surface velocity both before velocity sensors were available on site and as a reality check later. This turned out to be important when electronic velocity measurements appeared to be twice the value of the ball, and the erroneous factor of 2 was quickly discovered. The floating ball also offered the benefit of illustrating surface particle path. With the pool running at top speed the ball test took 21-22 seconds to make one circumference of the pool at approximately (2 +/- 1) foot from the outer edge of the pool. This gives a velocity estimate of 0.9 +/- 0.1 m/s.

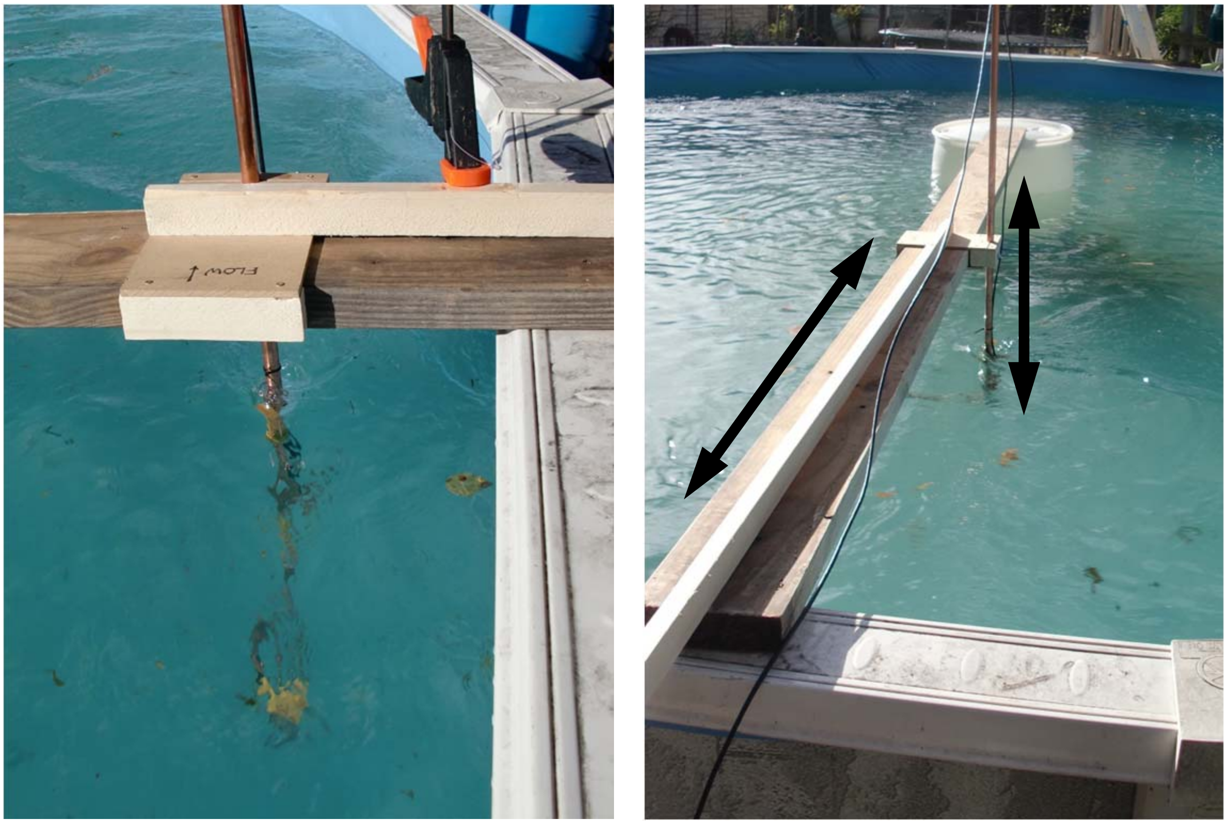

Figure 7: Velocity Sensor Positioning System (Radial and Vertical)

2.5.2 Vernier[8] Velocity Sensor
The Vernier "Flow Rate Sensor[8]" lists for $129 and requires either a $61 dollar electronic link to a computer or a $329 stand-alone data logger. This sensor uses a magnet rotated by a propeller to trigger a reed switch, and converts these pulses to a measurable voltage proportional to water velocity. The authors had difficulty obtaining repeatable results with this sensor, and it had the added disadvantage of having no method for recalibration. The authors have had good experience with Vernier sensors in the past, but at this time would not conclusively recommend this particular flow rate sensor for scientific work. The Vernier manual states the sensor is intended for educational purposes only, and not research.

2.5.3 Swoffer[9] Velocity Sensor
Our testing used a professional-grade $316 Swoffer[9] sensor (Figure 8) which gates a beam of infrared light through a bundle of fiber optics back to a photo-transistor. This high-quality rotor is normally part of a larger bundle including a data logger, which was outside of the project budget ($1,600 to $2,800). Instead, a student-built counter which displayed the number of pulses in binary (Figure 9) allowed use of the rotor along with a stopwatch at the expense of some data logging inconvenience. Figure 10 shows the Swoffer in action – made possible by a partially submerged transparent pie dish which gave a glass-bottom-boat effect by overcoming surface ripples. This visibility enhancing trick made it much easier to spot and remove the occasional leaf attached to the sensor.

Figure 8: Swoffer Velocity Sensor Rotor[*]

Figure 9: Custom Built Low-Cost Reader for the Swoffer Velocity Sensor

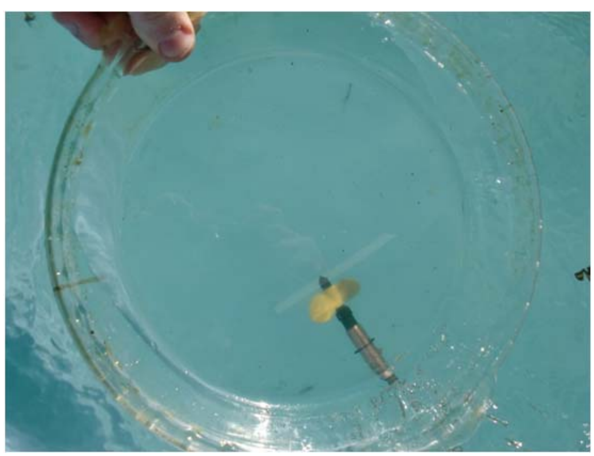

Figure 10: Swoffer Velocity Sensor in Action
(Underneath a Semi-submersed Pie Dish for Visibility)

[*] http://www.swoffer.com/img/rotor%20parts.jpg

2.5.4 Swoffer Velocity Sensor Calibration

The custom circuit (Figure 9) displays the cumulative pulses produced by the Swoffer sensor via LED's. Figure 11 shows calibration data obtained by walking the sensor 18.9m through a still indoor swimming pool at different average velocities. The calibration tests indicate that the sensor consistently produces 45.5 pulses/meter independent of velocity. In experimental testing this calibration number is used to convert sensor pulses into a distance of water passing over the sensor, and this distance divided by time gives water velocity in m/s.

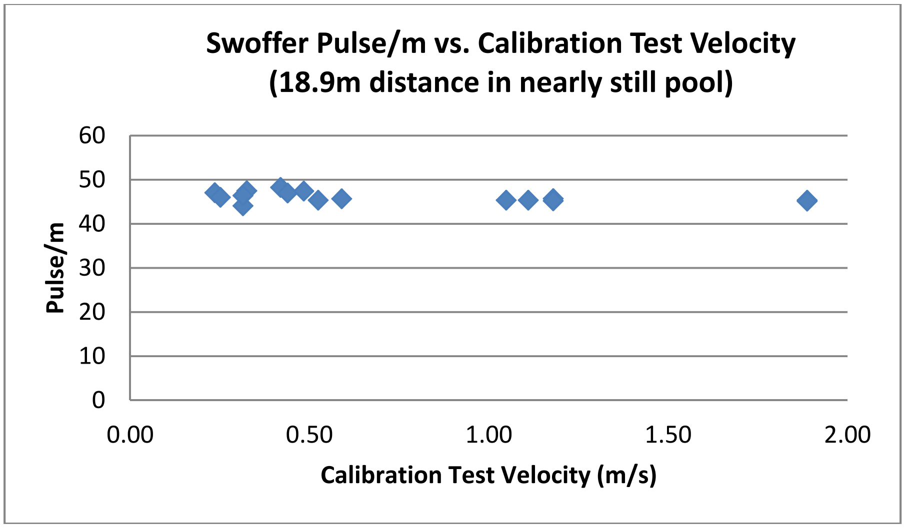

Figure 11: Swoffer Sensor Calibration Graph Showing 45.5 pulses/meter

3 River Simulator Testing Procedures and Data Analysis

3.1 Velocity Profile

Figure 12 shows the one-dimensional velocity profile obtained with the professional-grade Swoffer sensor and rigid support shown previously in Figure 8 and Figure 7 respectively. Each data point is an average velocity sampled over 7s to 25s. At the end of testing the first data point was repeated multiple times to insure repeatability. As expected, the graph shows a linear relationship between pool radius and water velocity. The trend line indicates that the velocity would be zero approximately 10.7ft from the pool edge, which is near the outer edge of the vortex-reducing barrel in the center. This indicates a 2 foot diameter hydro-kinetic device in these testing conditions would experience a velocity difference of 0.2 m/s from edge-to-edge.

An accidental failure of the power electronics delayed additional data collection past the publication date for this paper. During these tests the trolling motor was measured to draw 23V * 42A = 966W.

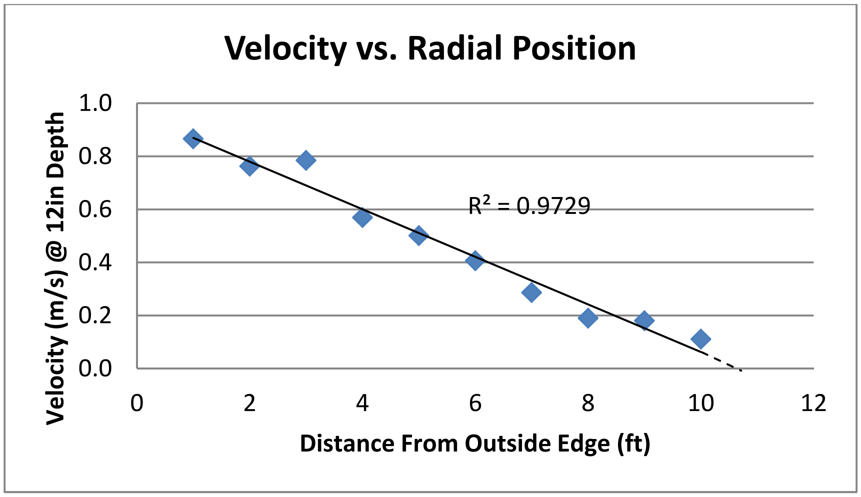

Figure 12: One-dimensional Velocity Profile (1ft Below Surface)
(24 Foot Diameter Pool, Single Motor Drawing 23V & 42A)

3.2 *Spin-Down and Spin-Up Data*

Based on the velocity profile data (Figure 12) the pool can be treated like a rigid disk such that velocity of each particle is proportional to the distance from the center of the pool and angular velocity is uniform in the pool. The total mass of the pool (12 foot radius, 42 inch water level) was calculated to be about 45,000 kg. The moment of inertia for the pool was calculated as 301,000 kg-m^2. For the spin-down and spin-up data presented in Figure 13 and Figure 14, velocity measurements were taken at a 2 foot distance from the outer edge (10 foot radius from the center.)

The shape of the velocity versus time graph during spin-down (Figure 13) can tell us about the dissipative forces on the spinning water. The assumption was made that any dissipative torques on the pool would be proportional to angular velocity squared. This results in the left-hand-side equation below: moment of inertia (I) times angular acceleration (α) = the drag coefficient (β) times angular velocity (ω) squared. (This equation is analogous to ∑F = ma, but for rotating rigid bodies is rather ∑τ = Iα, with the order reversed below.) This leads to a differential equation which has an analytical solution (obtained in this case via WolframAlpha[10] online) for angular velocity as a function of time, shown in the right-hand-side equation below.

$$I\alpha = -\beta\omega^2 \rightarrow \omega(t) = \frac{I\omega_0}{I + \beta\omega_0 t}$$

This function was fit to our data with β as a free parameter. The quality of the curve fit to the data suggests that the model for dissipative forces is accurate. The best fit value gave β = 6,740 kg-m^2.

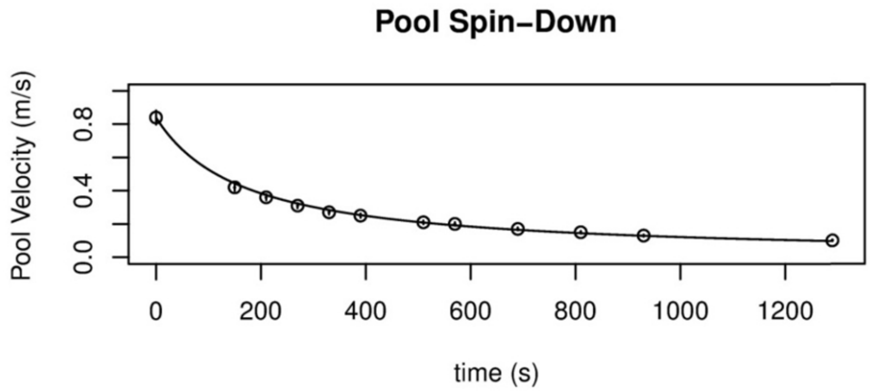

Figure 13: Spin-Down: water velocity at a 10 foot radius as a function of time while the pool was slowing down after power was removed from the trolling motor. The solid line is a best fit curve assuming drag forces which are proportional to velocity squared.

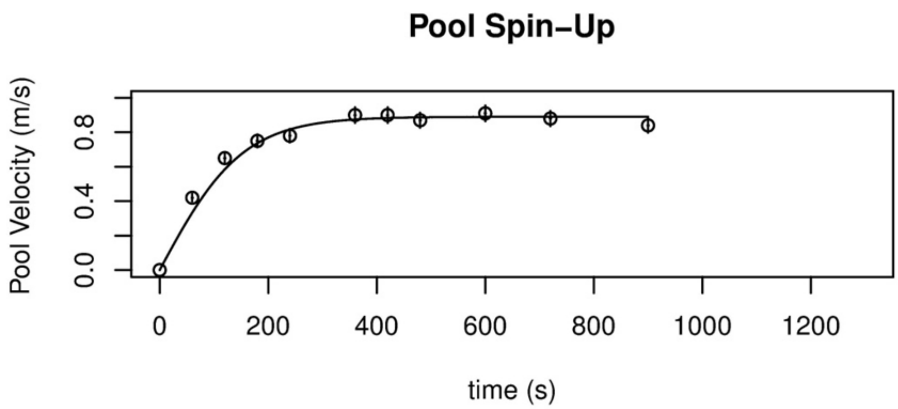

Figure 14: Spin-Up: water velocity at a 10 foot radius as a function of time while the pool was speeding up when power was first applied to the trolling motor. The solid line is a best fit curve assuming constant thrust from the trolling motor, and drag forces which are proportional to velocity squared.

The shape of the velocity versus time graph during spin-up (Figure 14) along with our knowledge of the dissipative forces can tell us about the effect of the trolling motor on the water. The assumption was made that the trolling motor provides constant thrust to the water at a fixed radius. This leads to the differential equation below which has an analytical solution for angular velocity as a function of time. (Here $r_{trolling}$ is the distance of the trolling motor from the center of the pool.)

$$I\alpha = (F_{trolling})(r_{trolling}) - \beta\omega^2 \rightarrow$$

$$\omega(t) = \sqrt{\frac{(F_{trolling})(r_{trolling})}{\beta}}\, tanh\left(\frac{\sqrt{(F_{trolling})(r_{trolling})\beta}}{I}\, t\right)$$

This function was fit to our data with $F_{trolling}$ as a free parameter (β was fixed from the previous fit). The quality of the curve fit to the data suggests that the model of constant thrust force from the trolling motor is reasonable, although a close inspection reveals that the thrust is higher when the pool is spinning slower. The best fit value gave a trolling motor thrust of 190 Newtons (43 pounds) or a little more than half of the rated thrust for the trolling motor.

These data allow us to calculate the power input to the pool by the trolling motor at the maximum water speed (165 W) and the total kinetic energy of the pool at the maximum water speed (13,000 J).

We can see that in order to increase the final water speed to 2.0 m/s (at a 10 foot radius), we will need to increase the effective thrust from 190 Newtons to 980 Newtons (220 pounds), a little over 5 times the current thrust. The rated thrust will probably need to exceed 400 pounds – outside the range available in a single trolling motor.

4 Sample Student Project Testing

Figure 15 shows the physical testing setup with a 24V trolling motor to drive the water flow, and a 36V trolling motor re-purposed as a generator and fit with a custom blade.

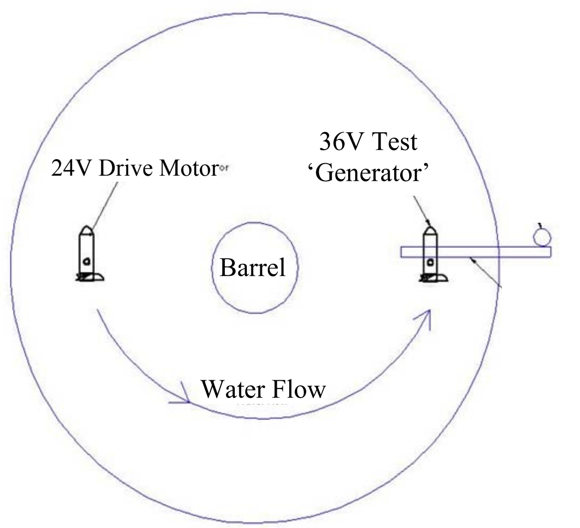

Figure 15: River Simulator Hydro-kinetic Testing Setup

Figure 16 shows the fabrication of a 6 inch pitch 24 inch diameter blade; students are heating the blades to enable bending the correct pitch angle. Maintaining a constant 6in pitch requires the angle of each blade to decrease as the radial distance from the hub increases, requiring care in manufacturing. Figure 17 shows the new blade design undergoing testing in the river simulator.

The data measured during testing indicated peak power of 0.16W despite a relatively large total incident power (18W calculated from $P=0.5\rho \cdot Area \cdot V^3$). This inefficiency was due to spinning the generator far too slowly for efficient electricity generation. Additionally, it was found that the large blade removed sufficient power from the pool to slow the maximum river simulator velocity from 0.89 m/s to 0.55 m/s. Although the testing results were disappointing from a device standpoint (~1% total system efficiency or η_{sys}=0.16W/18W), multiple learning outcomes were achieved related to power and energy conversions and some basic elements of renewable energy technologies.

Figure 16: Fabrication of a New Blade Design for Hydro-kinetic Testing (Heating Blades to Bend Pitch Angle)

Figure 17: Testing a New Blade Design

5 Conclusions and Future Work

Testing shows that a low-cost river simulator is both do-able and more complex than originally anticipated. The primary issue is providing adequate power to the water to reach a wider range of speeds (the local river is 0.7-1.0 m/s at normal stage, and other rivers can run much faster.) Since thrust input requirements scale with the square of water velocity, higher speeds will require a significantly larger power source, probably an outboard motor.

Future work involves more thorough velocity profiling, testing for turbulence with dye, reducing water drag, measuring the effect of various sizes (or the absence) of a vortex reducer, and testing the effects of flow straighteners.

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