Report for Offshore Energy Research Association

Tidal Turbine Marine Life Interaction study: Fish

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Abstract

To date there are limited laboratory studies on the interaction of marine life with marine renewable energy devices. The Aquatron Laboratory at Dalhousie University is designed to study marine life in a controlled marine lab environment. The 15.24 m diameter pool tank is equipped with four 75-HP circulation pumps that can generate tidal currents up to 2 m/s velocities using salt water. The process for modifying the facility to study the impact of hydrokinetic turbines on fish is presented. The installation of a 0.9m diameter 3-blade vertical axis turbine is described (Figure 1). The performance of the turbine was first validated against previous towing tank experiments at NRC St. John's. Tests were then performed for 3 weeks to monitor the impact of the turbine on Striped Bass (*Morone saxatilis*) behavior and to measure cortisol levels in the fish blood for different scenarios. The test protocol provided flow in the tank at 2 m/s continuously for 3 weeks with the turbine rotor locked during the first week, the rotor rotating at a tip speed ratio of 1.5 in the second week, and the rotor locked again in the third week. The intent of this study is to demonstrate the feasibility of using the Aquatron facility for turbine-fish interaction studies. The test protocol was kept relatively simple for this test series. Striped Bass (Figure 2) varying in age from 2 to 3 years were used for these tests. The turbine had a cage around the frame to prevent fish strikes in this first phase of tests. There was a second net placed across the centre of the tank to train the fish to pass by the turbine rotor to access food on the other side of the tank as fish passage behavior near the turbine is of prime importance. Within the tank three nets were placed at different distances (2m, 5m, 10m) away from the turbine and were hung in place by ropes tied to the bridge. Fish behaviour was monitored by counting fish passage as they swam to specific locations in the tank. Fish blood cortisol levels, velocity and location as well as general observations were recorded. Results presented should not be considered as definitive fish behaviour when encountering an operational turbine.

Keywords— Tidal Turbine, Fish, Striped Bass, Cortisol, Fish Behaviour, Controlled Lab, Interaction.

Figure 1 Tidal turbine and fish study experimental setup

Figure 2 Free swimming Striped Bass (*Morone saxatilis*)

Introduction

This report describes a multi-institutional OERA funded project that was completed in Winter 2017 at Dalhousie University Aquatron Laboratory (Aquatron) in Halifax, Nova Scotia.

The goal of this project was to show that the Aquatron Pool Tank, shown in Figure 1, traditionally a marine biology facility, can be used to test the interaction of turbines with marine animals. As a pilot study, it was not expected that the animal behaviour would be definitive but that the results would indicate whether it would be worthwhile pursuing further testing in this facility. The technical engineering work that was done first showed that a turbine tested in the Aquatron Pool Tank could produce similar results to the same turbine tested at a traditional towing tank facility. The data from the turbine, under a range of flows, is presented and a description of the experiments and modifications to the tank is included.

The fish interaction setup was designed to allow the team to observe the behaviour of free swimming fish when the turbine was running and when it was stopped. The free-swimming fish were protected from direct impact with the turbine blades by caging. This was a requirement of the animal ethics board and it is anticipated that in future tests this caging can be removed. The behaviour of the fish was monitored by researchers directly and recorded on a camera and the stress level of the fish was measured on the last day of each of the 3 weeks the test was run.

The Aquatron Pool Tank is a 15.24m diameter tank with a water depth for this test set at 4m. The water exchange system allows the tank to be emptied and filled very quickly. By modifying the inflow pipe and using the large pumps to provide flow in the range of 0.6-2.4m/s, a stream of flow, similar to a flume, was pushed into and across the tank. The computational flow model, see Figures 3 and 4, was developed and then verified using a flow meter and an acoustic Doppler current profiler, the Nortek Vectrino Profiler. Finally, a small turbine (~30cm in diameter) was placed in the flow and moved around the entry point of the flow to find out how the flow changed from the centre of the flow. It was determined that the flow was consistent close to the inflow site and in a cross sectional area that was large enough for the vertical axis turbine that was used for the tests.

The testing was versatile and yielded valuable results. It showed that the Aquatron Pool Tank can offer a unique testing space for marine renewable energy devices. It is anticipated that a range of future testing will be completed in the coming years. For example, testing the stress response using cortisol levels as a marker for other fish species, testing with crustaceans, testing with shark (dogfish), testing at night, noise monitoring to name several.

Having a test facility where animals can safely be tested with experts on staff to handle them that can be used all year round is very valuable for the marine renewable energy industry.

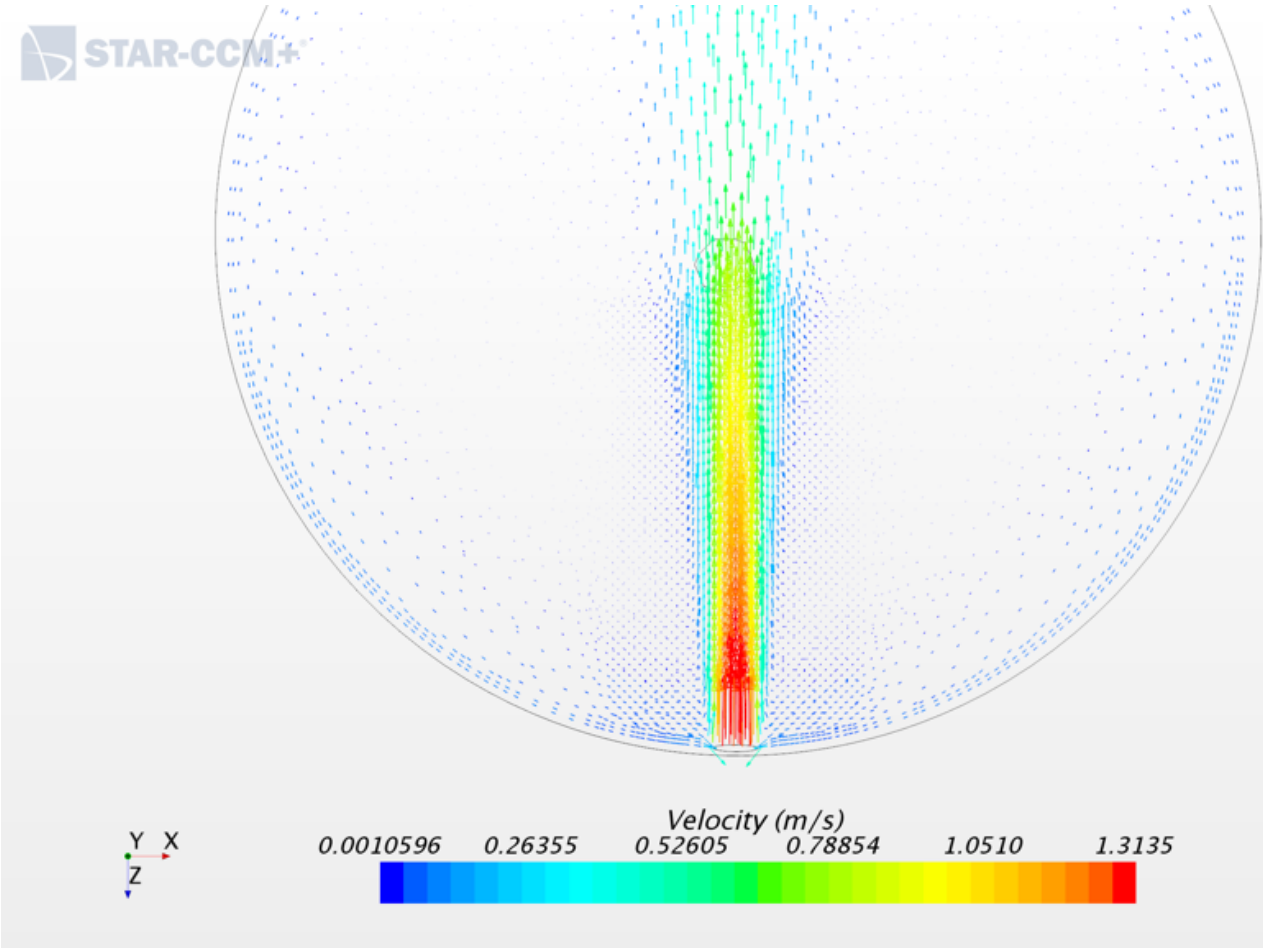

Figure 3 Modelled Inflow to a Large Tank, Overhead View

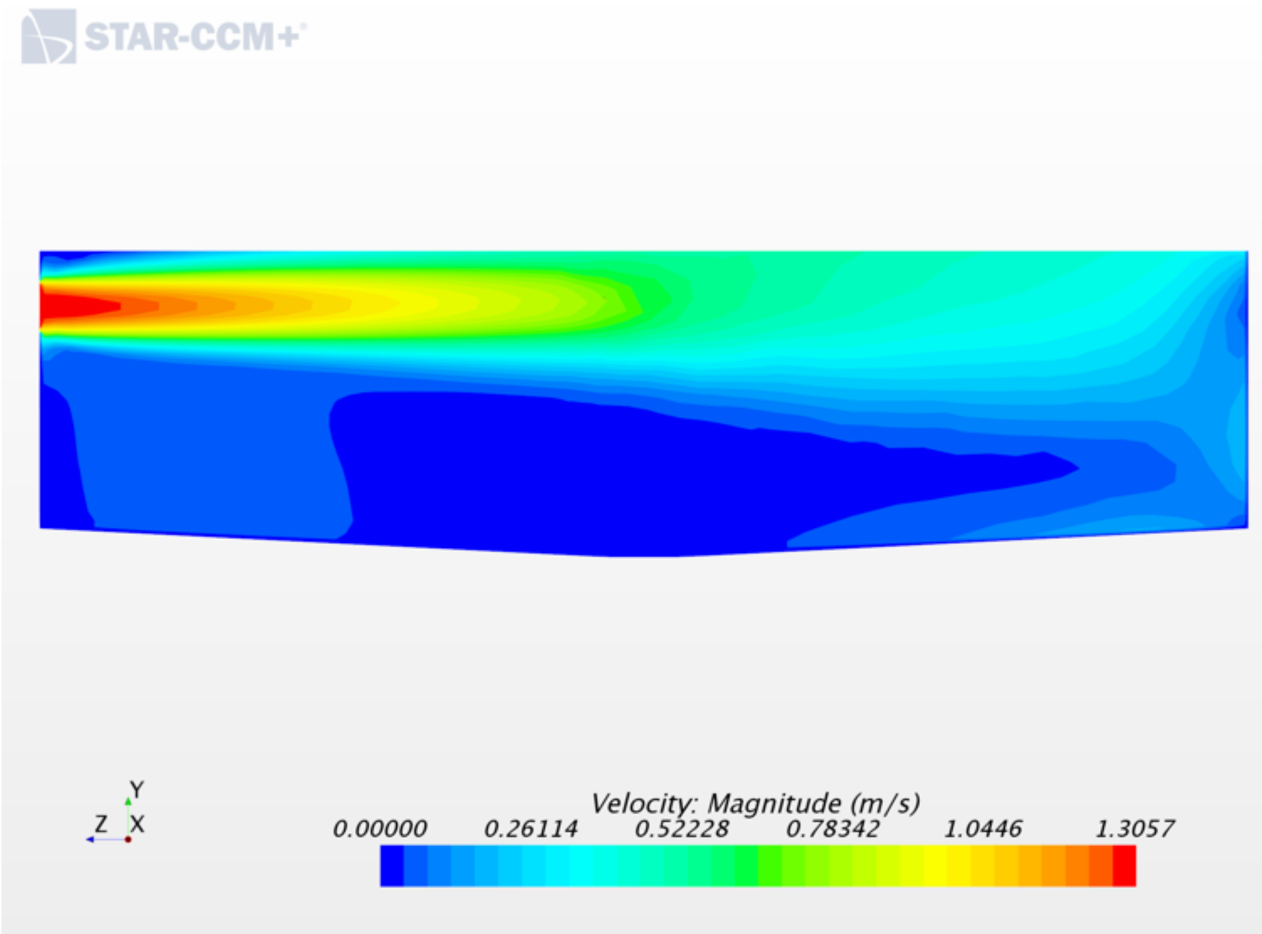

Figure 4 Modelled Inflow to a Large Tank, Side View

PROJECT ADMINISTRATION

Table 1 Timeline

Milestones	Dates
Student Hires	May 15th 2016
Visiting ENSTA students	June 12th 2016
Acoustic Baseline characterization of tank	June 10
Animal Ethics Approval	July 5th 2016
Visiting Student from U of Manitoba	July 10th to 15th 2016
Tank Flow Characterisation	July 10th to 15th 2016
Vertical Axis Turbine Constructed	July 15th to 28th 2016
Fish Cages Constructed	July 22nd 2016
Visiting Researcher from Queen's University Belfast	Aug 2nd to 5th 2016
Turbine installation	Aug 2nd to 12th 2016
Turbine troubleshooting	Aug 15th to Sept. 30th 2016
Fish Nursery	Sept 1st –Nov 15th 2016
Test setup	Dec 1st – Jan 5th 2017
Introduction of Fish	Dec 15th, 2017
Testing Week 1	Jan 13th, 2017
Testing Week 2	Jan. 20th 2017
Testing Week 3	Jan. 27th 2017
Testing Fish video analysis	Feb-Mar 2017
Test data analysis	Feb-Mar 2017
Cortisol Testing	Apr 2017
Cortisol Results	Apr 2017
Paper Submission - EWTEC	Apr 2017
Cortisol test analysis	May 2017
Final Report submission	May 2017

METHODS: TURBINE

Quantifying the performance of the turbine involved the following sets of measurements to be obtained.

1. Quantifying the electrical losses of the permanent magnet motor. This was performed by measuring the armature resistance of the motor. This allowed the evaluation of power losses due to the electrical current driving the motor.

2. Measuring the mechanical losses as a function of angular speed of rotation. This was the mechanical loss of the motor and gearbox the motor is connected to. This dataset was collected when the turbine was disconnected from the drive shaft.

3. The motor was used to spin the turbine, with no water flow, in the same direction that the water flow would spin the turbine. The input voltage and current to the motor at various rotational speeds was measured. This dataset was used to compare the same measurements when there was water flow.

4. Collect the input voltage and current to the motor and the angular speed of the turbine at various flow rates.

5. Calculate the mechanical power of the system that was harvested by the turbine being spun for various water flow rates.

The water flow rates for the data collection were 0.6, 1.2, 1.8, 2.4 m/s. The water flow rate was controlled through the water pumps at the Aquatron. The Aquatron Tidal Flow System is a web based control system that allows the user to create a powerful flume by recirculating the Pool Tank. The Pool Tank has a volume of 680 cubic meters. The water used to produce the tidal flume is drawn from the centre drain of the Pool tank into a header that feeds four 75 horsepower pumps. These pumps can produce a return current of 2.4 meters/sec back into the Pool Tank through a 20-inch return line that is submerged 1.5 m below the tank surface. The user can select the percentage power used by each pump and the number of pumps used to produce the flow. One pump at 100 % power produces 0.6 m/s, and each subsequent pump at 100% adds 0.6 m/s of flow to the overall speed maxing at four pumps at 100% providing a flow rate of 2.4 m/s.

The Tidal portion of the system does not produce a high or low tide in the true sense of the word within the Pool Tank, instead the program allows the user to preselect the percent power used by the preselected number of pumps at each of twelve programmable steps. The time between each of the twelve programmable steps can also be set by the operator. This allows the user to simulate changes in tidal speed over minutes, hours, or days and allows the pre-programmed cycle to continue to occur for up to a month. The control terminal for this can be observed in Figure 5 below.

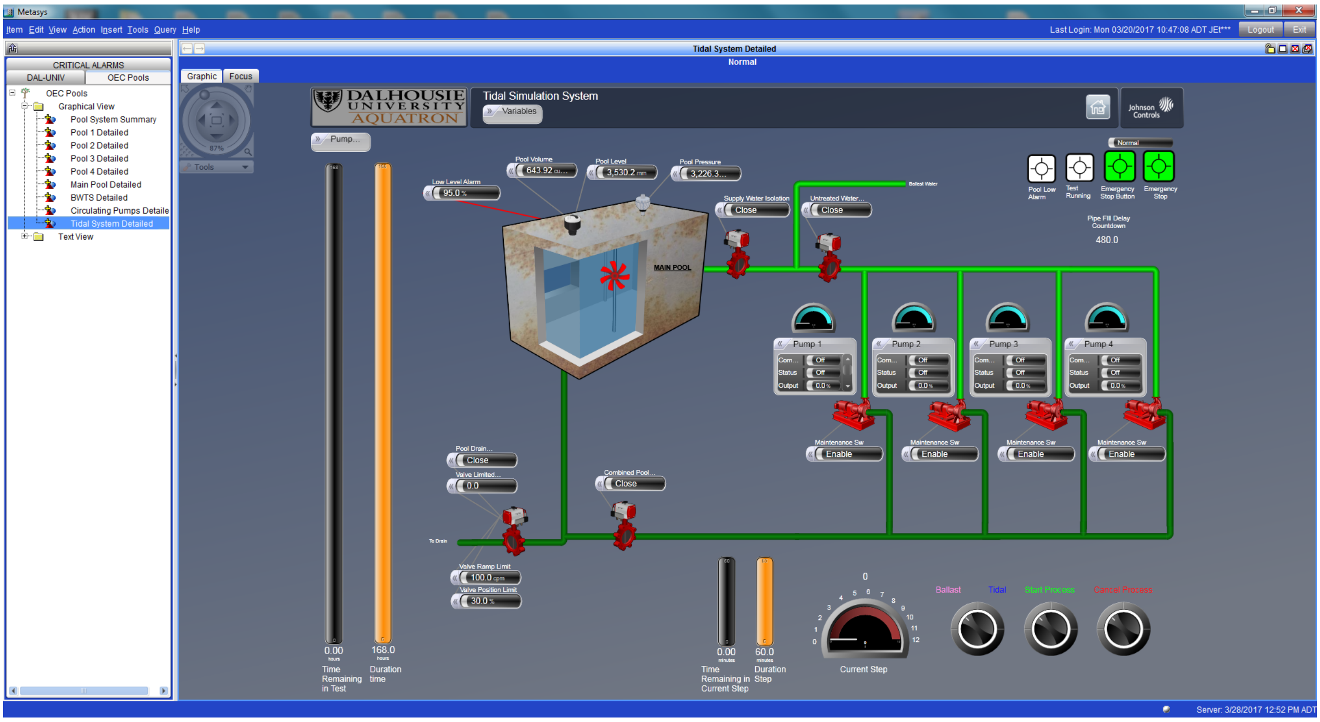

Figure 5 Aquatron Water Pump Terminal

In this experiment, the flow was not varied, it was fixed at 1.5 meters per/second with three pumps running at 85% percent for the duration of the study. All steps were set for the same 85% power level and the step between points was 60 minutes. The pumps ran for the duration of the study.

The power harvested by the turbine, is calculated as follows:

$$P_{no\ flow}(\omega) - [VI - I^2R - (\alpha + \beta\omega)] = P_{mech} \qquad (1)$$

Where, $P_{no\ flow}(\omega)$ is the mechanical power required to spin the turbine in water with no water flow present, V is the terminal voltage of the motor, I is the armature current of the motor, and R is the armature resistance of the motor (which was measured to be 1.45Ω), $\alpha + \beta\omega$ is the constant speed dependent friction/mechanical losses associated with the motor and gearbox assembly, and P_{mech} is the mechanical power harvested from the water flow by the turbine

Voltage and current were measured from an Accuenergy AcuDC 243 DC Power and Energy Meter. The angular speed was measured from a shaft mounted encoder disk and optical sensor. These can be observed in Figure 6 below.

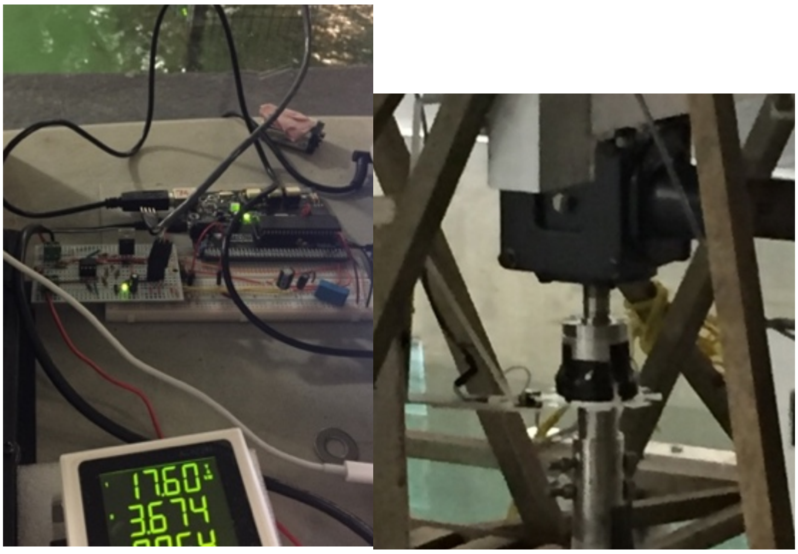

Figure 6 Data Measurement Devices

The mechanical losses of the turbine assembly were measured to have the characteristic shown in Figure 7.

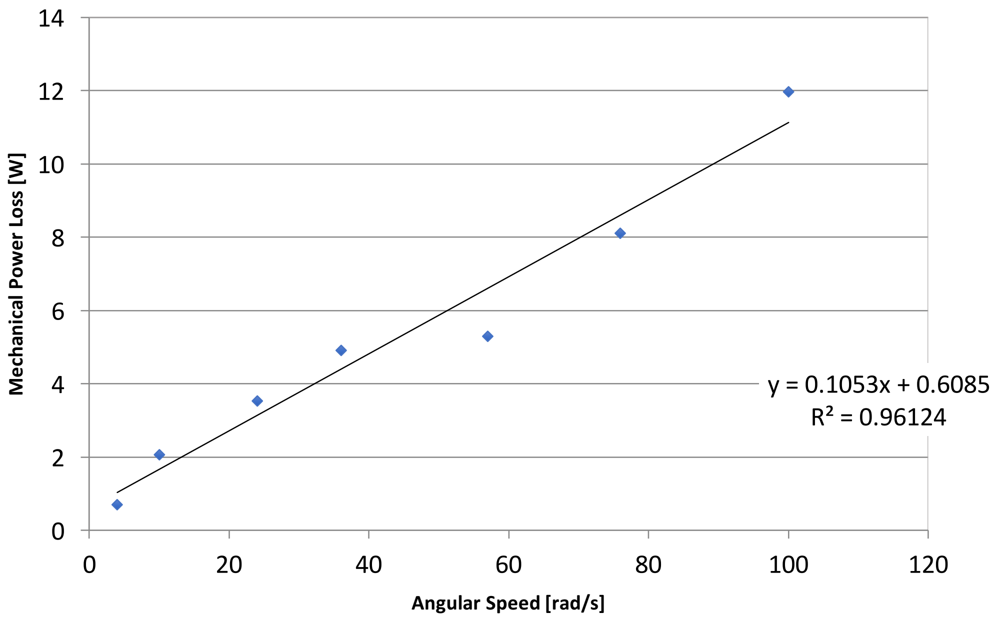

Figure 7 Mechanical Power Losses

It can be observed that the mechanical power losses are linearly related to the angular velocity of the turbine. The input electrical power to the motor at each water flow rate as a function of the turbines angular speed is shown below in Figure 8.

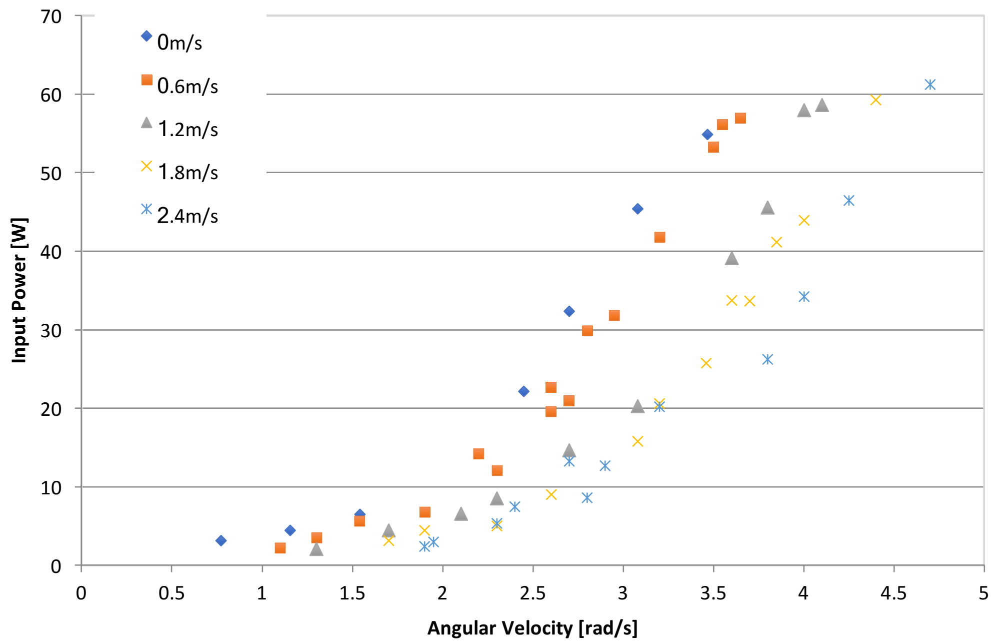

Figure 8 Input Electrical Power to Motor

From this plot, the data corresponding to 0m/s water flow can be analyzed. Taking this data set and subtracting the mechanical and electrical losses, the plot shown in Figure 9 can be obtained.

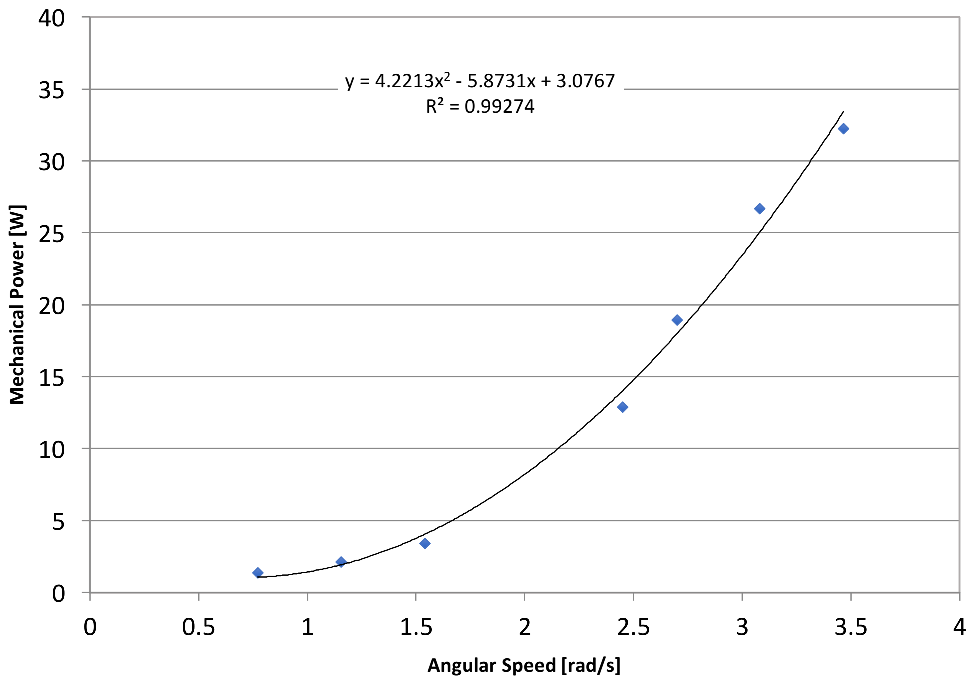

Figure 9 Mechanical Power at No Flow

This plot demonstrates the amount of power required to spin the turbine in the water with no water flow. This is calculated from the following equation:

$$P_{no\ flow}(\omega) = [VI - I^2R - (\alpha + \beta\omega)] \qquad (2)$$

The regression equation from this plot will be used as the function $P_{no\ flow}(\omega)$ for the remaining datasets. From these datasets, the amount of mechanical power harvested by the turbine from the water flow can be found and is shown in Figure 10 below.

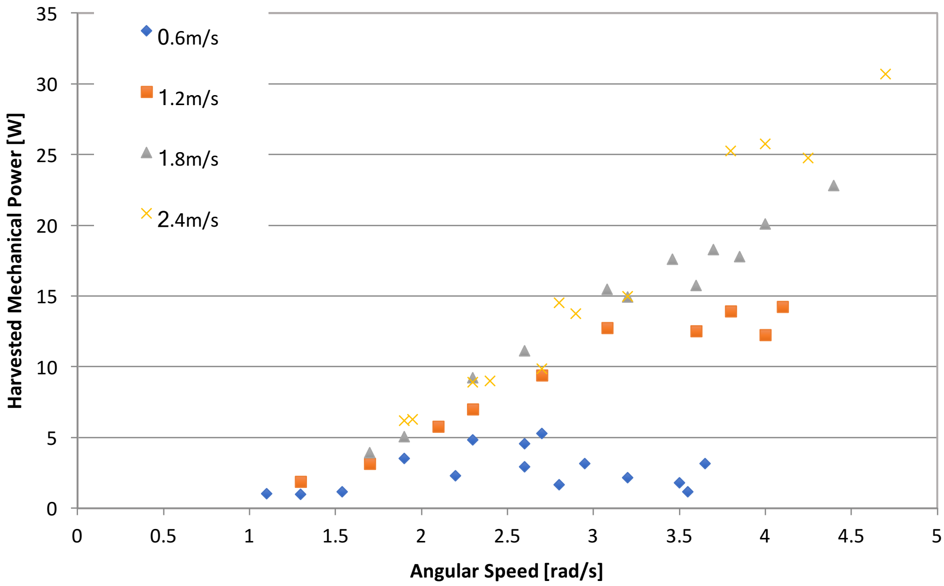

Figure 10 Harvested Mechanical Power

From this, the Turbine efficiency vs. Tip-to-Speed ratio (TSR) can be plotted. The turbine efficiency is calculated as the ratio of the harvested power to the theoretical power available. The cross-sectional area of the turbine was 0.457m x 0.686m. Figure 11 below represents the turbine efficiency vs. TSR.

These results coincided to a TSR ratio less than or equal to 1.6, which correlates to the lower range of data presented in [1] for a similar construction of turbine. It can be observed that the intersecting data correlates well with both findings.

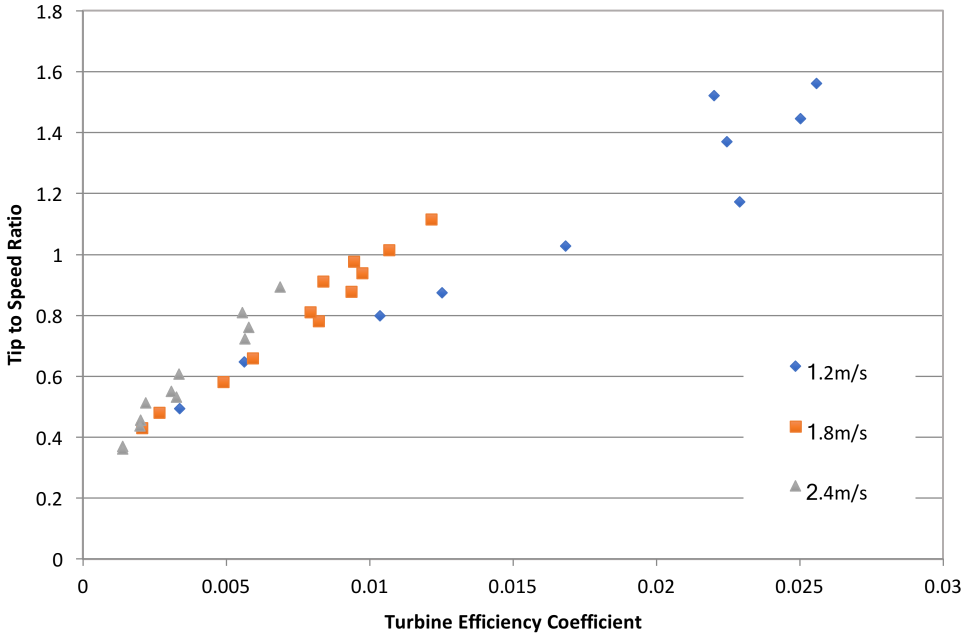

Figure 11 Tip to Speed Ratio and Turbine Efficiency

Methods: Fish

The species studied was the Atlantic striped bass (*Morone saxatilis*) (Figure 2) as they are a species of interest in the Bay of Fundy.

Two separate studies were carried out:

- A behavioral study where fish could freely swim around the tank and behaviour was assessed two ways; via a camera and visual observation.
- A stress response study assessing the physiological status of the fish by measuring the cortisol levels.

Behavioral Study

Fifty adult striped bass that were readily available at Aquatron were placed in the pool via dip netting and could free swim. In order to ensure the fish swam past the turbine to feed and were captured on camera, a net was hung and weighed to the bottom of the tank. This was achieved by attaching the net to a movable bridge that the turbine was attached to. The net was hung to the underneath of the bridge and weighed to the bottom of the tank. The net spanned the width of the tank with an opening at either end; allowing the fish to only pass through these two openings when travelling in the tank. Full representation of the experimental layout of the Aquatron pool tank can be observed in Figures 12 and 13. The blue line down the middle of the tank represents the net which is weighed to the bottom of the tank. The black box is the turbine cage with the black circle inside representing the turbine. The black arrows show the direction of the flow, and the red square shows placement of the underwater camera.

The fish behavioural study was run continuously for three weeks. The first week the flow was on and the turbine prevented from turning, the second week the flow was on and the turbine was operating and the final week the flow was on and the turbine prevented from turning. The fish were fed with 7mm pellets, Corey Aquasea 5mm, once a day until satiation by Aquasea. The fish were fed at the same spot of the tank at the same time each morning, directly under the camera.

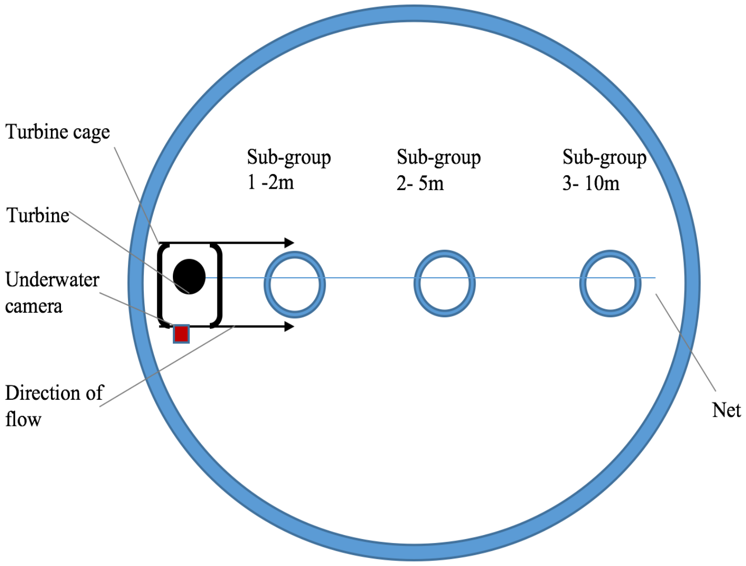

Figure 12 Experimental Design

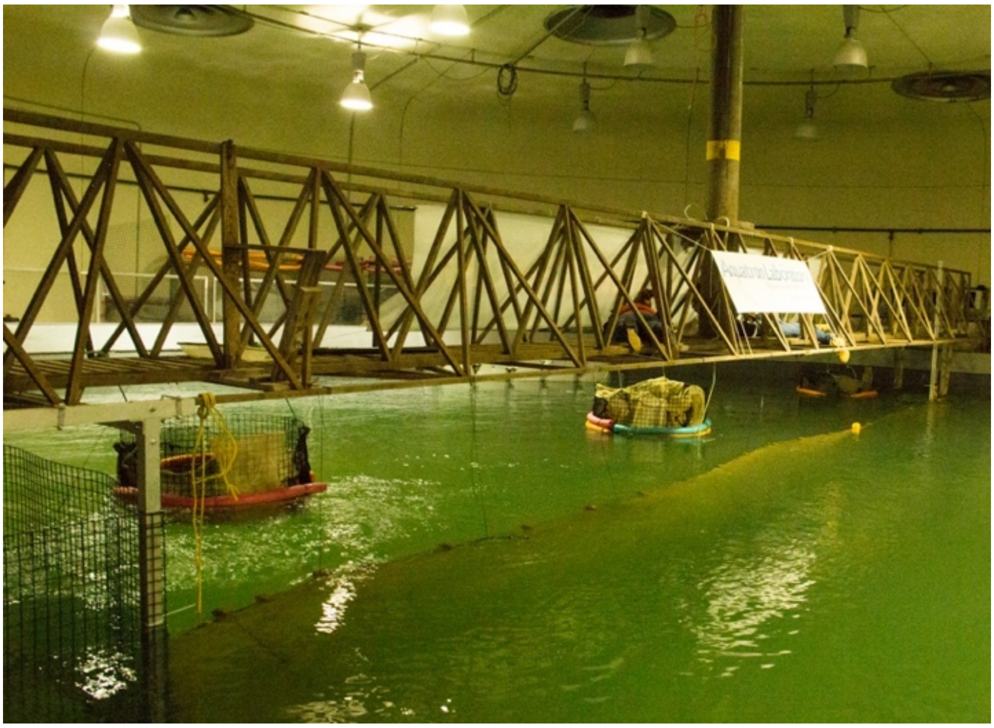

Figure 13 Aquatron Experiment Set Up

The underwater camera used to capture swimming behaviour was an Ocean Systems Splashcam Sidewinder 360. The camera was hung in the opening between the side of the tank and the turbine, see Figure 12. The camera recorded for 6 hours a day for later analysis of fish behaviour (Figure 14).

Each day, student(s) also observed the behavior of the free-swimming fish for 15 minutes under the turbine and the furthest spot from the turbine. The behaviors were recorded for qualitative analysis. The sampling occurred three times a day for the course of the study.

Figure 14 Fish Monitoring Camera Screenshot

Stress Response Study

Juvenile Striped bass (Figure 15) were used for the stress response study. For this study, small nets were hung in place on the bridge (Figure 16) at distances of 2, 5 and 10m away from the turbine (Figures 12 & 13). The nets were made from Aquamesh caging material measuring 1m in diameter and 1m deep. They were then lined with a 1 in. mesh net to ensure no fish escaped. Pool noodles were zip tied to the top of the nets enabling them to float in the water (Figure 16).

Figure 15 Juvenile Striped Bass

Figure 16 Aquatron Fish Net Side View

Thirty fish were placed in each net (Figure 17) and were called sub-group 1, 2, and 3 corresponding to distances 2, 5 and 10m from the turbine respectively.

Figure 17 Aquatron Fish Net Overhead View

All fish were placed in the tank for 7 consecutive days with the turbine off and the flow on. This allowed the fish to acclimatize to their environment before sampling. The fish were fed once a day with 5mm pellets until satiation by Aquasea.

After the 7 days of the turbine being off, the first sampling took place. One sub-group was sampled at a time. The nets were first moved to the side of the tank. Seven fish were taken from each sub-group via dip netting and were placed in TMS-222 anesthetic until mortality; each fish had to be bled within two minutes to minimize the impact of being removed from the net on cortisol levels in the blood. The tail of each fish was then cut off using a fillet knife and 1ml of blood was collected into labelled test tubes for later testing of the cortisol levels.

The first sampling took place on January 19th 2017. After the commencement of the first sampling, the turbine was turned on and remained on for 7 days. The second sampling occurred on January 27th 2017. The same protocol was followed as mentioned above, however 10 fish were taken from each subgroup during this sampling. After the second sampling was complete, the turbine was switched off and remained off for another 7 days. The third sampling took place on February 2nd 2017. Thirteen fish were taken from subgroup 1, eight fish from subgroup 2, and eight fish from subgroup 3. A different number of individuals were taken from each subgroup because it was the final sampling and the nets were required to be emptied. Some random mortality had taken place throughout the experiment leading to un-even numbers. Once sampling three was complete, the experiment was over.

Since the turbine was on one week, but not the next, the factor 'turbine' was not considered as a third factor in the analysis of the stress response of the juvenile striped bass as it occurred within the factor 'week'. Therefore, a two-way ANOVA was carried out with the cortisol levels of juvenile *Morone saxatilis* as a function of distance from the turbine (2, 5 and 10m), and week (1, 2 and 3). Post-hoc Tukey HSD tests were used for statistical comparison.

Results & Discussion

The results of this experiment are three-fold, analysis of the turbines performance, analysis of the fish behaviour and analysis of the stress response. The results and discussion will be outlined in the subsequent sections.

A. Turbine Performance

The Performance of the turbine can be observed in Figures 10 and 11 above. The turbine assembly can be observed in Figure 17 below.

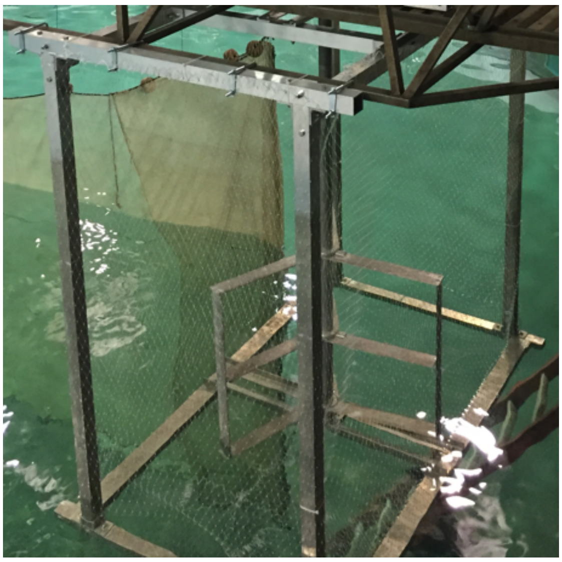

Figure 18 Turbine Assembly

These results provide plots of the TSR versus the turbines efficiency. This efficiency is the C_k term in the power extraction equation of a tidal turbine. The datasets collected represent the turbine operating at a relatively low TSR. It can be observed in [3] that the upper end of this collected data correlates to the lower end of the data collected in [3]. This presented data corresponds to a C_k value of 0.026 for a TSR of 1.5. In reference [3] the C_k value is approximately 0.031 for a TSR of 1.5. This discrepancy could be accounted for in several ways, the error in the area-of-attack angle, inhomogeneous water flow, error in the turbines vertical position, and the meshing surrounding the turbine disturbing the flow all impact the power extraction. In reference [3], a change of the area-of-attack of 5 degrees resulted in approximately a 50% change in the C_k.

B. Fish Behaviour study

During the 15-minute observation sampling at the furthest point away from the turbine in the first week of the experiment it was found that the fish schooled and circled the tank and the average time it took for the school to pass the observation window was 15s in the morning, 12s in the afternoon, and 17s in the evening, see Table 4. During the second week when the turbine was on it was found that the fish did not school together and were no longer circling the tank, therefore there is no circling time data during this week. The third week when the turbine was off, the average times were 17s in the morning, 14s in the afternoon, and 17s in the evening (Table 4). It was noted that in the afternoon the fish schooled much more tightly together than in the morning and evening when the turbine was off. When the turbine was on, the fish were either not all schooling when circling the tank, or swimming in a non-distinct pattern.

Table 4 furthest observation point from the turbine and represents data collected during observations at the furthest point away from the turbine from a viewing window, of the average time, in seconds, it took for the school of striped bass (*Morone saxatilis*) to pass during a 15-minute period at 8:00am, 12:00pm, and 5:30pm each day. This data was collected at Dalhousie Aquatron in January 2017.

Week	Turbine Switch	Avg. Morning Time [s]	Avg. Afternoon Time [s]	Avg. Evening Time [s]
1	OFF	15	12	17
2	ON	days	days	days
3	OFF	17	14	17

Table 5 illustrates the average times it took for the school of fish to pass the observation window directly under the turbine for each week when the turbine was either on or off. In the first week, when the turbine was off, the morning, afternoon, and evening averages were 8s, 5s, and 10s respectively. During week two, when the turbine was on, the fish were not seen to school together and pass the turbine within the first three days. During the first three days, the fish were circling the turbine cage and some individuals were circling the tank, or swimming in the tank with no distinct pattern. After the first three days, most of the fish returned to circling the tank but not as a tight school, some individuals swam in random patterns. During week three, when the turbine was switched off, the morning, afternoon, and evening times were 10s, 6s, 13s respectively, as shown in Table 5. During the third week, the fish returned to schooling tightly in the afternoon and circling the tank.

Table 5 nearest observation point to turbine and represents data collected during observations from a point directly under the turbine from a viewing window, of the average time in seconds it took the school of striped bass (*Morone saxatilis*) to pass during a 15-minute period at three different times during the day. The data was collected at Dalhousie Aquatron in January 2017.

Week	Turbine Switch	Avg. Morning Time [s]	Avg. Afternoon Time [s]	Avg. Evening Time [s]
1	OFF	8	5	10
2	ON	days	days	days
3	OFF	10	6	13

During each week, the total amount of time spent schooling as well as the total amount of time engaged in other behaviours such as circling the turbine cage, swimming under the turbine, or swimming alone, was calculated from the video recordings created each day. It was found that in the first week when the turbine was off, the fish spent 89% of the time schooling and 11% doing the other behaviour, see Figure 18. During week two when the turbine was on, the fish spent 43.41% schooling and 56.59% engaging in the other behaviour, see Figure 19. In Figure 20 it illustrated that during week three when the turbine was turned off, the fish spent 48.72% of the time schooling and 51.28% of the time engaging other behaviour.

Three outliers were observed in the dataset and removed because it was discovered that they were due to the camera image freezing. The average lap time of the school of fish was recorded. This was determined by starting the time recording from when the school first passed the camera and ending the time recording when the school passed the camera a second time. The results for each week were tested for normality, the average lap time for weeks 1 and 2 were normal while and week 3 was not. Week 3 was not included in the analysis due to lack of usable data points. A paired t-test was run between week 1 average lap time and week 2 average lap time. Using a 95% confidence interval the p-value was 0.9922 therefore, not significant and the null hypothesis, that there will be no change in average lap time between when the turbine is off in week 1 and when the turbine in on in week 2, cannot be rejected, see Table 6.

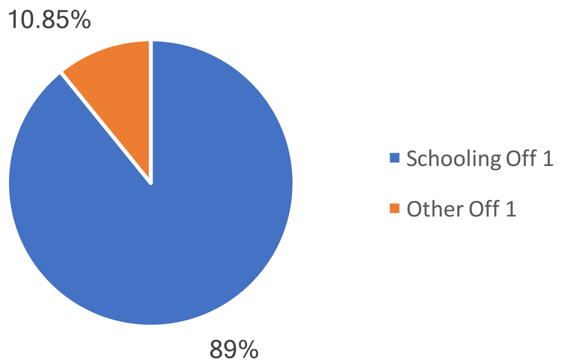

Figure 19 Week 1 Percentage of time analyzed by underwater video camera of striped bass (*Morone saxatilis*) illustrating schooling behaviour or other behaviour when the turbine was off. Other behaviours include swimming under turbine, alone, or circling turbine cage. Schooling behaviour was 89.15% of the time and other behaviour was 10.85% of the time. Data collected in Dalhousie Aquatron in January 2017.

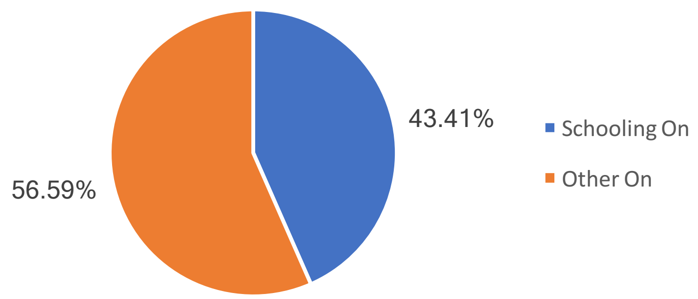

Figure 20 Week 2 Percentage of time analyzed by underwater video camera of striped bass (*Morone saxatilis*) illustrating schooling behaviour or other behaviour when the turbine was on. Other behaviours include swimming under turbine, alone, or circling turbine cage. Schooling behaviour was 43.41% of the time and other behaviour was 56.59% of the time. Data collected in Dalhousie Aquatron in January 2017.

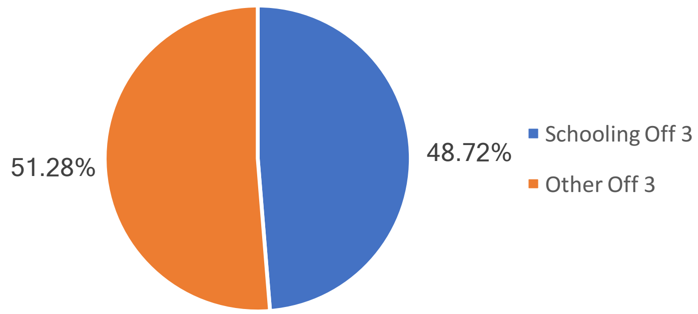

Figure 21 Week 3 Percentage of time analyzed by underwater video camera of striped bass (*Morone saxatilis*) illustrating schooling behaviour or other behaviour when the turbine was off. Other behaviours include swimming under turbine, alone, or circling turbine cage. Schooling behaviour was 48.72% of the time and other behaviour was 51.28% of the time. Data collected in Dalhousie Aquatron in January 2017.

The total time schooling during all three weeks was recorded and analyzed for hours 2, 4, and 6 of each day. The data was normally distributed. Table 6 below represents the statistical test of choice between different parameters measured during the experiment with their corresponding p-values. Parameters include; Week 1 Off (average lap time when the turbine was off), Week 2 On (average lap time when the turbine was on), Sch. Wk. 1 Off, Sch. Wk. 2 On, Sch. Wk. 3 Off (total time spent schooling in week 1 when the turbine was off, week 2 when the turbine was on, and week 3 when the turbine was off), Other Wk. 1 Off, Other Wk. 2 On, and Other Wk. 3 Off (Total time spent engaged in other behaviour during week 1 when the turbine was off, week 2 when the turbine was on, and week 3 when the turbine was off).

The total time schooling in week 1 when the turbine was off, Sch. Week 1 Off, was paired with the total time schooling in week 2 when the turbine was on, Sch. Week 2 On, for a paired t-test. Using a 95% confidence interval, the p-value was 0.0397 resulting in a significant difference between each week in the total time schooling. When the turbine was off, the fish spent 45.59% more time schooling than when the turbine was running, see Table 6. The same test was used to compare Sch. Wk. 2 On and total time schooling in week 3 when the turbine was off, Sch. Wk. 3 Off, the p-value was 0.6512. Interestingly there was no significant difference between when the turbine was on in Week 2 and when the turbine was off in Week 3.

The total time spent engaged in other behaviour was calculated the same way as above and was normally distributed. Data from week 1 other was found to be not normal, and week 2 and 3 were normal. Week 1 data was transformed to be normal for the analysis. Between Week 1 when the turbine was off, Other Wk. 1 Off, and Week 2 when the turbine was on, Other Wk. 2 On, the p-value resulting from a paired t-test was 0.0395. This result is significant suggesting that there is a change in other behaviour between treatments, see Table 6. The result of the paired t-test for other behaviour week 2 when the turbine was on and week 3 when the turbine was off, resulted in a p-value of 0.3143. This is not significant, thus, the null hypothesis, of there being no change in other behaviour during week 2 and week 3 cannot be rejected, see Table 6.

Table 6 test of choice analysis

Test	Parameter 1	Parameter 2	P-value	Result
Paired t-test	Week 1 Off	Week 2 On	0.9922	Not Sig.
Paired t-test	Sch. Week 1 Off	Sch. Week 2 On	0.0397	Sig.
Paired t-test	Sch. Week 2 On	Sch. Week 3 Off	0.6512	Not Sig.
Paired t-test	Other, Week 1 Off	Other, Week 2 On	0.0395	Sig.
Paired t-test	Other, Week 2 On	Other, Week 3 Off	0.3143	Not Sig.

C. Stress Response Study

The hormone cortisol is released by an animal in response to stress so that high values indicate that the animal possibly is stressed. What is unknown in this study is what the cortisol levels were of the individuals prior to being placed into the tank. However, fish species such as Atlantic char, Atlantic salmon, Common carp, Pallid sturgeon and Sea Bream, to name several, showed levels < 30 nmol/l prior to a stress stimulus [7 and references therein]. Therefore, potentially levels for *M. saxatilis* < 30 nmol/l indicate that the fish is not stressed.

Significant differences in cortisol levels were observed between the distance that the fish were located from the turbine as well as between weeks (Table 7 and Figure 22). Posthoc tests revealed that for distance, fish at 2 and 5m from the turbine, the cortisol levels were significantly different from the fish 10m away indicating that fish close to the turbine were less stressed than fish 10m away. Interestingly, in the weeks that the turbine was switched off (Week 1 and Week 3), post hoc tests indicate that the fish were more stressed than when the turbine was on for a week.

The cortisol results match with the behavioral results that when the turbine was switched on, fish behaviour changed significantly suggesting that something to do with the turbine had a less stressful effect especially for fish close by. What is unknown is whether this was because of factors such as a change in pressure waves, noise levels or lowered velocity. Changes in flow patterns perhaps requires more investigation as it is known that fish move out of the water column when flow rates reach above 0.8m/s [8]. This would agree with the results that the fish closest to the turbine, were less stressed then those farthest away. Even when the turbine was off, the presence of the structure would still have some influence disrupting the flow structure.

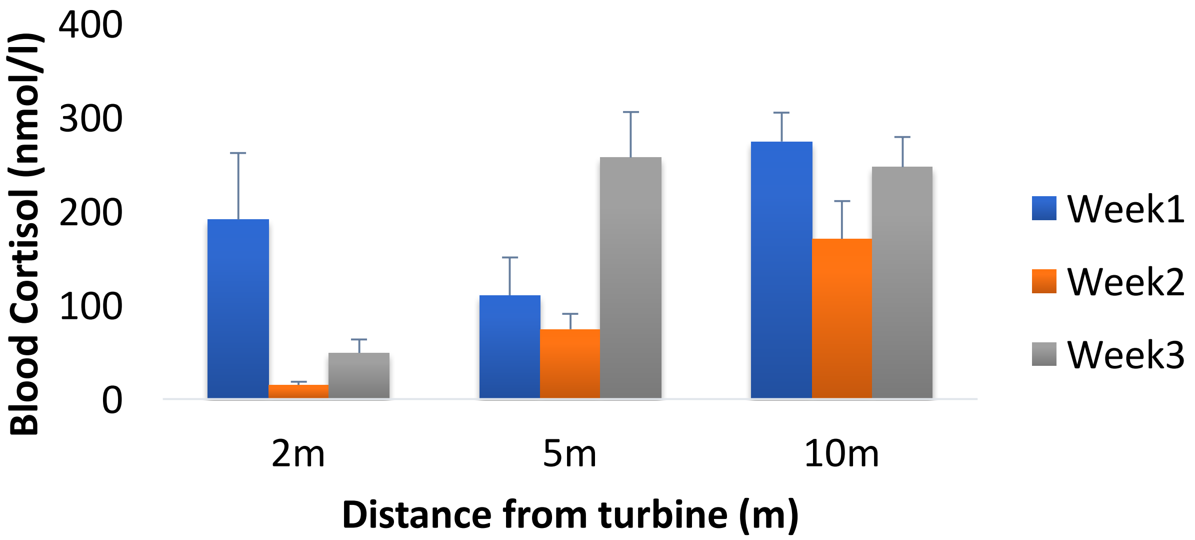

Figure 22 Cortisol levels (nmol/l) of juvenile *Morone saxatilis* from the three separate weeks and three distances from the turbine.

Table 7 Results of a two-way ANOVA for the cortisol levels of juvenile *Morone saxatilis* as a function of distance from the turbine (2, 5 and 10m), and week (1, 2 and 3).

	F	df	*P*
Distance	17.372	2, 73	<0.001
Week	10.204	2, 73	<0.001
Distance × Week	2.803	4, 73	0.032

Conclusion

The goal of using the Aquatron facility as a lab space for animal-turbine interaction studies was achieved. The facility is well suited to the kinds of interaction studies that are needed and the only restrictions are in the size of the turbines or energy extraction systems that are installed in the tank. The turbine performed better than expected and the results correlated very well with the turbine results from previous tow tank testing [3]. There were many questions about how to design a test of value using fish and turbine as there are so many variables to consider (noise, flow, turbine, nursery fish, depth, access to slower water and more) so the test was designed to give the team a starting point in this type of testing. The Aquatron Pool Tank was not designed for this purpose, but the modifications made have allowed the engineering and biology sides of tidal power to work in a controlled lab space and achieve valid and valuable results. The initial tests indicate that there are many more questions to be answered with respect to the behaviour of fish around tidal turbines and their stress response. Behaviour modifications were recorded as well as unexpected stress levels and now the different aspects of the test that were observed can be explored individually in more detail. It is possible to test for longer periods of time, investigate habituation, investigate noise impacts, investigate night versus day (turn out the lights and use a Ditson camera), and investigate more restricted movement.

At this point it cannot yet be concluded that the fish modified their behavior due to the turbine alone and controlling for additional parameters will be critical in future testing.

Future work will include leaving the turbine in a bio-fouling growing tank for a period of time and then re-installing it in the large tank so that the behaviour of crustaceans can be closely observed. Also tests with dogfish, other fish species and other parts of the marine renewable energy system will be studied. Future tests will likely be run without a netting around the turbine. It is anticipated that collaborations with a range of animal experts will enhance the understanding of animal interactions with marine renewable energy systems.

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References

[1] Alden Lab, https://www.aldenlab.com/Fish-Passage

[2] Aquatron, https://www.dal.ca/dept/aquatron.html

[3] Rawlings, George William, “Parametric characterization of an experimental vertical axis hydro turbine”, University of Victoria 2008

[4] Hammar, L., Andersson, S., Eggertsen, L., Haglund, J., Gullstrom, M., Ehnberg, J., & Molander, S., “Hydrokinetic Turbine on Fish Swimming Behaviour”, 2013, PLoS ONE. 8(12).

[5] Marras, S., & Domenici, P., “Schooling Fish Under Attack Are Not All Equal: Some Lead, Others Follow”, 2013, PLoS ONE. 8(6).

[6] Viehman, H. A., & Zydlewski, G. B., “Fish Interactions with a Commercial-Scale Tidal Energy Device in Natural Environment”, 2014, Coastal and Estuarine Research Federation, 38, S241-S252

[7] Martinez-Porchas, M., Martinez-Cordova, L. R., & Ramos-Enriquez, R., “Cortisol and Glucose: Reliable indicators of fish stress?”, 2009, Pan-American Journal of Aquatic Sciences, 4, 158-178.

[8] Broadhurst, M.,& Barr, S., “Short term temporal behavioral responses in Pollack, *Pollachius pollachius* to marine tidal turbine devices; a combined video and adcp doppler approach; Southhampton, 2011.