Memorial Bridge Hydrokinetic Power Generation

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Ocean Projects: TECH 797
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Cover Photo: Eric Gendron Photography

Abstract

A site-specific tidal energy resource assessment was performed to aid in the selection of a hydrokinetic power generation device for the Living-Memorial Bridge (LB). The Gulf Challenger was utilized for the deployment of an Acoustic Doppler Current Profiler (ADCP) which allows for the tidal current velocities of the Piscataqua River to be measured. These velocities were measured from the river at the NH side pier of the Memorial Bridge. Implementation of the ADCP from October 24th, 2013 to February 24th, 2014 yielded four months of velocity data for investigation.

The bathymetry of the Piscataqua River channel affects the depth, direction, and magnitude of velocity of the tidal currents. At approximately 2 meters from the bottom of the river the change in direction of the flow from ebb tide to flood tide is nearly a 180 degrees (East-West). Meaning that the flow completely reverses direction. The flow velocities are found to increase in magnitude at a representative depth of 7 meters from the bottom and the flow directions change slightly from ebb to flood. The flow at the surface changes by nearly 180 degrees from ebb to flood, but there are some random directionality differences from disturbances such as wind, waves, and surface traffic. From the tidal current velocities, the power from the flow is calculated by using the following equation:

Because power is a function of velocity cubed, the slightest increase in velocity results in an exponential effect on power. Measuring the site-specific velocities over a 4 month period allows for a comparison between months. It was found that each month produces a similar amount of power, with the exception of the month of December when a construction barge interfered with the velocity measurements. The month of February best represents the tidal currents over the 4 month assessment period. Therefore, data from the month of February is used as a representative data set for constructing a site-specific turbine selection design aid.

Tidal energy for the month of February is determined by integration of the power for a representative depth of 7m from the bottom of the river. Theoretical turbine designs include a variety of turbine efficiencies, start-up velocities, and “swept” areas. For each theoretical design, the quantity of energy that can be harnessed is calculated.

The amount of energy that can be harnessed by turbines of higher efficiency is greater than a turbine of a lower efficiency. A turbine with a low efficiency must occupy a greater area than a turbine with a high efficiency to harness the same amount of tidal energy. Due to limitations on available area for a tidal turbine device in the Piscataqua River, certain turbine designs are not attainable. Many tidal turbines have an inherent “start-up” velocity which limits when power can be harnessed from the river. A lower start-up velocity results in a larger amount of energy that can be extracted from the river. From this figure, a design can be selected which identifies the required efficiency, start-up velocity, and swept area of a tidal turbine for harnessing a specific amount of tidal energy.

Table of Contents

List of Figures:

List of Tables:

1. Introduction

1.1 Project Goal & Objectives

The goal of the Memorial Bridge Hydrokinetic Power Generation project was to perform a site-specific tidal resource assessment to aid in the selection of a tidal energy device for providing power to the new Memorial Bridge. An understanding of the tidal resource allowed for an estimate to be made regarding the size and type of tidal turbine necessary to harness the clean, predictable, and renewable energy of the Piscataqua River.

To accomplish this goal, several objectives were established. These objectives include:

1. Measure and analyze the tidal current velocities
2. Calculate the available hydrokinetic power from the tides
3. Estimate the power requirements of the Memorial Bridge
4. Develop a site-specific design plot to aid in turbine selection
5. Investigate commercially available tidal turbine solutions

Systematic completion of these objectives resulted in a method where the tidal energy potential of the Piscataqua River at the Memorial Bridge could be confirmed. From an understanding of the available energy and the bridge power requirements, a turbine design aid was established to assist in the selection of a hydrokinetic power generation device.

1.2 History of the Memorial Bridge

The Memorial Bridge is a thru truss lift bridge that crosses the Piscataqua River between Portsmouth, New Hampshire and Kittery, Maine. The original bridge's opening ceremony was on August 17, 1923 and was the first bridge without a toll to span the Piscataqua River connecting Portsmouth and Kittery. The Memorial Bridge is a valued part of both communities. It not only has thousands of vehicles crossing each day, but it is the only pedestrian and bicycle access across the river.

The bridge was dedicated as a World War One memorial, with a plaque above the entrance on the Portsmouth side that read: "Memorial to the sailors and solders of New Hampshire who participated in the World War 1917-1919." This bridge was open for 88 years to vehicle traffic from 1923-2011 and closed to pedestrians and cyclists at the beginning of 2012. For the replacement bridge's opening ceremony on August 8, 2013, the former Portsmouth Mayor, Eileen Foley was invited to cut the ribbon almost 90 years after she cut the ribbon for the original bridge's opening ceremony. Eileen served multiple terms as Portsmouth's Mayor over the lifespan of the Bridge.

1.3 Project Background

This project was a continuation of undergraduate's research performed in TECH 797: Ocean Engineering. Previous groups have worked on various aspects of the hydrokinetic power generation. With their main focuses ranging from research of a variable flux generator to building a barge mounted Gorlov Turbine, and a broad tidal resource assessment. Other projects from CIE 788: Project Planning and Design, have been focused on bridge monitoring systems and a support structure for a turbine.

2. Objective #1 - Acquire and Analyze Data

2.1 Data Acquisition

2.1.1 Site-Specific Location

The ideal location for the ADCP would be in the exact location where the turbine would be, which is directly on the New Hampshire side pier of the Memorial Bridge. This was the ideal location because the tidal current data recorded would best replicate those tidal currents that the turbine would experience. Due to restrictions at the time, the actual assessment location was slightly further away from the bridge pier, as shown in Fig. 1 below:

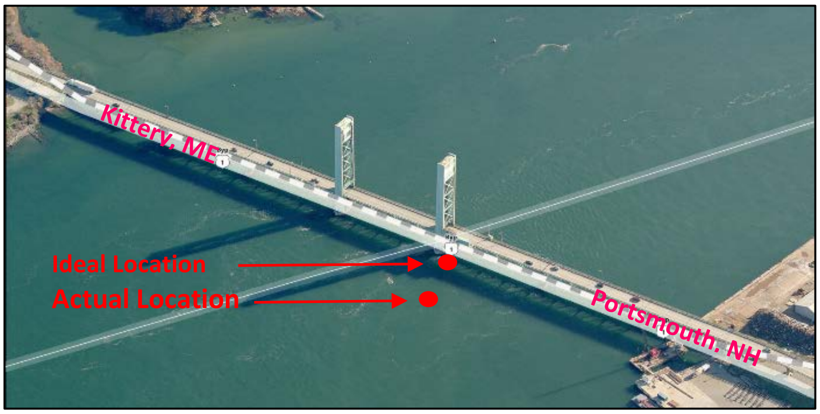


Figure 1: Location of resource assessment location - ideal location versus actual location

The New Hampshire side pier of the Memorial Bridge was specifically considered due to prior project research conducted by Dan Berry et al. in 2012. The following figure (Fig.2) demonstrates that the instantaneous velocity magnitude at the NH side pier was greater than the velocities closer to the Maine side of the bridge. Larger velocities lead to larger energy potential. Therefore, the NH side of the Bridge was the focus of a detailed, site-specific tidal resource assessment.

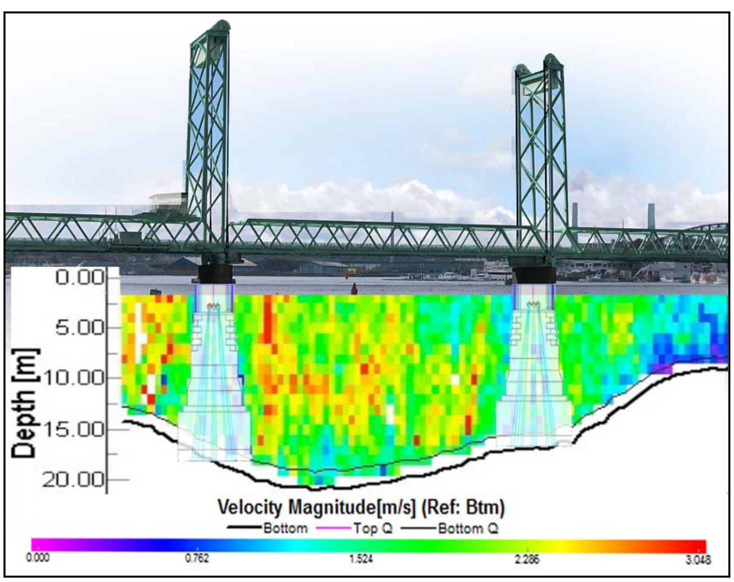


Figure 2: Magnitude of velocity transect data acquired by Dan Berry et al. 2012 for the Piscataqua River at the Memorial Bridge in Portsmouth, NH.

2.1.2 Equipment

The most important piece of equipment was the Acoustic Doppler Current Profiler (ADCP) as shown in Fig. 3. ADCPs use piezoelectric oscillators to transmit and receive acoustic signals. The acoustic back-scattering of the signal reflected off of particles that are suspended in the water result in a received signal that has a lower frequency than that of the transmitted signal. This is known as the Doppler Effect. Because of this effect, particle velocities can be determined and an estimation of the available power from the tidal resource can then be determined.

Additional equipment includes:

- The Gulf Challenger that was used for deployment.
- A steel frame that the ADCP was attached to while resting on the bottom of the river.
- Lead bricks that were hose clamped to the frame to help weigh it down.
- An auxiliary battery pack to help maintain a constant power supply for the ADCP.

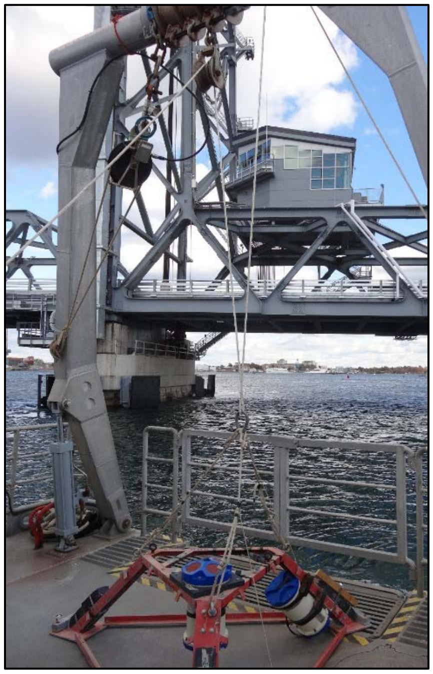


Figure 3: Equipment utilized for the acquisition of tidal current velocity measurements for performing a detailed tidal energy resource assessment

2.1.3 Deployment and Retrieval

The ADCP deployment took place on October 24th, 2014 with the help of the Gulf Challenger, its crew, and the Ocean Measurements class. Using the Gulf Challenger's winch the ADCP was lowered into the river without a surface buoy. The ADCP is used to record tidal current data for a 4 month period at the Memorial Bridge. This will provide for a more complete understanding of the tidal current over a longer period of time. The process of retrieving the ADCP started with a team of divers that attached a buoy to the ADCP so that at a later date the Gulf challenger could come by and pull it up with its winch. The retrieval date was February 24th, 2014.

2.2 Initial Data Analysis

The following figures show the velocities recorded by the ADCP for the representative depth of 7 meters from the bottom of the river for each month of the four month deployment. Each of the four months of velocity data represent a full tidal cycle (spring & neap tides)

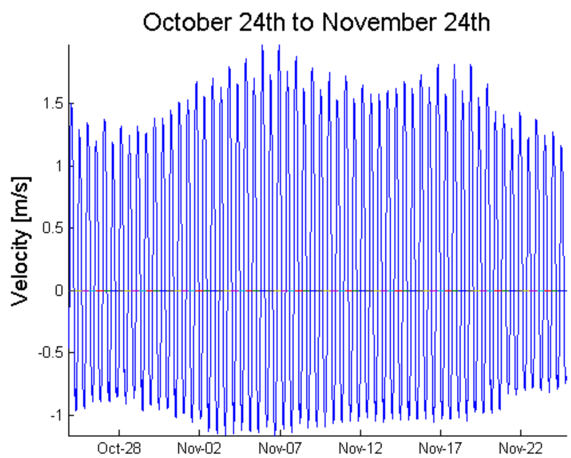


Figure 4: Tidal current velocity measurements from Oct. 24th - Nov. 24th (November) for representative depth of 7m from the bottom of the Piscataqua River

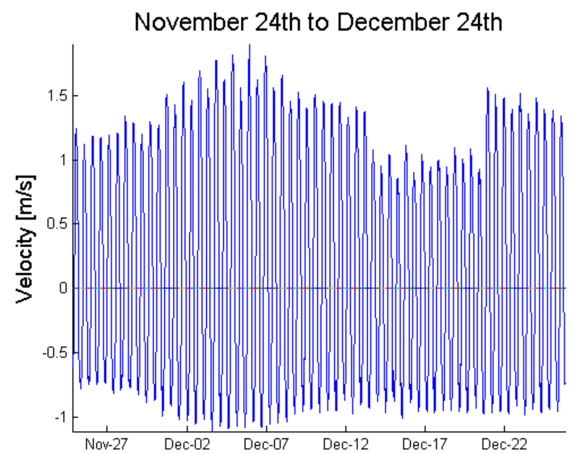


Figure 5: Tidal current velocity measurements from Nov. 24th - Dec. 24th (December) for representative depth of 7m from the bottom of the Piscataqua River.

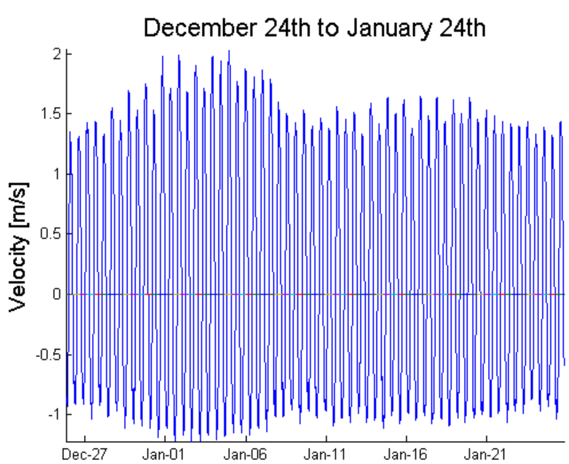


Figure 6: Tidal current velocity measurements from Dec. 24th - Jan. 24th (January) for representative depth of 7m from the bottom of the Piscataqua River.

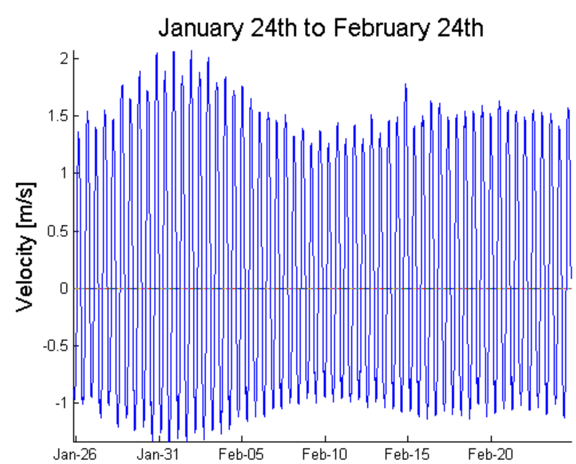


Figure 7: Tidal current velocity measurements from Jan. 24th - Feb. 24th (February) for representative depth of 7m from the bottom of the Piscataqua River.

It was found that the incoming and outgoing flow velocities were non-symmetrical. Due to the bathymetry of the Piscataqua River the velocities we found to be greater for the outgoing current flow, known as the ebb tides. When comparing the overall velocities for each month the data showed to be very similar with the exception of the month of December. This was to be expected due to the disturbances from a construction barge parked over the ADCP for the majority of that data set. For the rest of the data analysis only the month of February was examined because it was a good model of the entire 4 month data set.

Using the measured data a 3D surface plot was created, as shown in Fig. 8. It was beneficial in that it allowed for a quick overall understanding of the tidal current behavior for all depths and over the month of February. Spring and neap cycles can be identified and general velocity magnitudes can be examined.

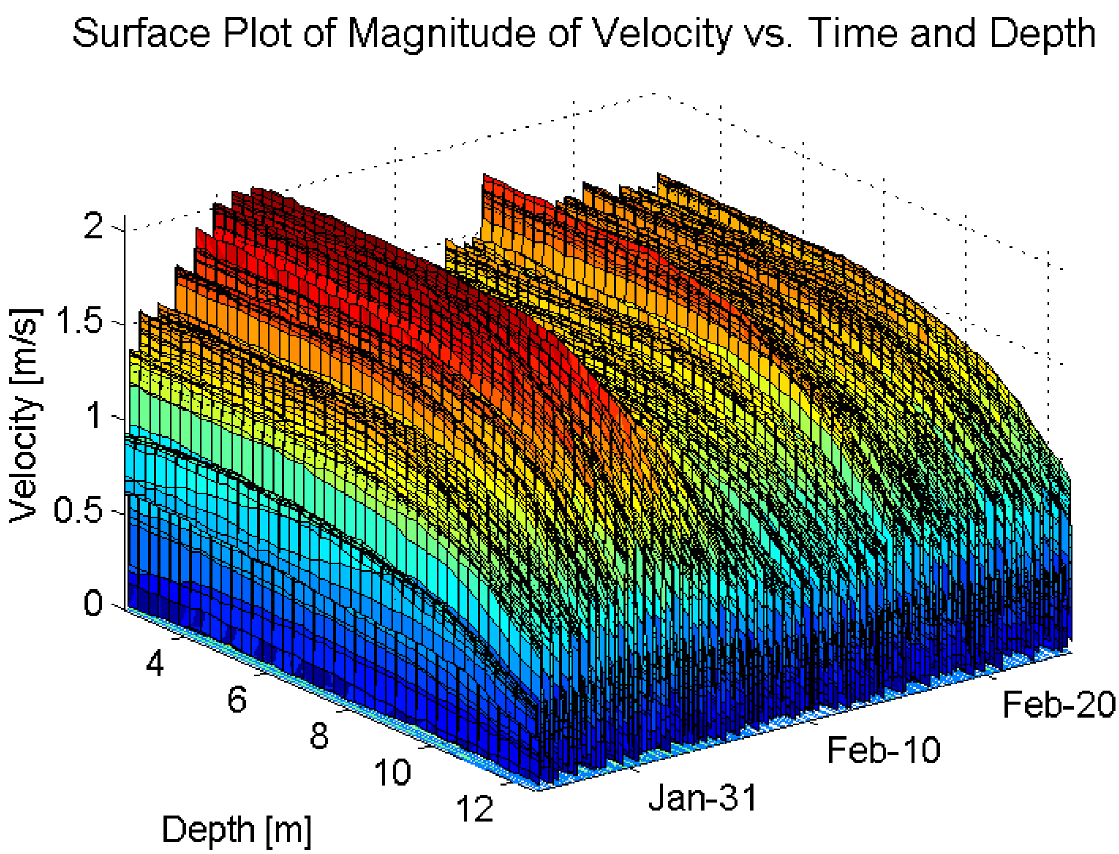


Figure 8: Surface plot representing the measured tidal current velocity magnitude data as acquired by the ADCP versus the depth of the measurement and the time of that the measurement was recorded.

For a more in depth look at the data, the Magnitude of Velocity plot for all depths (shown on the same figure) represents how velocity is affected by depth. You can see the boundary layer effect toward the bottom of the river. Where the velocities were slower. Which was caused by the friction of the bottom of the river acting against the flow of the current.

This representation of data was beneficial because it allows for decisions to be made regarding the appropriate depth that a turbine should be located in the water column, as well as turbine size decisions. With that in mind, the best depth for a turbine would be above 4 meters from the bottom of the river because the velocities between 4 to 12 meters from the bottom are relatively constant.

When examining the direction versus velocities for the tidal currents, the following compass plots show that not only do the velocities change with depth, but the direction of the velocities with depth change as well. For these plots 90 degrees represents East and 270 degrees represents West.

The first figure (Fig. 9) on the left shows the direction versus velocities at a depth close to the surface of the river. It was shown that there are some scattered velocities in the plot. Most likely caused by wind, waves and boat traffic. It also shows that ebb and flood tide velocities are non-symmetrical, where the ebb tides reach just over 2 m/s and the flood tides only reach approximately 1 m/s.

Ebb

Flood

12 meters from bottom

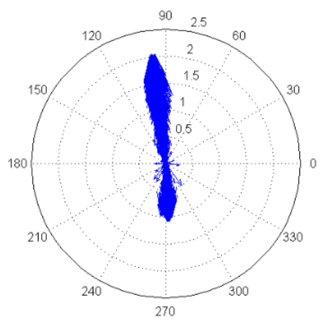


Figure 9: Compass plot demonstrating magnitude of velocity of tidal currents versus the direction of flow for depth of 12 meters from bottom of river

7 meters from bottom (representative data set)

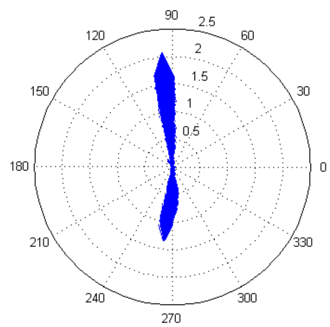


Figure 10: Compass plot demonstrating magnitude of velocity of tidal currents versus the direction of flow for depth of 7 meters from bottom of river

2 meters from bottom

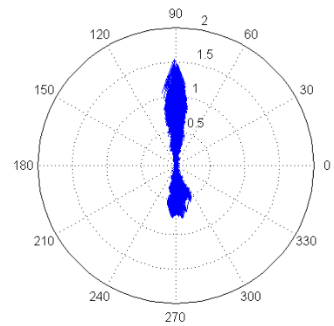


Figure 11: Compass plot demonstrating magnitude of velocity of tidal currents versus the direction of flow for depth of 2 meters from bottom of river

East

West

As it was already discovered that the ebb tide velocities were greater in magnitude but now it was shown that the change in direction from east to west was not an exact 180 degree change in direction. The next figure (Fig. 10) in the middle was for the representative depth and it shows the direction of the flow and its velocity.

As you can see the ebb tides are similar to that of the surface magnitude of velocity and direction, but the plot looks cleaner due to a decrease in the effect of surface disturbances. It also shows a change in the direction and magnitude for the flood tides, in which the velocities now reach almost 1.5 m/s. This was unlike the flow characteristics shown at the bottom of the river. Shown on the figure on the right, where the velocities go from 90 degrees to 270 degrees and both the ebb and flood tides decrease in their velocity magnitudes to approximately 1.5 m/s and 0.75 m/s respectively.

2.3 Necessity of a Site-Specific Assessment

The importance of performing a site-specific tidal resource assessment was proven in two ways. First, an ADCP transect of the Piscataqua River at the Memorial Bridge was analyzed to evaluate the speed of the tidal currents across the river. Second, velocity data acquired through the site-specific assessment was compared to a tidal current assessment performed by Karl Kammerer in 2007 in the mid-channel of the Piscataqua River at a location near the Memorial Bridge.

From the following figure (Fig. 12) it was noticed that the tidal current velocities vary across the river. The currents are strongest on the NH side of the river and weaker towards the Maine side of the river. Because of the variance in velocity from one side of the river to the other, an assessment at different locations would yeild different results. This was one reason why a site-specific assesment was performed.

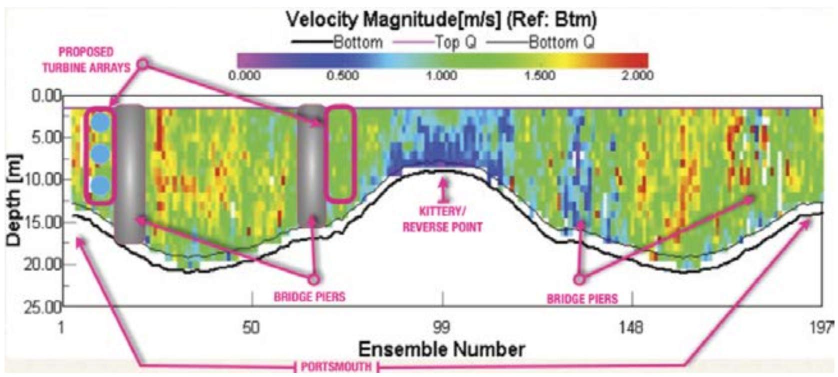


Figure 12: ADCP transect performed by Dan Barry et al. showing the variation in velocity across the Piscataqua River at the Memorial Bridge in Portsmouth, NH

Similarly, a tidal current assessment performed at mid-channel at the Memorial Bridge by Karl Kammerer in 2007 shows that the symmetry of the ebb and flood tidal currents cannot be assumed to be the same at two separate points in the river. Compare the mid-channel tidal current velocity figure below to the site-specific tidal current velocity figures (Fig. 4, 5, 6, and 7)

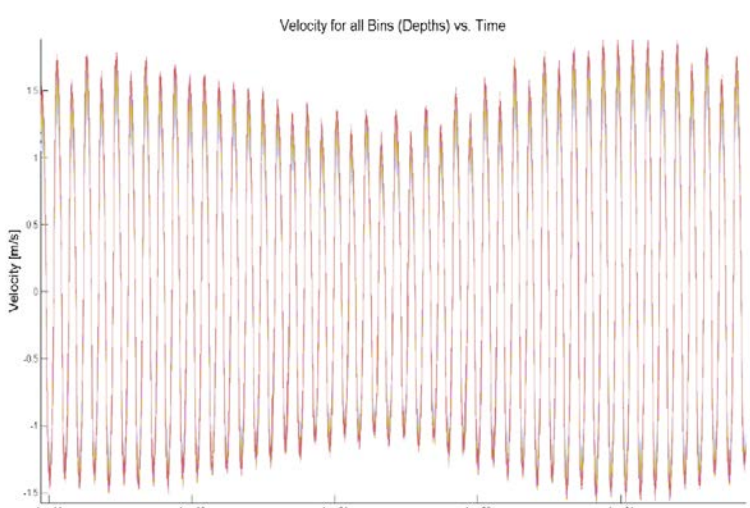


Figure 13: Tidal current velocity data for all depths acquired by (NOAA) Karl Kammerer in 2007 at mid-channel of the Piscataqua River near the Memorial Bridge in Portsmouth NH.

3. Objective #2 – Calculation of Power

Ultimately a calculation of the tidal power had to be made to determine the available tidal energy in the Piscataqua River. The available energy must be known to conclude if the power needs of the Memorial Bridge can be met by the renewable energy resource. The following equation represents how power was calculated:

$$Power = \frac{1}{2}\rho A v^3 \tag{1}$$

Where,

ρ = density of Piscataqua River
A = flow cross-sectional area
v = tidal current velocity

The density of the river was found to be approximately 1011.4 kg/m^3. A conductivity-temperature-depth (CTD) experiment was performed in November of 2013 in the Piscataqua River to determine the density from both salinity measurements and temperature measurements. For the purposes of evaluating the power, an area (A) of one square meter was assumed. This was also known as the power density.

Most importantly, notice that power was a function of velocity cubed. With a small increase in velocity, the power exponentially increases. For example, see the following table comparing the power for two instantaneous velocities:

Power Density for Velocity of 1 m/s		**Power Density for Velocity of 2 m/s**	
Density	1011.4 kg/m^3	Density	1011.4 kg/m^3
Area	1 m^2	Area	1 m^2
Power	0.506 kW	Power	4.046 kW

Table 1: Instantaneous power density example for two different velocities to explain the effects of velocity on power.

The percent difference between these two power densities is 156%. This leads to the realization that smaller values for velocity contribute significantly less than larger values of velocity when calculating power. Fig. 14 below further exhibits the effects of velocity cubed in the equation for power.

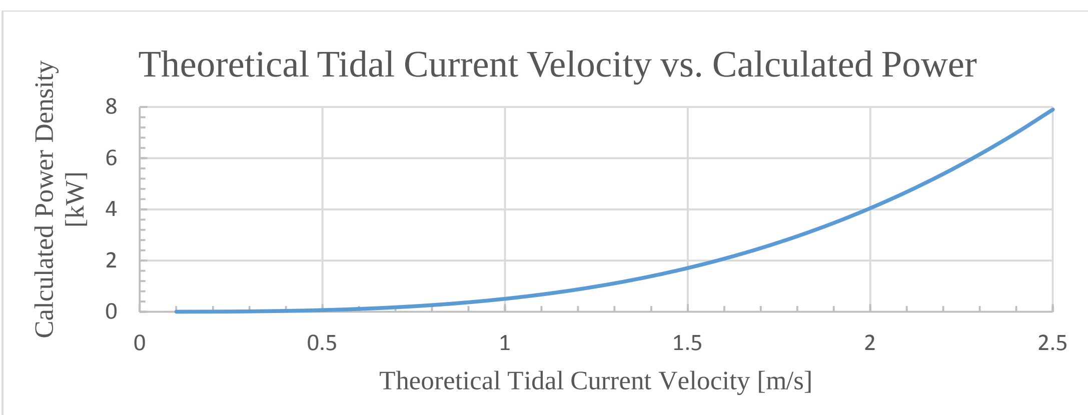


Figure 14: Theoretical tidal current velocity versus calculated power showing how power was affected by increase in velocity.

The following four figures are the result of applying the power (density) equation to the velocity data set from the tidal resource assessment:

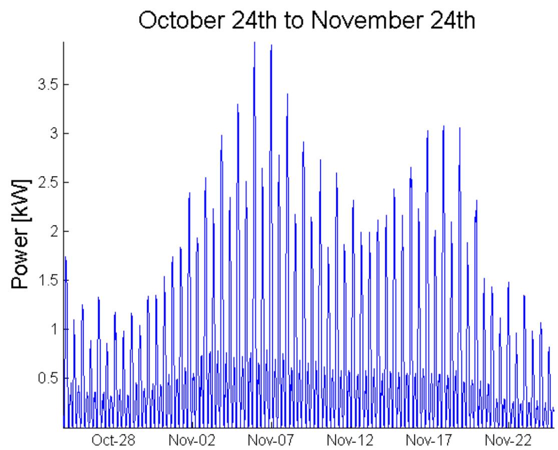


Figure 15: Tidal power from Oct. 24th - Nov. 24th (November) for representative depth of 7m from the bottom of the Piscataqua River.

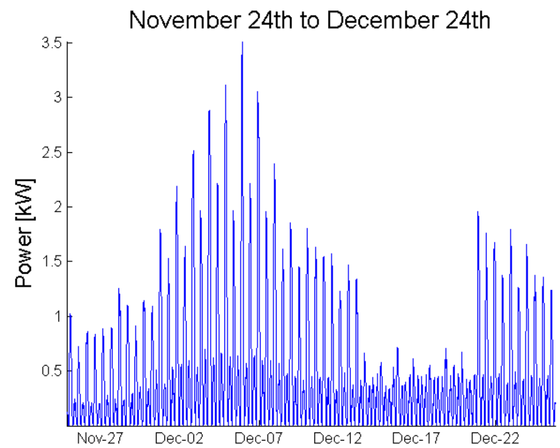


Figure 16: Tidal power from Nov. 24th - Dec. 24th (December) for representative depth of 7m from the bottom of the Piscataqua River.

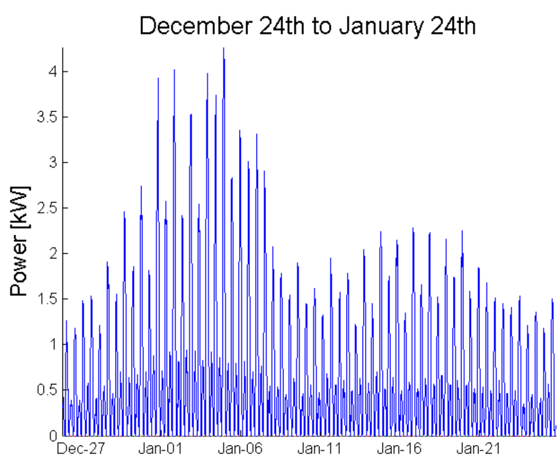


Figure 17: Tidal power from Dec. 24th - Jan. 24th (January) for representative depth of 7m from the bottom of the Piscataqua River.

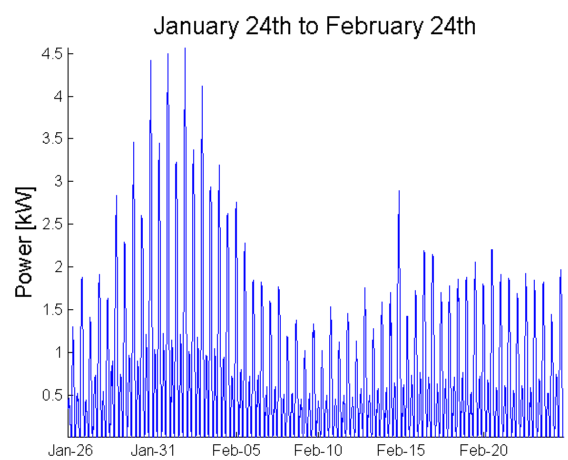


Figure 18: Tidal power from Jan. 24th - Feb. 24th (November) for representative depth of 7m from the bottom of the Piscataqua River.

Due to the non-symmetry of the tidal currents, the power calculated for the flood tide does not reach the larger magnitudes of the ebb tide. This explains the two visually distinct regions in each of the figures above. The larger magnitudes of power are the result of faster tidal current velocities.

Once again, the data from the month of December was omitted due to the interference from a construction barge. Comparing the remaining three months (November, January, and February), it was found that February sufficiently describes the tidal cycle behavior, therefore, the data from the month of February was used for the remainder of analysis, including developing the turbine design aid.

4. Objective #3 - Bridge Power Requirements

Prior to developing a design aid to assist in the selection of a tidal turbine for the Memorial Bridge, the power demand of the bridge must be known. Through information from the New Hampshire Department of Transportation (NHDOT), the following table summarizes the aesthetic and safety power requirements:

Power Demands of Memorial Bridge
High-efficiency LED aesthetic lighting
Traffic, aerial, and marine navigation lighting
Structural monitoring system
Performance monitoring
Surveillance cameras
Informational and educational display

Table 2: Summary of the aesthetic and safety power demands of the Memorial Bridge

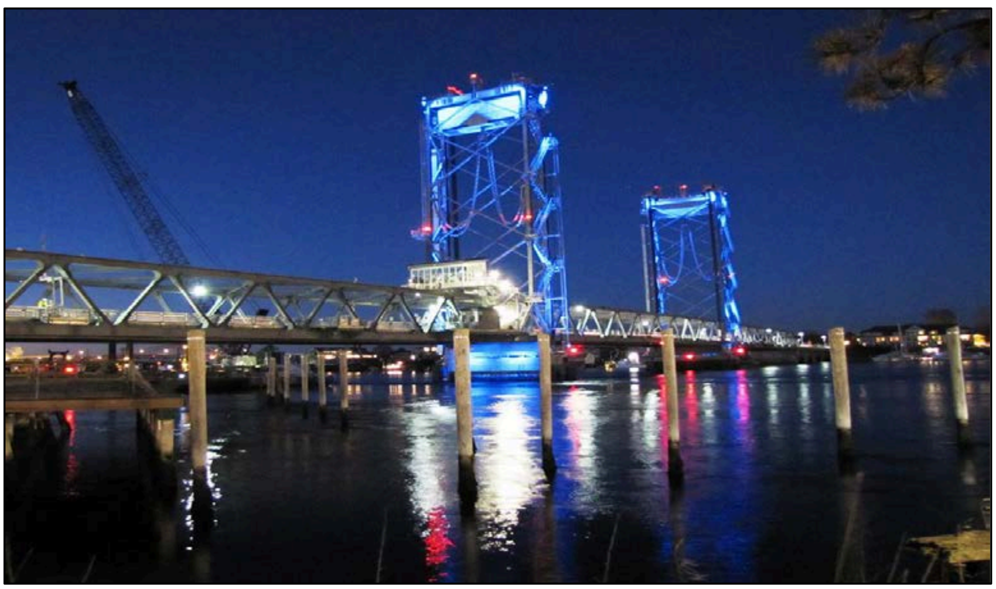


Figure 19: Annotated figure representing the lighting power requirements of the Memorial Bridge

From the figure above, the blue lights are the aesthetic lighting of the bridge while red lights are traffic, marine, and aerial navigation lighting. The bridge monitoring systems is located at various locations across the bridge to provide live information about the bridge conditions. The energy demand for these power requirements was totaled at 0.9 MWh per month. With the power demand known, the design aid could be constructed.

5. Objective #4 - Turbine Design Aid

When it comes to the ability of a tidal turbine to harness energy from a tidal resource, there are three specific parameters which have crucial roles: 1. Turbine efficiency, 2. Turbine Start-up velocity, and 3. Turbine “swept” area. Note that the turbine “swept” area is the cross-sectional area of which the turbine intercepts the tidal current flow. Because these parameters are of such significance, a design aid which includes all three must be developed.

5.1 Integration of Power

The energy density available from the tidal resource is calculated by integrating the area under the power density curve. As previously mentioned, the month of February was the month which was analyzed. Therefore, the turbine design aid was based off of one month of velocity/power/energy data. The equation for energy per month (30 days) is as shown below:

$$E = \int_{0}^{720\,hrs} P dt \qquad (2)$$

Equation #2 above, is the calculation of available energy based on the available tidal power (P). However, when investigating the potential of a turbine, there are certain parameters (as previously mentioned) which limit the amount of this available energy that can be harnessed.

There are two tools (plots) that were developed which provide information on the effects that efficiency, start-up, and “swept” area have in harnessing power. The first tool examines the effects that start-up velocity has on the amount of energy that can be harnessed while the second examines the effect that varying the “swept” area has on the quantity of energy that can be harnessed.

Before the tools could be developed, the equation for power (Eq. #1) had to be modified to include the turbine efficiency. This equation is shown below:

$$Power_{turbine} = \eta \frac{1}{2} \rho A v^3 \qquad (3)$$

The efficiency is defined by $\boldsymbol{\eta}$. Appropriate ranges for the efficiency, start-up velocity, and area were also selected to ensure that the design tools provide meaningful information. If, for example, the efficiency range was an unrealistic value, then the design tools would not assist in the turbine selection process. The following table displays the ranges for the described parameters:

	Turbine Parameter		
	Turbine Efficiency	Turbine Start-up Velocity	Turbine “Swept” Area
Range	25%	0.5 m/s	1 m^2 – 20 m^2
	35%	0.7 m/s	
	45%	1.0 m/s	

Table 3: Summary of the theoretical turbine parameter range explored to develop a tidal turbine design aid

5.1.1 First Turbine Design Aid

The following figure visually shows the amount of tidally energy per month which can be harnessed from the site-specific tidal resource. The energy was calculated by using Equation #2 and the previously mentioned range of theoretical turbine parameters.

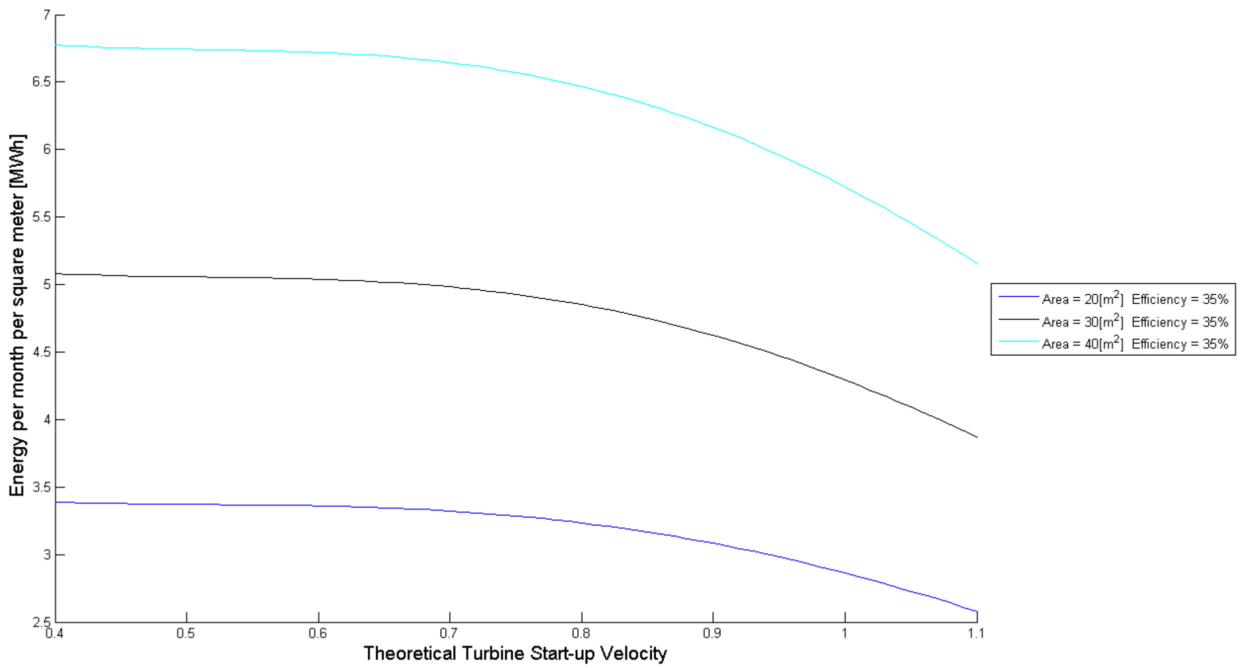


Figure 20: Tidal turbine design aid #1 - shows the amount of tidal energy which can be harnessed versus a range of tidal turbine start-up velocities for specific efficiencies and "swept" areas.

The parameter range was slightly increased for this design tool to help emphasize the dramatic effect that start-up velocity contributes to a turbines ability to extract power from the tidal resource. Notice how for each of the curves shown (light blue, black, and dark blue) that the amount of energy harnessed was constant from a 0.4 to 0.7 m/s start-up velocity range. However, after an approximately 0.7 m/s start-up velocity, the theoretical tidal turbine harnesses a considerably less amount of power for the same area and efficiency.

A higher start-up velocity results in a smaller amount of power that could be harnessed by a turbine. As an example, a turbine with a start-up velocity of 0.4 m/s, efficiency of 35%, and area of 20 m^2 could harness nearly 3.4 MWh, but a turbine with 1 m/s start-up velocity, efficiency of 35%, and area of 20m^2 could only harness approximately 2.8 MWh. The selection of a turbine based on start-up velocity does not have a considerable impact unless the start-up velocity of the turbine is much greater than 0.7 m/s.

5.1.2 Second Turbine Design Aid

Similar to Figure 20 above, the energy harnessed by a theoretical turbine can also be determined for a range of theoretical turbine efficiencies and start-up velocities, but instead of being plotted against start-up velocity, the energy is plotted against turbine "swept" area. The harnessed energy was once again calculated using Equation #2. The results of the development of this tool are shown below:

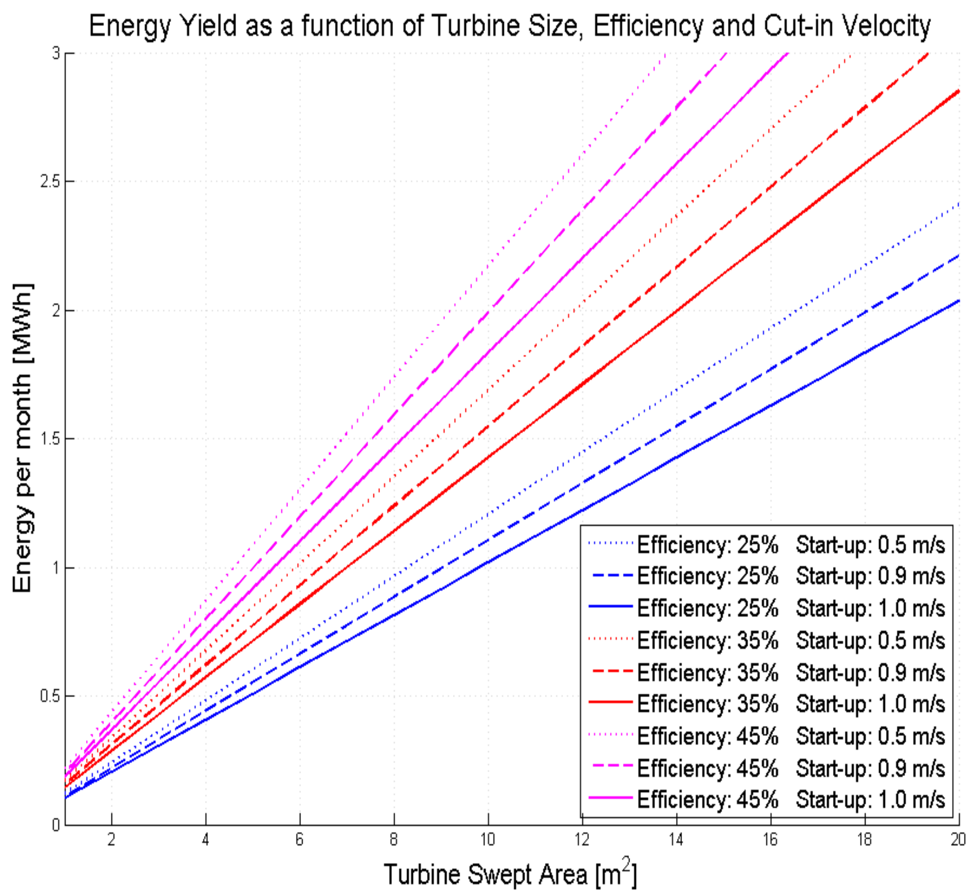


Figure 21: Tidal turbine design aid #2 - Energy yield as a function of turbine size, efficiency and start-up velocity. Plotted as the energy which can be harnessed per month by a theoretical turbine versus a range of "swept" areas.

This tidal turbine design selection aid was beneficial, in that the exact parameters were identified for many turbine solutions. With a known power demand of the bridge of 0.9 MWh, a list of solutions could easily be acquired. However, to ensure that enough power would always be generated by a turbine, a "factor of safety" of two was implemented. Therefore, it was assumed that the power demand of the Memorial Bridge was 2 MWh per month.

Specifying this value for energy, a list of tidal turbine solutions can be easily identified which would provide enough power for the energy demands of the Memorial Bridge. Imagining a horizontal line at 2 MWh per month helps in visualizing these solutions. Efficiency, start-up velocity, and turbine area are all identified by evaluating the intersection of the horizontal line with the design curves (lines of constant efficiency and start-up velocity).

Three examples of turbine solutions determined from design aid #2 (Figure 21 above) are shown in the following table:

Parameter	Turbine Solution #1	Turbine Solution #2	Turbine Solution #3
Efficiency	45%	35%	25%
Start-up Velocity	0.9 m/s	0.5 m/s	0.9 m/s
Turbine “Swept” Area	10 m^2	12 m^2	18 m^2

Table 4: Three solutions acquired from the turbine selection aid by evaluating where the energy per month required by the Memorial Bridge intersects the turbine design curves.

In addition to evaluating a range of theoretical turbine parameters, a commercially available turbine with known parameters can be evaluated to determine the required “swept” area to harness enough energy to power the Memorial Bridge.

6. Objective #5 - Commercially Available Turbine Solutions

Some of the commercially available tidal turbines taken into consideration are shown in the figures below.

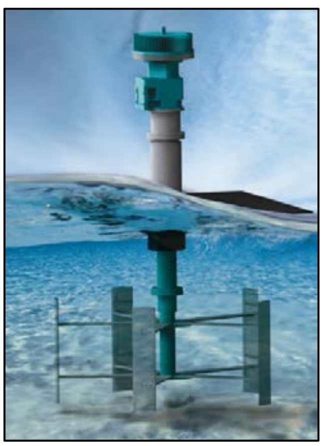


Figure 22: Darrieus style tidal turbine by EnCurrent – New Energy Corp.

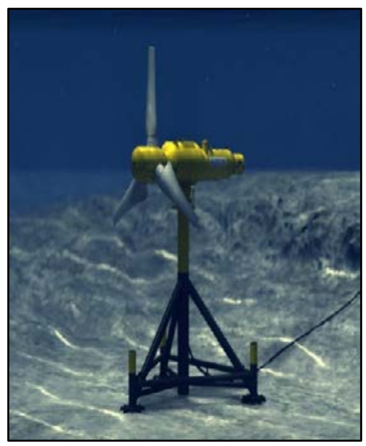


Figure 23: Axial-flow style tidal turbine by Alstom renewable energy

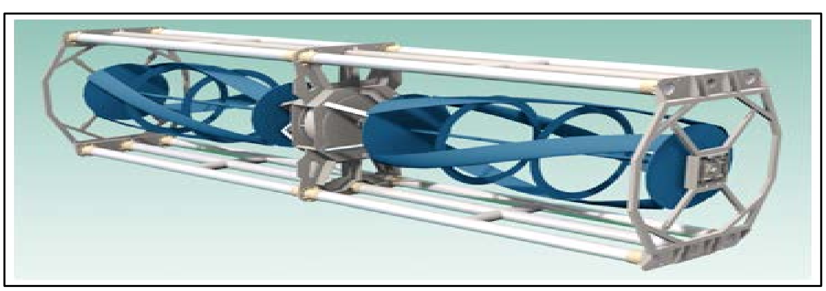


Figure 24: Helical (similar to Gorlov) turbine by Ocean Renewable Power Company (ORPC) - Turbine Generator Unit

The Darrieus is shown on the left in Fig. 22, the axial flow is on the right in Fig. 23, and the Gorlov is on the bottom in Fig. 24. Each of these turbines have similar efficiencies and operational cut in speeds. The Darrieus and Golov have efficiencies between 30-35% and cut in speeds between 0.7-1 m/s. While the axial flow efficiency is between 35-40% and cut in speeds slightly lower than Darrieus and Gorlov. However, the Gorlov Turbine can operate with omni-directional flows and the Darrieus Turbine can operate at all flows in the horizontal plane. Both turbines also can be oriented vertically so that the generator would be out of the water for easier maintenance. Most axial flow turbines can only operate in one horizontal directions, but there are other axial flow blades that can harness hydrokinetic power from flows in two directions with similar efficiencies and cut in speeds. Or the axial flow can be set up to yaw back and forth for the change in tidal flow. Unfortunately the generator is located on the same shaft as the axial flow turbine's blades so the generator would be located underwater. Drag turbines were looked at, but not considered because they cannot operate faster than current flow.

7. Turbine Recommendation

The recommended tidal turbine to install on the New Hampshire side pier of the Memorial Bridge is a Gorlov Turbine. The Gorlov Turbine can be oriented vertically as shown below in Fig. 25, with its generator out of the water for easier maintenance. It can operate with omnidirectional tidal currents. Its efficiency is slightly better than the Darrieus Turbine. The main difference was that most of the area from the Gorlov was in the vertical direction. The Gorlov was designed after the Darrieus and one of the changes made in its design was to increase the length of the blades and decrease the rotational radius without a decrease in efficiency.

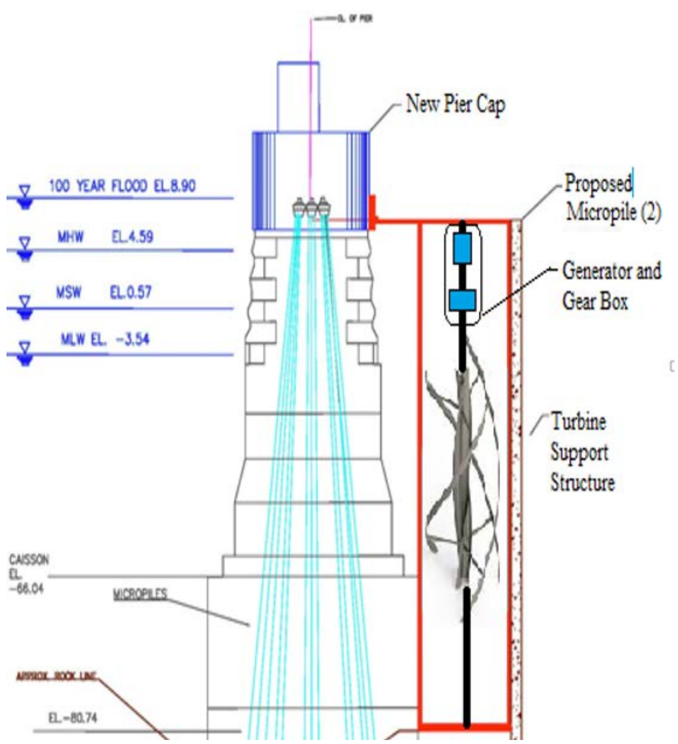


Figure 25: Recommended implementation of Gorlov style turbine in Piscataqua River at the NH side pier of the Memorial Bridge.

Conclusion

By deployment of an Acoustic Doppler Current Profiler (ADCP) in the Piscataqua River near the New Hampshire side pier of the Memorial Bridge, the measurements of the tidal current characteristics were recorded. Using the measured velocity data at the site-specific location a recommendation was made for a Gorlov Turbine, which is best suited to harness energy to power the Memorial Bridge. This was accomplished by several important steps. First by recording the tidal current velocities over a 4 month period and comparing the data sets. Since the months were similar the representative month of February could be modeled and used to gain a yearly power density of 5.76 MW at the representative depth of 7 meters from the bottom of the Piscataqua River.

The velocity magnitudes for ebb tides reached about 2 m/s where the flood tides velocity magnitudes were just under 1.4 m/s. For the same depth of 7 meters from the bottom, the direction of the ebb and flood tides had a 160 degree change in direction, which meant that the Darriues and Gorlov Turbines would have worked best at this point. Both turbines are able to operate with multidirectional tidal currents and their generators are located at the top and out of the water for easy maintenance. One of changes in the design from Darrieus to Gorlov was an improvement on the amount of vibrations created while operating. To select the size of a turbine necessary to power the Memorial Bridge requirements with a safety factor of 2, based off efficiency and cut-in speed, the design plot shown in Fig. 21 shows the swept area for a turbine would have to be between 10-14 square meters.

Appendix A – Progress Reports

Progress Report #1

University of New Hampshire
Mechanical Engineering – TECH 797
Hayden Hicks and Joel Griffith
November 7th, 2013

Overview: This project's objective is to complete a detailed resource assessment using site specific data of the New Hampshire side of the Memorial Bridge pier. To determine whether or not the tidal currents beneath Memorial Bridge will be sufficient to generate hydrokinetic power using a tidal turbine. This will be accomplished with the Acoustic Doppler Current Profiler (ADCP). ADCPs use piezoelectric oscillators to transmit and receive acoustic signals. The acoustic back-scattering of the signal reflected off of particles that are suspended in the water result in a received signal that has a lower frequency than that of the transmitted signal. This is known as the Doppler Effect. Because of this effect, particle velocities can be determined and an estimation of the available power from the tidal resource can then be determined. The ADCP will be recording data for 40 days at the Memorial Bridge. This will provide for a more complete understanding of the tidal current over a longer period of time. The ideal location for the ADCP is right where the turbine would be, so that data recorded would best replicate those velocities.

Deployment: The ADCP deployment took place on October 24th with the help of the Gulf Challenger, its crew, and the Ocean Tides class. The deployed, metal structure included the following materials: the ADCP, an auxiliary battery pack, 9 lead bricks secured by hose clamps, and 2 bungee cords that secured the clearance of the ADCP when the rope lines came to rest. The method of deployment for the ADCP used the plan B approach due to the strength of the tidal currents. The plan B approach is in the same general-line-of-flow as the ideal location but it is downstream from the pier which made for a safer deployment during high tide. This approach also including removing the buoy and dropping the ADCP without any line to the surface. Next time we deploy the Instrument we hope to get within closer proximity to the pier and to leave a buoy attached so we won't have to have divers retrieve it.

Future: The data that will be collected shall be used to produce the time of the tidal cycle that the velocity is greater than 2 m/s and the power available during this time of the tidal cycle. These results will contribute to the selection of a tidal turbine that can operate most effectively in the sinusoidal tidal cycle. The plan A recovery of the ADCP is set for the 25th of November and in case of bad weather the plan be is 2 days later on the 27th the day before thanksgiving. Both plans include the divers diving during slack water time and the use of a Hydrophone to detect the ADCP's location. Retrieval at these dates will put the data recording length just under 5 week.

Progress Report #2

University of New Hampshire
Mechanical Engineering – TECH 797
Hayden Hicks and Joel Griffith
December 3rd, 2013

Overview: Since November 7th, 2013 three aspects of the Memorial Bridge Project have been evaluated, which include: ADCP recovery, a comparison of turbine efficiencies, and an exploration of commercially available tidal turbine solutions. By comparing the efficiencies of various types of turbines, it becomes possible to narrow the search for commercially available products. This "narrowing down" process allows for a decision to be made regarding which turbine is the most viable product for the tidally driven Piscataqua River resource.

ADCP Retrieval: The Acoustic Doppler Current Profiler is scheduled to be recovered during the week of 12/09/2013. By retrieving the ADCP after this date, velocity measurements will have been obtained for over a 40 day period, which fulfills the goal of recording data over the course of a full tidal cycle. Because the ADCP was deployed without a line to the surface, the only means of recovery requires the use of a dive team. From the Gulf Challenger research vessel, an anchor (with line attached to Gulf Challenger) will be dropped to the ocean floor near the expected location of the ADCP. From there, two diver will scan the ocean floor by working their way from the anchor outwards until the ADCP is located. With the ADCP found, a diver clips the tripod frame to the line which can then be pulled to the surface by the winch of the Gulf Challenger. Data will be extracted from the ADCP and saved to an external hard drive and then evaluated.

Turbine Evaluations: Three types of turbines were evaluated based on efficiency and operating range to establish a grounds for the most suitable turbine for the Memorial Bridge tidal currents. These turbines include: Darrieus style turbine, Gorlov style turbine, and a horizontal axis turbine. Each type of turbine was assumed to occupy the same area and to experience the same tidal current velocities. Knowledge of the velocities allows for the available power for the given area to be determined. Through this study, the Gorlov was found to harness the most power from the power available. This was followed by the horizontal axis turbine and then the Darrieus style turbine. Each of these turbines are potential options for implementation at the Memorial Bridge.

Commercially Available Tidal Turbines: Several companies were examined which presently implement tidal energy devices. These companies include: EnCurrent, Natural Currents, and Ocean Renewable Power Company. The following figures represent the solutions that two of the companies presently offer:

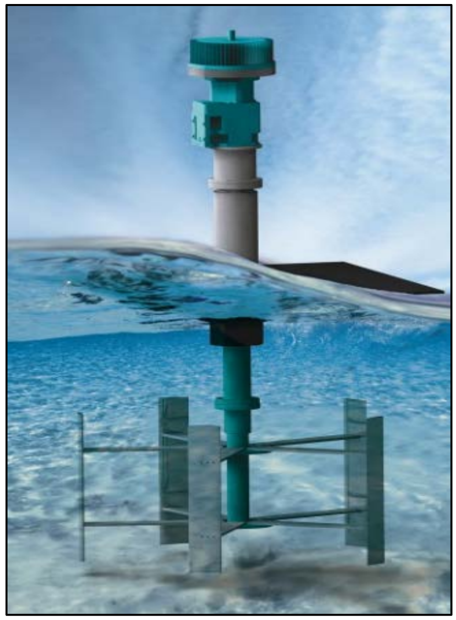


Figure 26: EnCurrent Tidal Energy Darrieus Style Turbine

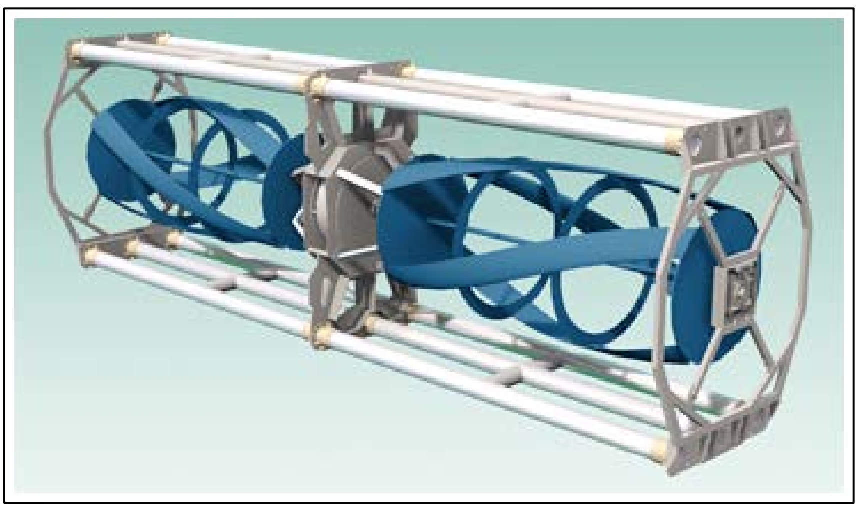


Figure 27: Ocean Renewable Power Company Tidal Energy Helical Turbine

Natural Currents also offers a Gorlov style tidal energy device. These companies each have their own solution for harnessing power from tidal resources. A solution would be preferred that incorporates one of these designs, but with a vertical axis such that it is possible for the generator unit to be above the surface of the water.

Progress Report #3

University of New Hampshire
Mechanical Engineering – TECH 797
Hayden Hicks and Joel Griffith
February 6th, 2014

Overview: Since December 5th, 2013 progress has been made in the analysis of the ADCP output data. Although, the ADCP that was deployed on October 24th has not yet been recovered. This is due to minor setbacks. First, a barge parked over it and prolonged the recovery about a month and then came holidays, poor weather conditions and jumbled scheduling with the divers. Our new goal is to have the ADCP by the end of next week. Meanwhile, our budget has been updated to include the cost for divers and discontinue other expenses we won't be using. Matlab code has been developed to process the data. This was accomplished by using existing ADCP tidal current information ("bin" data) from a study by Kammerer in 2007 in the Piscataqua River. Many types of plots and histograms were generated to represent the behavior of the tidal currents in the Piscataqua River over a full tidal cycle. Data was plotted in the following forms:

1. 3D Surface plot – Representing Time, Depth, and Velocity
2. Velocity plot – Separate plot for each bin (depth) with velocity model
3. Magnitude of Velocity plot – Magnitude of Velocity at all depths on one figure
4. Color map – Represents Time, Depth, and Velocity where velocity is shown by color
5. Power Density plot – Represents Power Density at all depths on one figure
6. # of Occurrences – Shows the frequency of different ranges of velocity magnitudes for each depth.

The 3D surface plot is beneficial in that it allows for a quick overall understanding of the tidal current behavior for all depths and over the entire duration of the deployment. Spring and neap cycles can be identified and general velocity magnitudes can be examined. For a more in depth look at the data, the Magnitude of Velocity plot for all depths (shown on the same figure) represents how velocity is affected by depth. This representation of data is beneficial because it allows for decisions to be made regarding the appropriate depth that a turbine should be located in the water column, as well as turbine size decisions.

Progress Report #4

University of New Hampshire
Mechanical Engineering – TECH 797
Hayden Hicks and Joel Griffith
March 6th, 2014

Data Acquisition: On February 24th, the Acoustic Doppler Current Profiler that was used to acquire tidal current velocity measurements from the Piscataqua River was retrieved. Though the retrieval took place more than two months later than originally planned, more data was attained meaning a further understanding can be developed regarding the tidal current behavior. The use of divers was necessary for finding the ADCP from the bottom of the river, which now imposes an additional cost to the budget.

Data Analysis: Four months of data are able to be processed. Proper analysis will allow for an educated decision to be made about the type of turbine (Gorlov, Darreus, or Horizontal Axis) and some decisions about size limitations, such as the depth and diameter. The code used to process the data also allows for the power from the tidal currents to be calculated, thus giving an estimate to the amount of power a turbine can harness (assuming that efficiency and operating range of the turbine options are known). Below are several figures which represent the data that was recorded between October 24th, 2013 and February 24th, 2014:

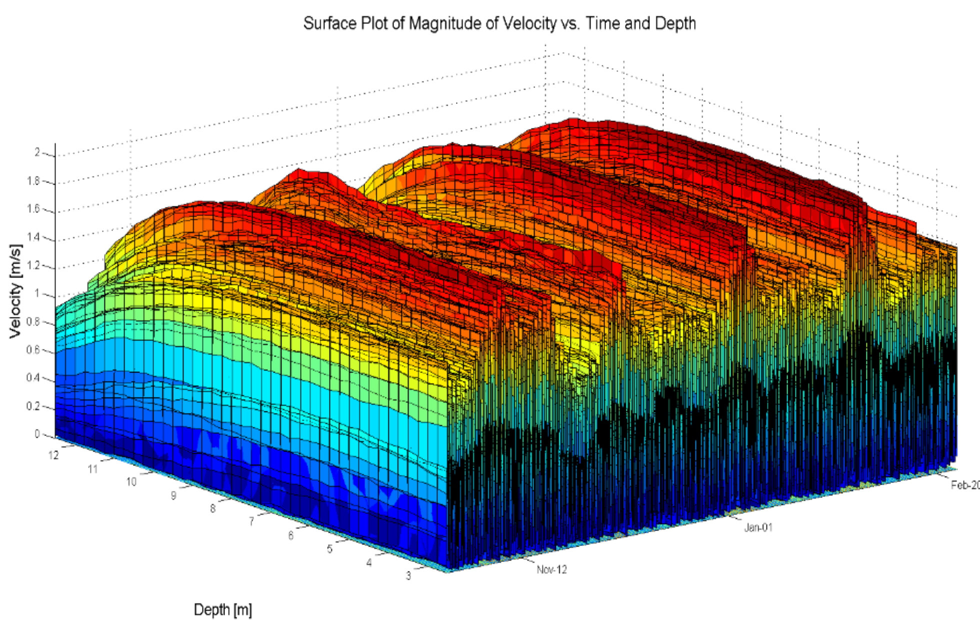


Figure 28: Surface plot representing the magnitude of velocity versus the depth of the river and the time the measurement was recorded

Figure 29: Tidal current velocity for representative depth versus time that the measurement was recorded

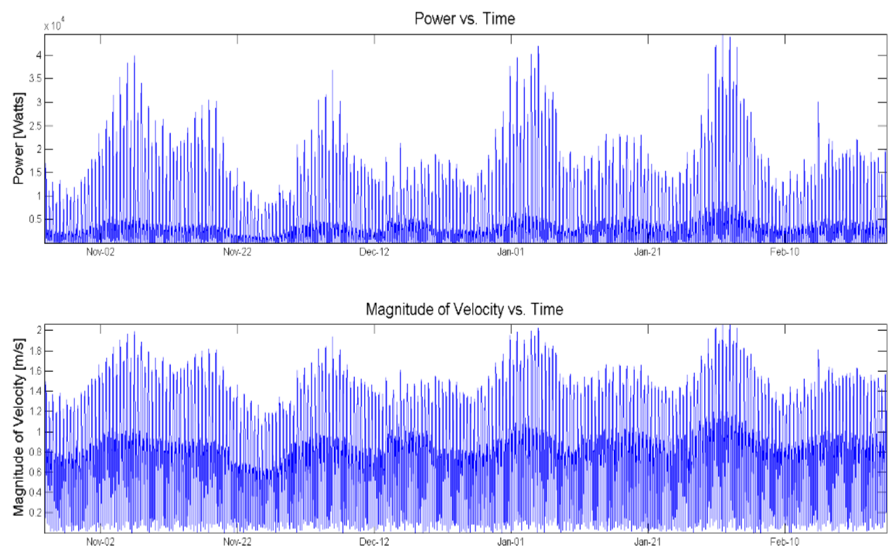


Figure 30: Power and Magnitude of velocity for all recorded measurements

From Figure 1, it can be noticed that the velocity is relatively constant with depth. At about 10 meters from the surface, the velocities begin to decrease closer to the boundary. Evaluation of the constant velocity portion versus depth, provides beneficial information regarding possible sizes of a turbine. Figure 2 shows that the velocities during the ebb part of the tidal cycle are greater than that of the flood. This information allows for decisions to be made about the effects that operating ranges have on power of potential turbines. The final figure, Figure 3, demonstrates the total amount of power available to a turbine as calculated from the tidal current velocities. Because the power is a function of velocity cubed. Lower velocities do not have as significant of an impact as larger velocities.

Progress Report #5

University of New Hampshire
Mechanical Engineering – TECH 797
Hayden Hicks and Joel Griffith
April 3rd, 2014

Data Analysis: From the four months of tidal current velocity data acquired by the ADCP, the power is calculated for each month of the data (Oct. – Nov., Nov. – Dec., Dec. – Jan., and Jan. – Feb.). Integration of the calculated power provides information about the amount of energy available for the month being analyzed. It is found that the energy available is nearly the same for each month, with the exception of December due to the barge interfering with the data collection.

The energy density calculated for the Jan. – Feb. data set is determined to be an average of the typical month (tidal cycle). Therefore, future calculations are based off of the Jan. – Feb. data set. With knowledge of the energy density, different tidal turbine possibilities can be explored. The following plot represents the energy that can be harnessed per month versus a theoretical turbine "swept" area (m^2) for turbines of different efficiencies and start-up velocities.

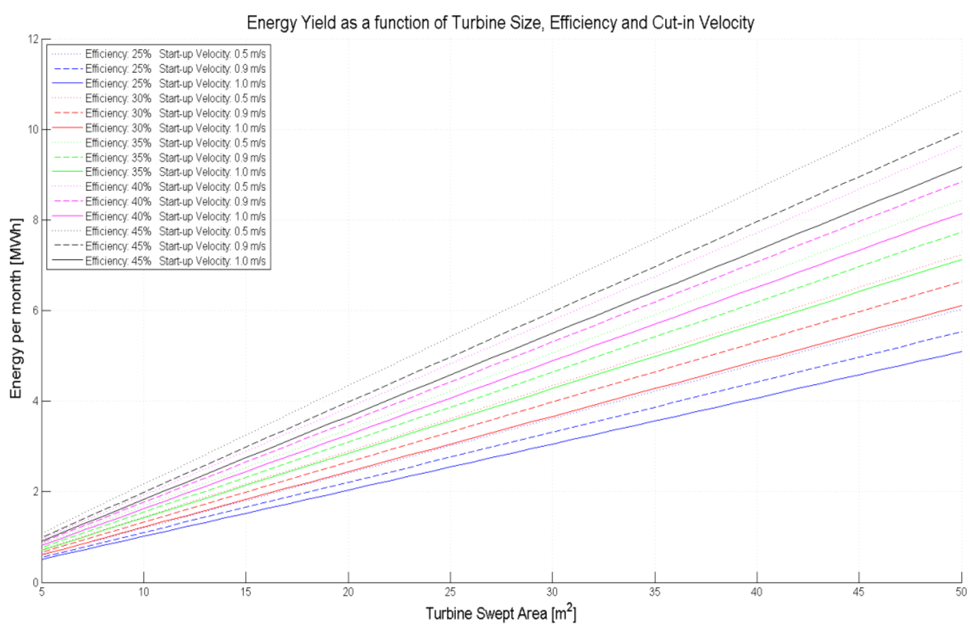


Figure 31: Energy yield as a function of turbine size, efficiency, and cut-in velocity (theoretical turbine efficiencies and cut-in speeds are explored). Representative data for depth of 7 meters from the river bottom.

If the energy required from the bridge is known, then a variety of turbine solutions can be easily identified by using the information from figure 1. Also to explore is how the energy varies with cut in speed. The following plot represents this situation:

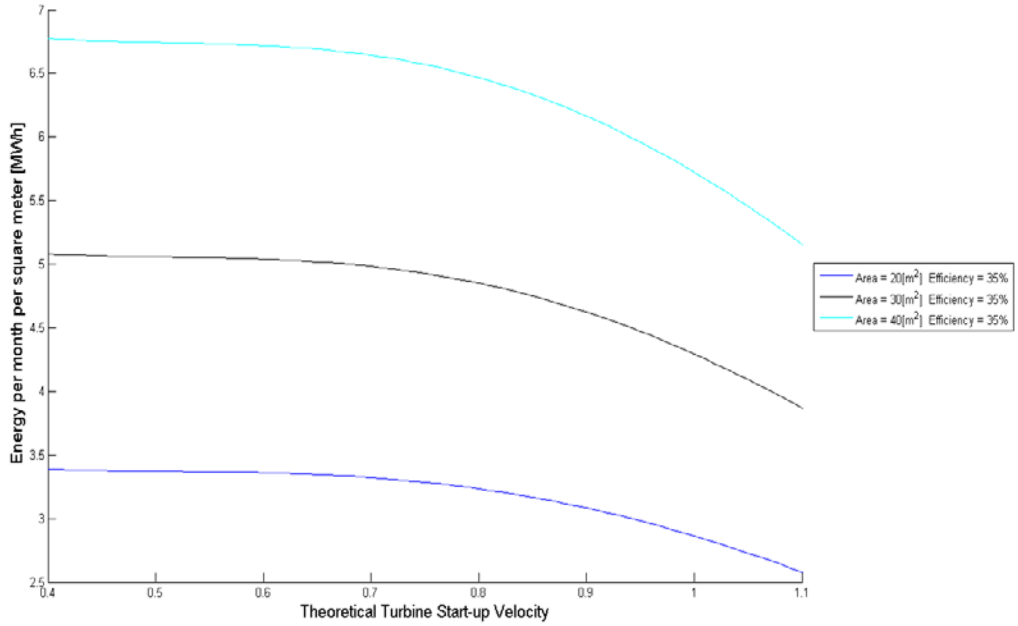


Figure 32: Lines of constant area and efficiency demonstrate the effects of energy per month with changes in theoretical turbine start-up velocity. Representative data for depth of 7 meters from the river bottom.

For a more detailed understanding of how the tidal currents behave with depth, the following plots representing tidal current velocity and direction can be studied:

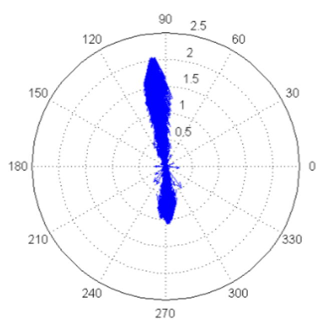


Figure 33: Velocity & Direction @ 12 m from bottom

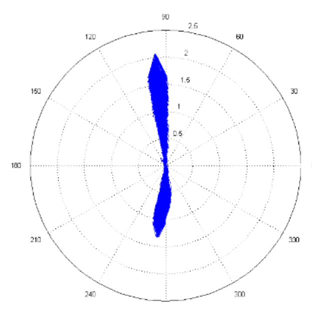


Figure 34: Velocity & Direction @ 7 m from bottom

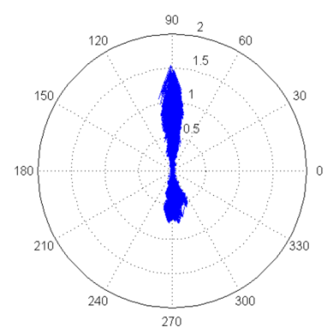
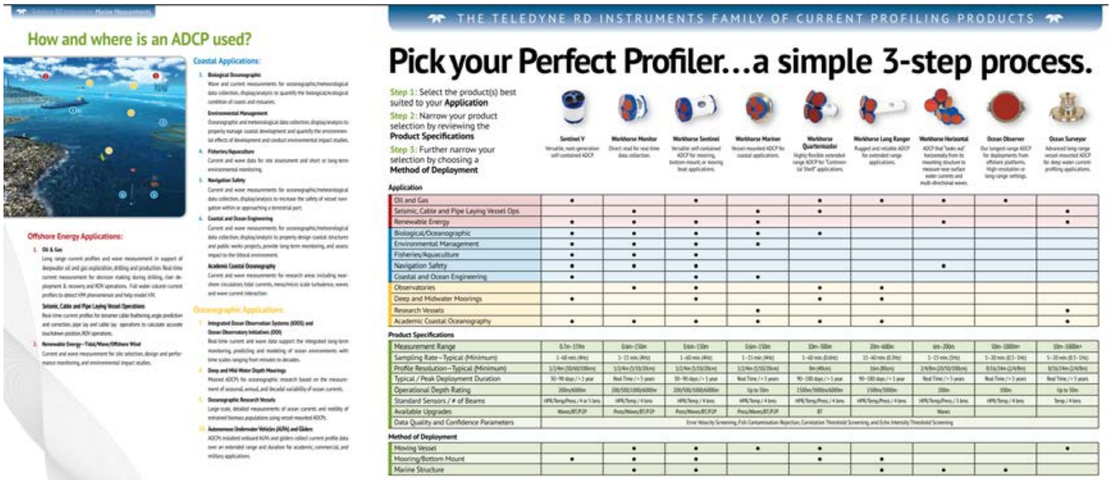


Figure 35: Velocity & Direction @2 m from the bottom

Appendix B – Teledyne Report



Appendix C – References

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