Final Report

Creek Tides Energy & Power – Reactive Reversible Blade Turbine for Power Generation

Awardee: Creek Tides Energy & Power

Awardee point of contact: Scot Cumming

Facility: FAU Hydrodynamics Laboratory

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1 INTRODUCTION TO THE PROJECT

This project will be the first characterization of the performance of a novel reactive reversible blade system designed for power generation. The reversible blade system is composed of a series of blades that can pivot around their span axis while the forces on the blades generate a torque that may be useful for power generation (Fig 6). It is theorized that as the blades rotate, drag will decrease on the system, thus allowing an increase in rotational speed and power output. The system may therefore be well suited for slow currents.

As no previous numerical models or testing of the Creek Tides technology are available, these tests will gather preliminary fundamental performance data on the turbine concept without *a priori* scaling requirements. Rather than the typical approach which identifies full scale system performance goals and then selects suitable scaled experimental conditions, these tests will evaluate the prototype's performance at its current scale and extrapolate equivalent larger scale projected performance.

A prototype of the turbine with a set of 5 reactive blades has been constructed by Creek Tides (CT), and will be tested in Florida Atlantic University's (FAU) Hydrodynamics Laboratory recirculating flume at varying flow speeds, with and without mechanical load applied. These experiments will 1) measure the rotational speed as a function of incoming flow speed 2) measure torque as a function of incoming flow speed and 3) compute power efficiency as a function of flow speed.

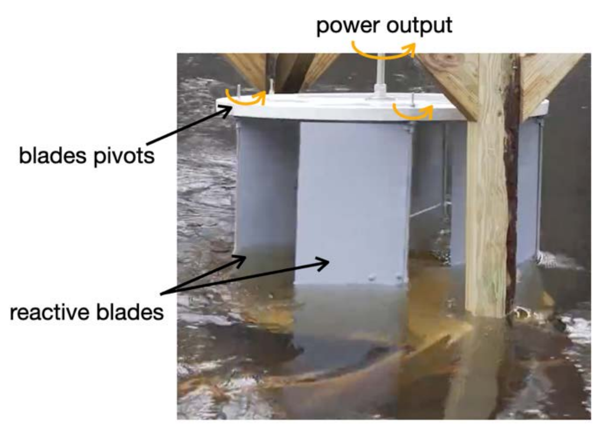

Figure 1: Testing of the reactive reversible blade turbine for power generation featuring blades that can pivot around their span axis to minimize drag. A scaled version will be tested in laboratory conditions.

2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

The applicant, Scot Cumming (CT), will provide a prototype of the power generation system to FAU. Mr. Cumming will participate in bi-weekly meetings during test setup, performance, and data analysis phases.

2.2 Network Facility Responsibilities and Tasks Performed

FAU will be responsible for the following:

- Characterizing the performance of the prototype. This includes:
  - Measuring rotational speed
  - Measuring mechanical power output
  - Data analysis (computing power output and efficiency, non-dimensional parameters)
- Provide a report of results and upload data to MHKDR
- Host weekly progress meetings to discuss milestones, objectives and the experimental results. In addition, FAU will update the applicant, Scot Cumming, in a bi-weekly basis.

3 Project Objectives

The overall objective of this project is to investigate the fundamental performance of a drag-based turbine concept, with the goal of characterizing its potential for larger scale applications and compare it to other drag-based turbines. By evaluating an 11”x11” prototype of a “reactive reversible blade turbine,” shown in Figure 4, CT hopes to observe its operation in controlled laboratory conditions, establish a baseline for its performance at that scale, and calculate non-dimensional parameters that can be used to estimate its performance at larger scales.

4 Test Facility, Equipment, Software, and Technical Expertise

The proposed research will be performed in the Hydrodynamic Laboratory at the Department of Ocean and Mechanical Engineering at FAU in the Institute for Ocean and System Engineering (SeaTech) campus at Dania Beach, FL.

Figure 2: SeaTech Campus at Dania Beach. This educational and research center has access to the Intracoastal waterway and Atlantic Ocean. It houses multiple labs including the Hydrodynamics Lab and the Autonomous Underwater Vehicle (AUV) Lab.

SeaTech campus: SeaTech is a 4,645 square meters educational and research center aimed at solving problems in the ocean and related fields. It is located in eight acres of land between the Atlantic Ocean and the Intracoastal Waterway in Dania Beach, FL with valuable easy access to the ocean and estuaries.

Hydrodynamics Laboratory: The room has an area of approximately 21.3 x 6.2 m. This room houses a low-turbulence water tunnel and a wave/towing/flume tank (described below). The laboratory is equipped with working benches, mechanical tools, electronics (oscilloscopes, voltmeters, power supplies, etc.), compressed air, optics, cameras, and lenses.

Wave/towing/flume (18.3 x 1.2 x 1.2 m): A recirculating water system that can generate simple waves, and can tow physical models. The flume can obtain velocities of 0.5 m/s and the tow carriage can achieve maximum speeds of 1 m/s (combined 1.5 m/s). All walls are made of glass. Specific capabilities to be used for these experiments include:

- Acoustic doppler velocimeter: high-resolution acoustic velocimeter to measure 3D water velocity at a 25 Hz rate (Nortek Vectrino).
- Force sensors: The lab has multiple force sensors including a 6-component force transducer (ATI ISA Gamma load cell with a force range reading of 1-100 lbs), 5 lbs, 2 lbs, 1 lbs, and 100g load cells (Futek, LSB200).
- DAQ boards and amplifier system: National Instruments cDAQ 9178 and NI USB-6211 with different modules for analog inputs/output running with LabView.
- High-speed camera and optics: three Photron FASTCAM Mini UX50 with 4 GB of memory. This camera can record at maximum resolution of 1280 x 1024 pixel resolution at 2,000 frames per second (fps). Photography accessories: tripods, multiple lenses, filters, Nikon camera and lighting.
- Others: oscilloscopes, various small dc motors with gear heads and encoders (Maxon motors), power supplies, computer software (Matlab, SolidWorks, Rhinoceros), working benches and sort of mechanical and electronic tools.

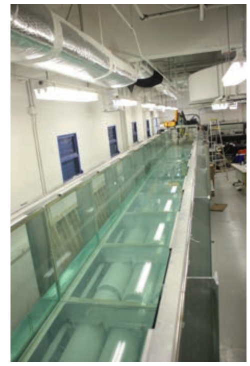

Figure 3: FAU's wave, towing, and flume tank (test section is 1.2 x 1.2 x 18.3 m).

Below is the estimated free stream velocity in the flume as a function of the motor controller frequency for a water depth of 16 inches. Note that the flow speed will change depending on the water fill height, which will be carefully selected for the intended target free stream flow speeds. For proposed experiments, we expect to operate pump motor controllers up to 40 Hz to avoid overheating equipment.

Table 1. Recirculating flow pump motor controller frequency vs. flow speed

Motor Controller Freq., Hz	Flow speed (V), m/s
10	0.102
20	0.170
30	0.261
40	0.355
50	0.431
60	0.500

Velocities greater than 0.5 m/s can be achieved with the following options: 1) reduction in the frontal area of the test section or 2) a combination of flow speed with the motor controller (flume) and moving the turbine in the carrier thus increasing the relative velocity between the turbine and the surrounding fluid. However, the intention is to limit evaluation flow for this preliminary assessment of the prototype's performance. Higher speeds may be considered for future assistance requests.

Computing*:* The Hydrodynamics Laboratory is equipped with 5 Dell computers - 2 desktops and 2 laptops with high-speed Internet connections for data acquisition. There is one IT employee dedicated to SeaTech. There is also a server in the Hydrodynamic Laboratory for data storage.

Expertise:

- Dr. Oscar Curet will coordinate and oversee the overall project and is the faculty manager of the Hydrodynamics Laboratory.
- Mr. John Frankenfield, a staff engineer at SeaTech, will be responsible for experiment set up and conducting experiments.
- Dr. Gonzalo Garcia, will analyze experiment data and will assist with in-lab testing.
- Dr. Manhar Dhanak will assist with experiment management and will provide feedback on the progress and results.

Additional Technical support can be provided as needed by two electrical engineers and one machinist.

5 Test Article Description

The device to be tested is a current energy converter. Primary potential advantages include efficient performance in low-speed flows and can be installed in multiple orientations. It is expected that the prototype would work submerged in a current up to approximately 90 cm/s, potentially outperforming fixed blade turbines of similar scale (higher cut-in speed). The CT turbine is predicted to also perform in flows that reverse in direction without re-orientation of the turbine. The design allows blades that have rotated past their maximum angle of attack to feather away and not induce additional drag as they rotate back into their position exposed to incoming flow.

Description of the system

The small scale proof-of-concept prototype (device under test or DUT) consists of five blades that rotate on the outer disk edge on a five-star pattern (Figure 4). The blades pivot on a single $1/4$ " threaded road attached at the outer edge of the disk on a five-star pattern. The prototype design includes mechanical stops that prevent over-rotation of each blade and allow for the transfer of force from the blades as rotational torque around a center shaft. The prototype's blades are made of a dense wood and are hinged to each $1/4$ " rod. A removable screen is available that can be used to further constrain blade motion and is intended to ultimately deflect debris/marine life from turbine blades. The shaft is made from $1/4$ " square stock. The turbine assembly utilizes a top and bottom disk made of $1/2$ " thick clear Lexan.

Figure 4: Reactive reversible Blade Turbine Prototype for Power Generation.

6 Work Plan

Turbine characterization will investigate two operating states: no-load and loaded performance. Because no previous numerical models or performance evaluation results are available, it is imperative to first determine the turbine's cut in speed and observe its basic operation. After unloaded cut-in speed is observed, turbine performance under loaded conditions can be evaluated. Finally, data analysis and results will be prepared. The test campaign includes three phases: (1) experiment set-up, (2) no load evaluation, and (3) under load evaluation.

Phase 1: Experiment Set Up

1) CT turbine will be fitted to temporary frame for attachment to flume (suspended from tank walls)
2) Nortek Vectrino 3D will be installed and oriented in the tank to measure free stream incoming flow
3) CT turbine will be lowered into tank to its experiment position
4) Encoder and Prony brake system (load cell) will be fitted and connections tested (as well as camera)
5) Final tank fill to experiment depth
6) Flume pump motor frequency will be calibrated to actual measured flow velocities

Phase 2: No Load Testing

1) The Prony brake system will be disengaged so the CT turbine can rotate freely in the flow. Starting from slowest speeds, with motor controller increments of 5 Hz, the flow will be increased until the CT turbine begins to operate. Turbine kinematics will be observed and recorded.
2) From turbine cut-in speed to 40 Hz (at intervals of 5 Hz), shaft RPM will be recorded.

Phase 3: Under Load Testing

1) The Prony brake system will be engaged with minimal torque applied (10%) and flume flow will slowly be increased (5 Hz slower than the previously observed cut-in speed) until loaded cut-in speed is observed. Flume flow will then be increased 5 Hz until maximum flume flow is reached (or mechanical instability is observed).
2) This procedure will be repeated at 10% torque increments through 100% torque or turbine cut-out.
3) Output shaft RPM will be recorded for all combinations of torque and flow speed.

6.1 Experimental Setup, Data Acquisition System, and Instrumentation

The experiments will be conducted in the Hydrodynamic Laboratory's large flume/wave/towing tank (Figure 3) at SeaTech. The turbine prototype will be installed on a fixed structure with respect to the flume, and submerged into the water, see schematic in Figure 5. The friction torque sensor will be attached to the turbine as well a digital encoder. Data will be sent to a computer through a National Instrument data acquisition system and MATLAB will be used to process the data. One camera will used to also observe the kinematics of the blades.

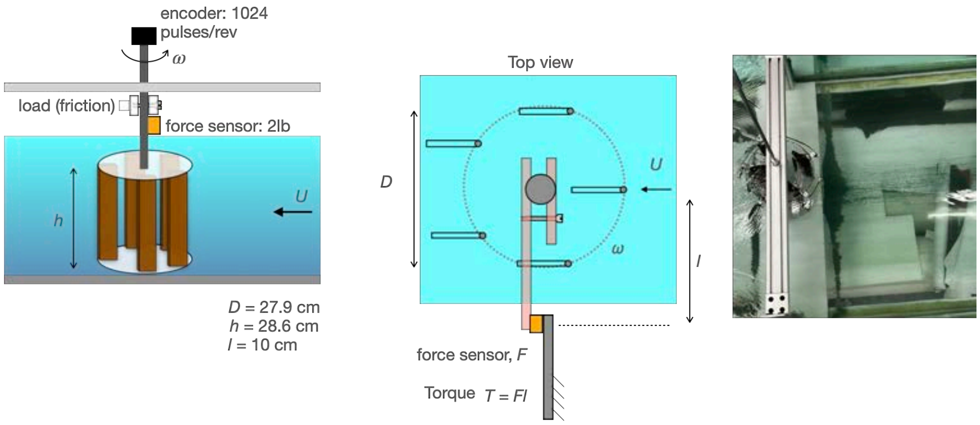

Figure 5: Overview of the experimental setup. Left and Center: Schematic of the experimental setup. Right: Top-view picture of the model turbine in the flume. Some parameters are also shown: *h* and *D* = height and diameter of the turbine, *l* = torque arm length.

The main bulk of the tests will obtain quasi-steady state values of critical variables, including rotational power, rotational dynamic torque, and rotational speed. Time varying values will be recorded when possible (for example, rotational speed, motion of blades). Each test will be characterized by a stream flow velocity in the flume, with the prototype turbine fixed with respect to the laboratory reference system.

Control Parameters:

- Motor frequency to control flow speed
- Load friction (Prony brake system)

Measured Parameters

The following measurements will be obtained:

- Incoming free-stream flow, *U* (acoustic velocimeter)
- Turbine output shaft angular velocity, ω (digital shaft encoder)
- Linear force, *F* (load cell)

Incoming free-stream flow:

A high-resolution acoustic velocimeter will be used to measure the speed of the incoming flow (Nortek Vectrino 3D). This instrument can measure 3D velocity at a particular point at sample rate of 1-200 Hz at with an accuracy of ± 0.5% of the measured value ± 1 mm/s.

Angular shaft speed:

The angular speed as well as angular acceleration will be derived from measuring the angular position as a function of time, through a digital encoder. Speed and acceleration will be calculated by numerical differentiation of the angular position and low pass filters.

Rotational dynamic torque:

The brake power of the system will be controlled using a Prony brake device (conceptual configuration shown in Figure 6), also known as a friction brake, where varying friction is applied to a rotating shaft. The torque will be measured using a load cell (HTC Sensor TAL221).

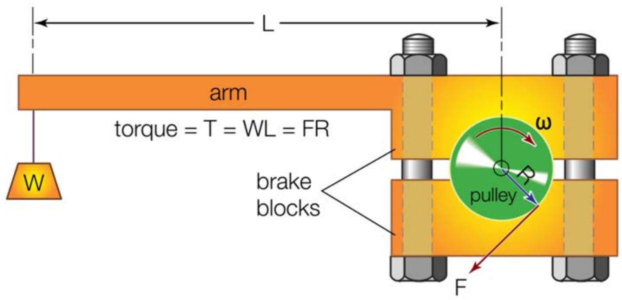

Figure 6: Elements of a Prony brake system to measure torque on a rotating shaft. Pictured modified from Britannica. (Picture Source: Wikipedia).

Computed Parameters

- Torque, $T = Fl$
- Power flow,
  $P_{in} = \dot{m}\frac{U^2}{2} = \frac{1}{2}\rho(hD)U^3$
  where $\dot{m} =$ mass flow rate, ρ = water density, h and D are turbine's height and diameter, and U is the incoming flow speed.
- Mechanical power, $P_{out} = T\omega$
- Efficiency, $\eta = P_{out}/P_{in}$

Key non-dimensional parameters computed:

- Reynolds number based on the incoming flow, *U,* and tip velocity, V_{tip}.

  $$Re_U = \frac{\rho UD}{\mu}, \qquad Re_V = \frac{\rho V_{tip} D}{\mu}$$

  where μ is the dynamics viscosity of water.

- Strouhal number

  $$St = \frac{\omega D}{U}$$

- Tip-speed and flow speed ratio

  $$\frac{V_{tip}}{U}$$

Turbine performance

The turbine performance was evaluated based on the hydrodynamics efficiency given by the mechanical power to incoming flow power ratio:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{T\omega}{0.5\ \rho h D U^3}$$

6.2 Test and Analysis Matrix and Schedule

Table 3 summarizes the experiments conducted. The first set of experiments was to measure the flow speed in the flow for different pump frequencies. The flow speed was measured with a acoustic velocimetry (Vectrino) at a sampling rate of 200 Hz.

The second set of experiments are the experiments conducted to evaluate the turbine. The frequency of the pump was varied from 0 Hz to 60 Hz in steps of 5 Hz (13 speeds in total). For each flow speed the load in the turbine was varied for 9 different loads, L1 = no load, and L9 is the higher load. In this set of experiments, the force was measure with a 2-lb load cell (Futek) and the rotational speed was measures with an encoder with a resolution of 1024 pulses for revolution. Force and encoder measurements were recorded at a sampling rate of 10,000 Hz. Experiment set 2 was ran twice, for a total of 162 test experiments (9 flow speed x 9 loads x 2 repetitions). Data collection was for a 20 seconds period. There was a waiting period of approximately 2 minutes when the frequency of pump was changed, prior to initiating data collection to allow equipment and tank flow to reach stead-state.

Table 3. Experiments conducted.

Experiment	f_{pump} (Hz)	Load	Measured	Sampling rate, Hz
1 (flume calibration)	5:5:60	–	U	200
2	15:5:60	L1:L9 (no load): (higher load)	*F*, ω	10,000

6.3 Safety

All the experiments and data collection will be conducted in accordance with the safety protocols and under the guidelines provided by the Office of Environmental Health and Safety at Florida Atlantic University (https://www.fau.edu/ehs/) .

6.4 Contingency Plans

The following major risks for the completion of the test plan were identified:

- Failure of the physical model
- Failure of the motor and/or motor controller that drive the flume flow speed

- Failure of test tank
- Failure of sensors

Failure of the physical model
In the unlikely event of the physical model is damaged, the model is simple enough that is straightforward to repair or remake (the Seatech campus and university are equipped with machine shops for onsite repairs). The installation of the system will be coordinated between FAU and Mr. Cumming to ensure that the system is well mounted. The physical model will be tested with small increment of flow speed to mitigate potential damage of do to increase in the load.

Failure of motor or motor controller for flume flow speed

In case the motor or motor controller for the flume fail, they will be replaced. As an alternative option, the experiments could be conducted by mounting the turbine in the carrier above the tank and towing the turbine along the tank without a flow. For this experimental setup, the speeds to be tested will be slightly greater (from 0.16 m/s to 1.5 m/s). Using the carrier, how long each test can be run is changed, but within test outcome scope.

Failure of test tank

Failure of the test tank could result in a critical test failure. The approximated water level for the experiments will be around 16 inches (the turbine is 11 inches high). These water levels are not high risk for the tank size. If there is a major leakage in the tank, the tank will be emptied, re-sealed on the affected area and refilled incrementally, resulting in test completion delays but not critical experiment failure.

Failure of sensors

It is possible that one of the required sensors fail during operation. Below are alternatives if one of the main sensors fail:

- Rotational encoder (measure rotational velocity): Replace.
- Acoustic doppler velocimetry (measure free stream velocity): Alternative - measure velocity by recording the motion of a particle or object in the water along a known distance (manually/PIV system).
- Prony brake system (measure power output): Alternative - electric alternator.
- Video camera (observe blade kinematics): Swap (several replacements are on-hand).

6.5 Data Management, Processing, and Analysis

6.5.1 Data Management
All data either raw data, preprocess and processed data is stored on a server on the Boca Raton Campus at the College of Engineering and Computer Science. All data obtained in tests, including raw data, preprocessed data, and processed data will be submitted to MHKDR upon request.

6.5.2 Data Processing

Raw data will be preprocessed by applying low pass filters to damp out noises embedded in measured signals, inherited from the sensors, especially the friction brake. All different tests will be repeated during the session, for the same settings. This will give a set of consistent data that would be merged to reduce variability and outliers.

6.5.3 Data Analysis

Raw data will be filter out before processing. This includes the application of low pass filters. Data will be measured and stored digital text files in SI units. All diagrams and graphical plots will be done using MATLAB.

When the frequency of the pump is changed to achieve another flow speed, to ensure that steady-state flow is achieved, a minimum 2 minute delay before the next recorded experiment will be enforced. All data will be recorded for multiple cycles to ensure high quality average calculations and standard deviations. If fluctuations in peak-to-peak measurements of power and kinematics are present, the average values will be computed for a fixed number of cycles.

Data will be in principle not discarded. Data will be eliminated only after redoing the faulty test, and after correcting the source of any error of alteration of the current test setting.

7 PROJECT OUTCOMES (REQUIRED FOR POST ACCESS REPORT ONLY)

7.1 RESULTS

Figure 7 shows the results from the Experiment set 1 where the incoming flow speed in the flume was measured for the different pump frequencies. In the graph a linear fit is also shown for the data collected.

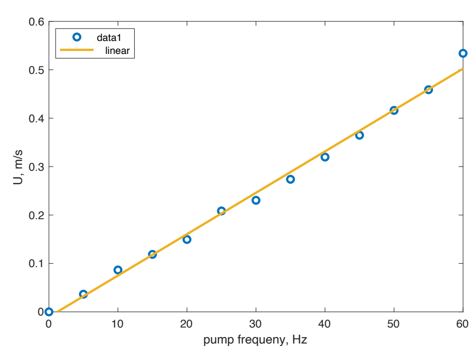

Figure 7: Experiment set 1: incoming flow measurements vs. pump frequency. Circles: experimental flow measurements, solid: linear fit.

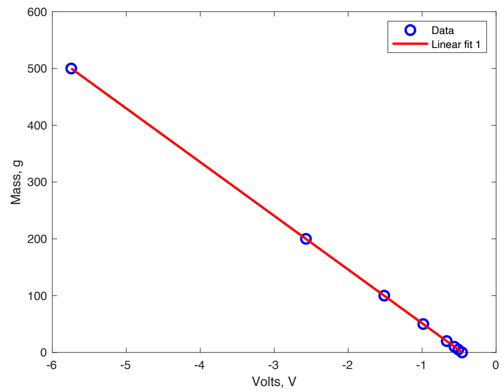

Figure 8: Calibration of the load cell, circles: experimental data, solid line: linear regression.

Figure 8 shows the calibration of the load cell. A linear fit was obtained from the calibration data. This linear fit was used to convert the recorded data from the experiments to force.

Figure 9 shows the force as a function of time (blue line) and the average force for the duration of the experiment (dashed line). This case is for U = 36.5 cm/s and a load level 8. This case corresponds to the peak efficiency of the turbine.

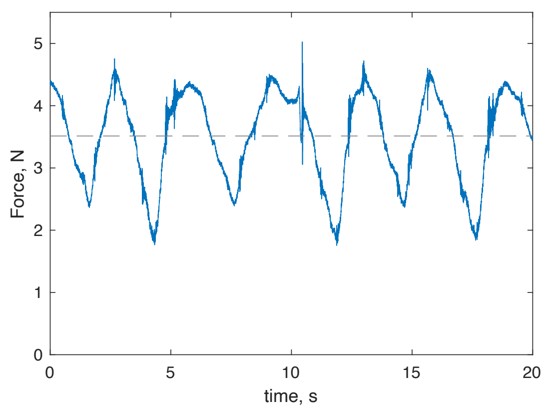

Figure 9: Force measurement as a function of time, U = 36.5 cm/s and L = 8 (case with peak efficiency). Dashed line shows the average force.

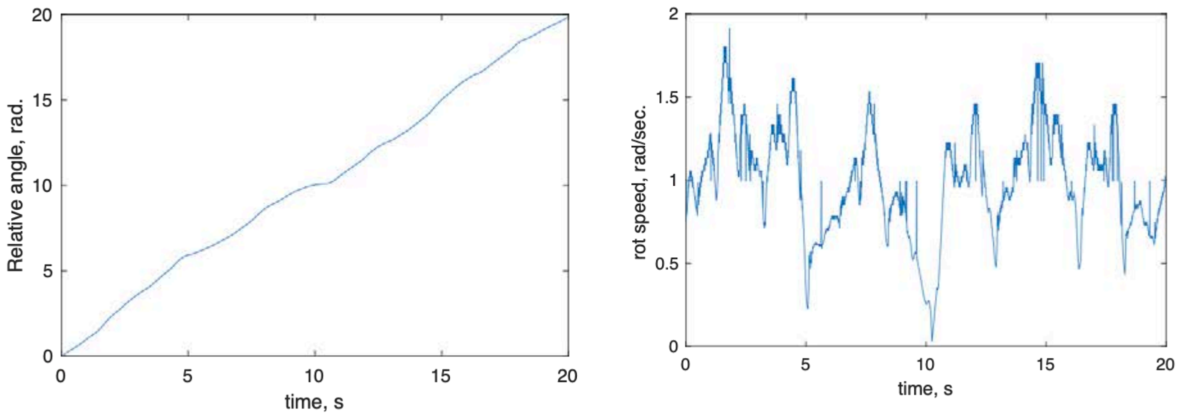

Figure 10: Rotation vs. time. Left: relative angel vs. time. Right: rotational speed, ω, vs. time.   U = 36.5 cm/s and L = 8 (case for peak performance)

Figure 10 (left) shows the relative angle of the turbine as a function of time. The differentiation of this data with respect time was used to compute the rotational speed (Fig. 10 right). From these data, mean rotational speeds were computed.

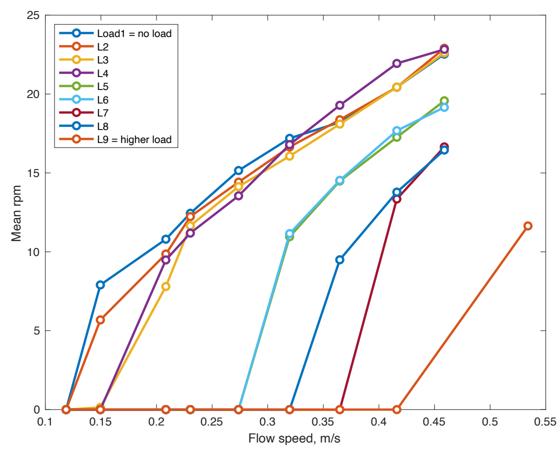

Figure 11: Mean rotational speed in revolutions per minutes (rpm) vs. flow speed. Each line represent a different load.

Figure 11 shows the mean rotational speed of the turbine in revolutions per minute as a function of flow speed. For low load conditions the turbine starts to spin at lower the flow and the flow speed where the turbine starts to spin increases with load.

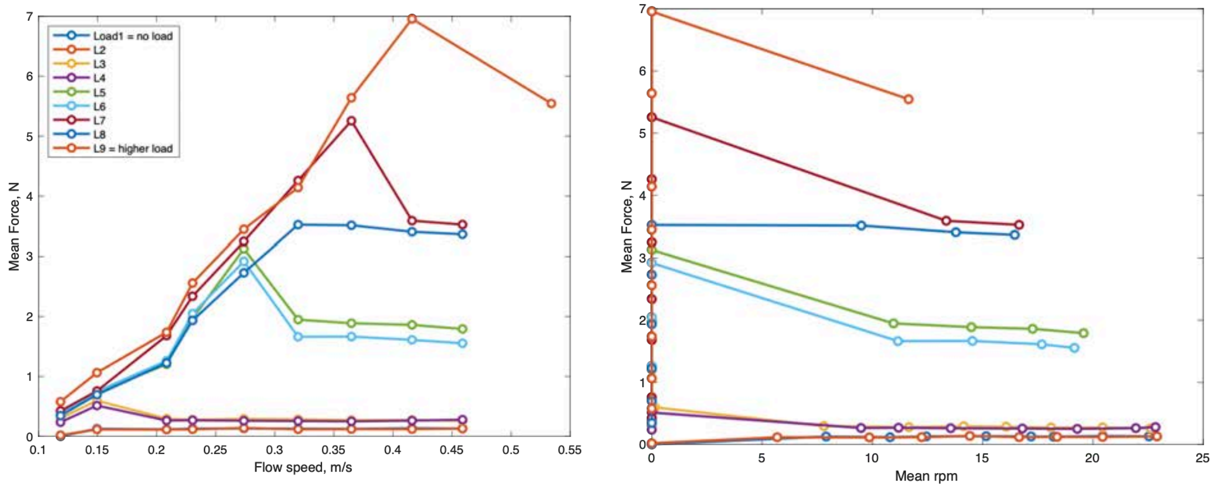

Figure 12: Mean force vs. flow speed (left) and mean force vs. rotational speed (right).

Figure 12 shows the mean force measured as a function of flow speed. In general, the force in the turbine increases with flow until it drops or plateau. This drop in force corresponds when the turbine starts to spin.

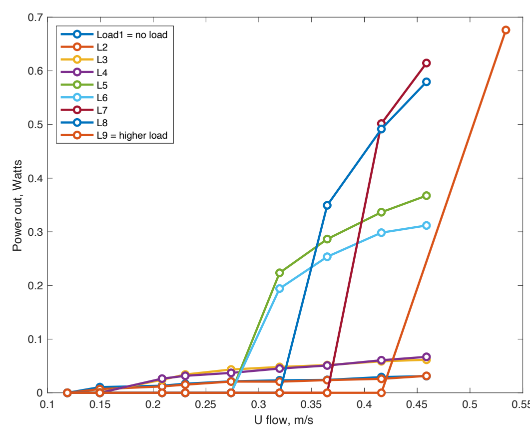

Figure 13: Hydrodynamics turbine power output vs. flow speed for different load conditions.

Figure 13 depicts the mechanical power generated by the turbine, based on the torque and rotational speed of the turbine, $P_{out} = T\omega$. As it can be observed, even though the low-load cases (L1-L4) have a high rotational speed (Fig. 11) , the torque in those cases is very small (Fig. 12) resulting in low power output. In the other hand, the higher load cases, L5-L9, are able to generate higher power given the torque output and rotational speed.

Figure 14 shows the efficiency of the turbine (left panel) and the incoming power from the flow as a function of flow speed. The efficiency of the turbine is zero while it is not spinning then increase rapidly when it starts to spin follow by a decay of the efficiency. The peak efficiency occurs for the case with load L8 and a flow speed of approximately 0.36 m/s.

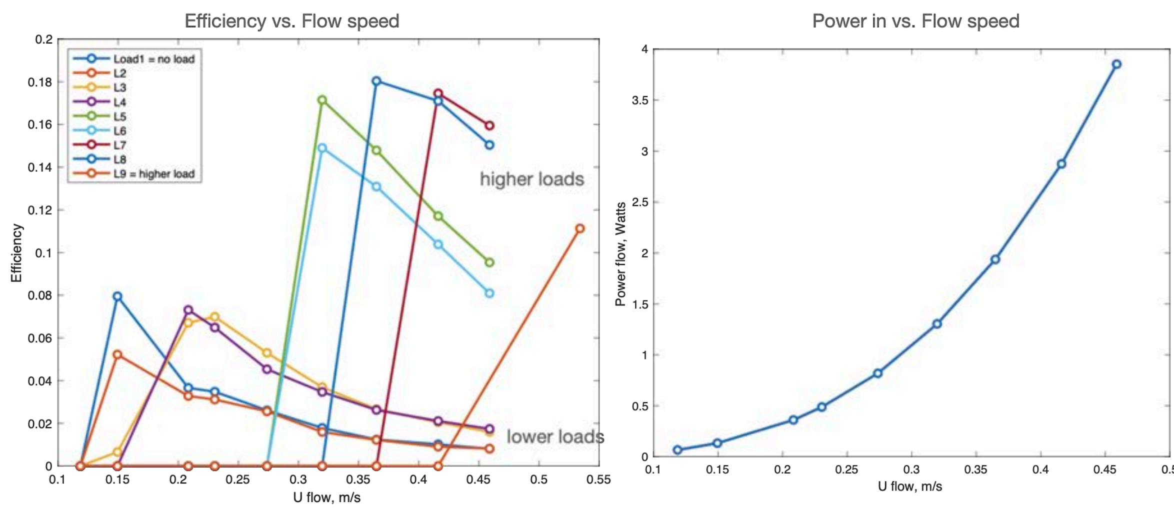

Figure 14: Turbine efficiency vs. incoming flow speed (left). Incoming flow power vs. flow speed (right).

Figures 15-18 shows the efficiency of the turbine as a function of different parameters: ratio between tip and flow speed (Fig. 15), tip velocity (Fig. 16), Reynolds number based on tip velocity (Fig. 17), and Strouhal number (Fig. 18).

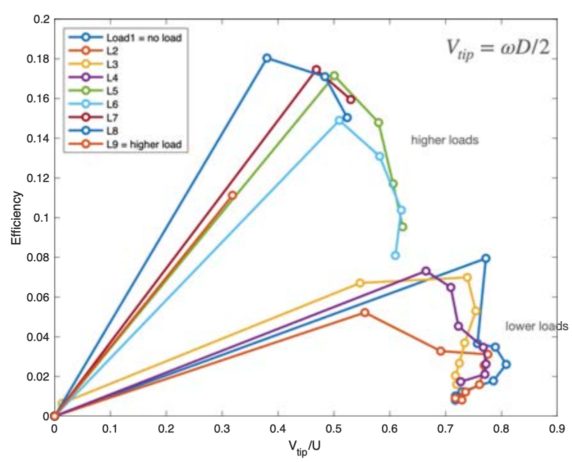

Figure 15: Turbine efficiency vs. *V_{tip}/U* for different load conditions.

In Figure 15 it can be observed that the efficiency follows a common trend between the different cases where there is a sudden increase in efficiency followed by a decrease in efficiency as V_{tip}/U increases. The cases for lower loads (L1-L4) and higher loads (L5-L9) seams to cluster as for higher loads results in lower V_{tip}/U for the flow speeds tested. For the turbine tested the peak performance was around 0.18 for a $\frac{V_{tip}}{U} \approx 0.4$.

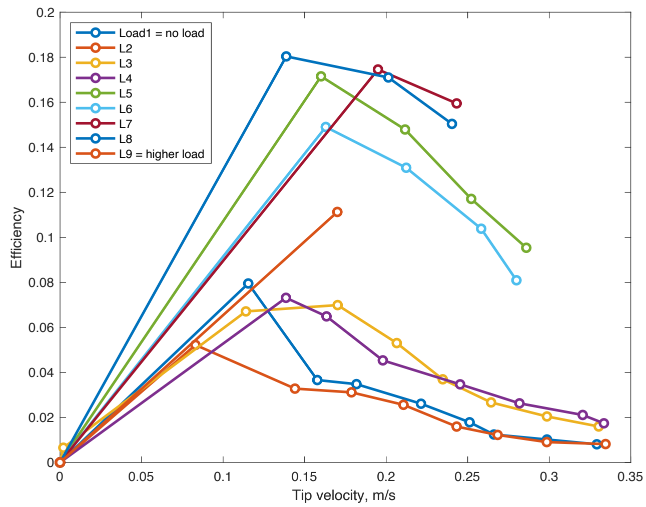

Figure 16: Turbine efficiency vs. V_{tip}

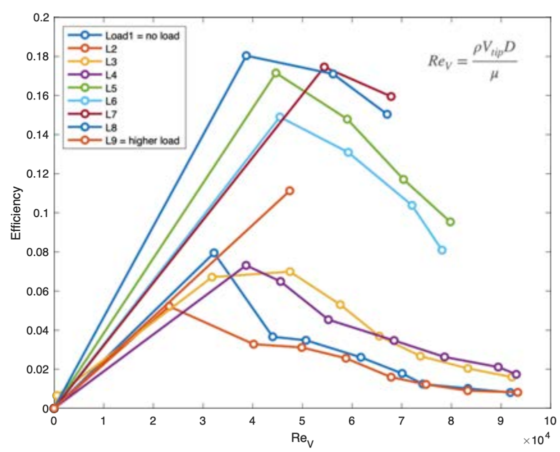

Figure 17: Turbine efficiency vs. Re_V

The efficiency as a function of tip velocity and Re_V are show in Figures 16 and 17, respectively. The peak performance for the different load tested occurred around $Re_V \approx 4\,x\,10^4$.

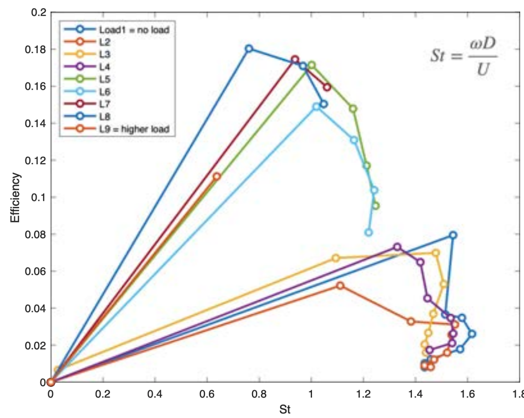

Figure 18: Turbine efficiency vs. Strouhal number

Figure 18 shows the efficiency as a function of Strouhal number which follow same trend as Fig. 15 given that Strouhal number is based also in the ratio between rotational and incoming flow speed. The peak performance occurred when Strouhal number was approximately 0.7-0.8.

7.2 Lesson Learned and Test Plan Deviation

This project took longer than expected in part to ensure that the mounting and support for the turbine were adequate. Initial testing of the mounting had high friction. However, once the setup for the turbine was satisfactory the data collection and analysis were conducted as planned.

8 Conclusions and Recommendations

In this work a model of a "reactive reversible blade turbine for power generation" from Creek Tides Energy & Power was tested in the Hydrodynamics Laboratory at Florida Atlantic University. The turbine features a set of 5 blades that can rotate around its leading edge while also the entire turbine rotates around its central axis. The turbine had an overall diameter of 27.9 cm and a height of 28.6 cm. The turbine was tested in a re-circulating flume (122 width and water height of 30 cm) with a flow speed between from 0 to 0.5m/s. In total nine loads and nine velocities were tested in which the rotational speed and torque of the turbine were measured. The kinematics, force and power output are presented for the different cases. The hydromechanical power of the turbine is computed based on the power output and rotational speed. The turbine has a maximum efficiency of approximately 18% when the V_{tip}/U is approximately 0.4. The efficiency follows a common trend between the different cases where there is a sudden increase in efficiency followed by a decrease in efficiency as V_{tip}/U increases.

Future recommendations: There are many ways that the efficiency of this turbine could be improved including: hydrofoils designs for the blades, bearings to reduce friction in the rotation of the blades. In addition, further optimization on the rotational angle of the blades could be explored to improve efficiency. Future work could also include connection to a generator and evaluation of electric output, higher flow speeds and field testing.