Tidal Turbine Deployment Platform: Seakeeping and Safety

University of New Hampshire

TECH 797 Undergraduate Ocean Research Projects 2015-2016

April 29, 2016

Team Members

Tyler Haddock – Mechanical Engineering

Peter Wingate – Mechanical Engineering

Undergraduate Assistants

Kaelin Chancey – Mechanical Engineering

Jamison Couture – Mechanical Engineering

Project Advisors

Dr. Martin Wosnik

Dr. M. Robinson Swift

Ian Gagnon

Sea Grant New Hampshire

Table of Contents

List of Figures and Tables

Abstract:

The “Living Bridge” project will transform the Memorial Bridge in Portsmouth, NH into a self-diagnosing, self-reporting smart bridge. To do this, the bridge will be instrumented with a suite of sensors and a tidal turbine will be installed in the estuary. The sensors will monitor both the structural health of the bridge and the estuarine environment. The tidal turbine will power the sensors using a locally available source of renewable energy. The turbine deployment platform (TDP) floats on the surface of the water and moors to the side of the bridge pier using two vertical guide posts that allow the platform to rise and fall with the tides. The objective of this project was to design and fabricate a 1:13 Froude-scaled model of the turbine deployment platform and bridge pier and use it to experimentally validate design loads for the full scale TDP. The scale model was tested in UNH’s wave/tow tank in the Jere Chase Ocean Engineering building. The mooring points between the TDP and the vertical guide posts were instrumented using two submersible load cells. The TDP was subjected to a range of towing velocities from 0.1m/s to 0.7m/s without the bridge pier, and towed at 0.6m/s while varying the bridge pier’s angle with respect to the towing direction. The platform was also tested in 0.058m high waves both perpendicular and parallel to the length of the TDP.

Background/Introduction:

The full scale Tidal Turbine installation project is a small part of larger "Living Bridge" Project taking place at Memorial Bridge. The objective of this project is to transform the bridge into a self-diagnosing, self-monitoring structure. The bridge construction process used state-of-the-art technologies (such as non-Gusset plates) and the designers are interested in understanding how they respond over time to various loads applied to the bridge. To obtain this data, sensors have been placed on various locations of the bridge and can record data such as bridge structural health information, sea levels, and tidal information. The Portsmouth harbor experiences relatively significant tides, thus a tidal turbine can be utilized to harness power from the tides. A short-term goal of the Living Bridge Project is therefore to deploy this turbine, which will likely be completed in the next year.

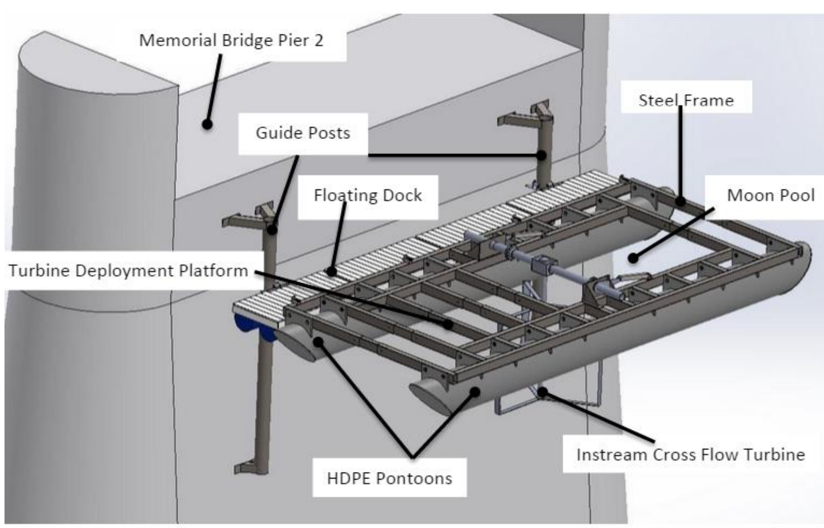


Figure 1- Full Scale Tidal Turbine Deployment Platform

Initially only the turbine deployment platform will be put in place. The geometry of the Piscataqua River dictates that the ebb tide currents are significantly faster than the flood tide, as the river narrows upstream of the bridge. An ACDP survey confirmed this, indicating the maximum expected current velocities are about 2.2 m/s on the ebb tide. As a result, the tidal turbine is positioned facing this direction, to maximize power generation. A SolidWorks image of the platform and turbine that will be fabricated can be seen on the previous page in Figure 1, with the important components are labeled. The year-long objective for our senior project was to complete a scale model analysis of the tidal turbine deployment platform.

Objectives:

Before the tidal turbine deployment platform is installed at Memorial Bridge, it is important to verify that it can withstand potential environmental conditions that it will be subjected to. The main objective of this project was to create a Froude-scaled model of the tidal turbine deployment platform and bridge pier to obtain various forces within the system. These forces were obtained by testing in the UNH Tow Tank, located in the Jere Chase Ocean Engineering Building. The goal of these tests was to simulate various environmental and human generated scenarios and experimentally validate the expected responses of the deployment platform. These tests will help to ensure that the prototype model (the full scale model that will be implemented at Memorial Bridge) can withstand all possible forces. This will be done by applying certain loads and wave motions to test the platform's response and obtaining the resulting mooring forces.

Design Process:

The first step of the project was to decide on a scale ratio to fabricate both the deployment platform and bridge pier. Both material and testing constraints limited the size of the scale that was chosen. It was important that the scale model was not too large; the UNH Tow Tank that was used is approximately four meters wide, so it was important that it would not be cumbersome to put both the platform and pier into place when testing. It was also important that the scale model was not too small; this was due to the method of Froude-scaling. When scaling from the prototype scale, it was very important to select a scale that allows one to obtain useful data from the scaled down model. Froude scaling was selected, as the flow within the system of interest involved the free surface. The Froude number is the ratio of inertial to gravitational forces, as shown in Equation 1 below:

$$Fr = \frac{U}{\sqrt{gL}} \tag{1}$$

The Froude number is a unitless value that keeps properties (length, mass, velocity, etc) comparable between the prototype (full sized model) and the scale model. The driving dimension when scaling was the outer diameter (O.D.) of the pontoons, because they interact directly with the free surface of the water. A scale range of approximately 1:7 to 1:13 was considered.

However, when Froude scaling, it was important to remember that different parameters scale differently. For as shown in Equation 2 below length scales linearly

$$L_R = \frac{L_m}{L_p} \tag{2}$$

where L represents length and the subscripts *m*, *p*, and *r* denote model, prototype, and ratio of the model to the prototype, respectively. However, mass scales cubically, as shown below

$$m_r = \frac{m_m}{m_p} = \left(\frac{\rho_m \bar{V}_m}{\rho_p \bar{V}_p} \right) = \left(\frac{\rho_m L_m{}^3}{\rho_p L_p{}^3} \right) = \left(\frac{L_m}{L_p} \right)^3 \tag{3}$$

Table 1 below shows some key dimensions and how they change in magnitude from full scale to model scale.

Table 1 – Various Turbine Deployment Platform Parameters for both the Full Scale and Model Scale

Prototype Scale			**1:13 Model Scale**	
Pontoon O.D.	1.07 m		Pontoon O.D.	0.83 m
Platform Length	12.3 m		Platform Length	0.95 m
Platform Width	6.77 m		Platform Width	0.45 m
Total Mass	11,022 kg		Total Mass	5.11 kg
Flow Speed	2.2 m/s		Flow Speed	0.6 m/s

From Table 1, the impact and difficulty of Froude-scaling can be seen more clearly; when dealing with smaller Froude-scale ratio's, it becomes increasingly challenging to find materials that not only satisfy the length-scale criteria, but also mass-scale criteria, etc. Because the O.D. of the pontoons were the driving dimensions, it was important to use a material for the pontoons that were lightweight. Therefore, cardboard tubes were used with an O.D. of approximately 0.83 m, a length of 1.06 m, and a mass of each pontoon of approximately 0.68 kg. This outer diameter ratio between the model scale and prototype scale solidified a 1:13 scale to follow. The cardboard tubes were donated to us by Hard Core Spiral Tube Winders Inc. in Brentwood, NH.

Next, the remaining hydrodynamically important components had to be considered, Froude-scaled, and a material selected. A pine plywood sheet was selected to represent the steel frame and decking; this was due to its incredibly lightweight but durable properties for both cutting a hole for the moon pool, as well for handling in the Tow Tank. When accounting for the mass of the steel frame, both the Thru-Flow decking material and railings were included in the mass. All Froude-scaled properties can be found in Table 2.

Table 2 – Froude-scaled steel frame parameters for both the full scale and model scale

Prototype Scale Steel Frame			**1:13 Scale Model Steel Frame**	
Frame Thickness	.25 m		Frame Thickness	.020 m
Frame Length	12.32 m		Frame Length	.95 m
Frame Width	5.79 m		Frame Width	.45 m
Moon Pool Length	5.95 m		Moon Pool Length	.46 m
Moon Pool Width	3.46 m		Moon Pool Width	.27 m
Overall Mass	4,333 kg		Overall Mass	1.97 kg

The Froude-scaled design for the turbine deployment mechanism (gearbox, brake, etc.) was based off of both SolidWorks images of the prototype model, as well as referencing the dimensions Instream cross-flow turbine currently in use in the Roza Canal within Yakima, Washington. An image of the cross-flow turbine being deployed can be seen in Figure 2 below.

Figure 2- Instream Cross-Flow Turbine in Roza Canal, Washington

Carbon steel of various shapes/lengths were selected to represent the turbine deployment mechanism. The rotor was simplified to a flat plate with the length scaled properties of the rotor. This simplification could be made because on the prototype model, when the turbine is rotating and generating electricity, the turbine reacts to the flow acts similar to that of a flat plate. An image of the design can be seen below in Figure 3a. These components were Froude-scaled and analyzed against failure for the expected Froude-scaled forces.

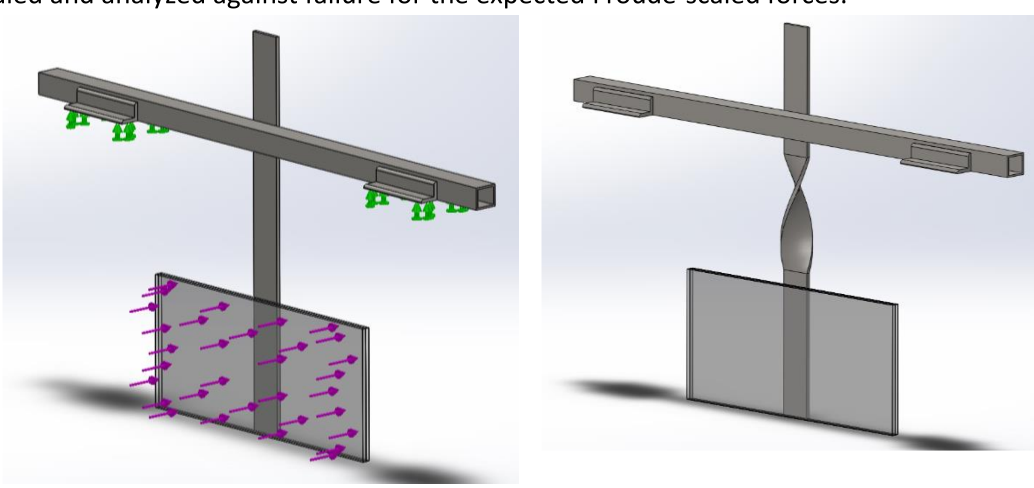


Figure 3a- Scale Model Turbine Instrumentation Subjected to Expected Forces,
Figure 3b- Optimized Instrumentation Design

It is important to note that when Froude-scaling the turbine deployment mechanism components, complex geometries could be simplified because they did not contact the free surface. This simplification could be made so long as the center of mass as well as the center of gravity of the entire turbine deployment platform did not deviate. A SolidWorks analysis was completed in order to both confirm that the materials chosen would not fail, as well as create a design to minimize the amount of deflection seen. When towed at the scaled down maximum channel velocity of 0.6 m/s, the components will not fail. The scale model instrumentation was optimized using SolidWorks Simulation in order to minimize deflection on the steel by twisting and stiffening the material. This optimization can be seen on the previous page in Figure 3b.

A table of Froude-scaled properties for the turbine deployment mechanism can be found in Table 2 below. The prototype model turbine that was fabricated for testing was the 2.5m x 3 m, although the turbine size that was tested is not completely guaranteed to be used underneath Memorial Bridge. The turbine at the 1:13 scale was represented through the use of a Lexan sheet, which is both stiff and lightweight to satisfy the length and mass-scaled criterion. An in-depth study of drag forces on flat plates were completed to ensure that the experimental Froude-scaled drag forces matches the predicted drag force values which can be seen in the Experimental Results section.

Table 3 – Froude-scaled Instrumentation Parameters for both the Full Scale and Model Scale

Prototype Scale Instrumentation			**1:13 Scale Model Instrumentation**	
Turbine Height	2.5 m		Turbine Height	.19 m
Turbine Length	3 m		Turbine Length	.23 m
Turbine Mass	590 kg		Turbine Mass	.27 kg
Instrumentation Mass	2,087 kg		Instrumentation Mass	.95 kg
Water Level to Rotor	.40 m		Water Level to Rotor	.031 m

In order to obtain accurate force readings from the scale model, it was important to ensure that the Froude-scaled rotor was submerged the proper distance. Otherwise, the overall center of mass of the scale turbine deployment platform would have a completely different response when subjected to current and waves. It is known after Froude-scaling the prototype that the scaled turbine needs to be .031 m below the water. The buoyancy force of the entire turbine deployment platform must be considered in order to fabricate the instrumentation to guarantee that the turbine will be in the proper location. The buoyancy force was found using the equation

$$F_b = V * \rho * F_g \tag{4}$$

Where V is the volume of the pontoon, ρ is the density of the working fluid, and F_g is the gravitational force. By comparing the gravitational force to the buoyancy force, it can be confirmed that the scale model turbine deployment platform will float. In addition, through the use of the buoyancy force, it was determined that the pontoons from the weight of the platform and instrumentation submerge about 55 mm below the water level. Figure 4 below shows the various portions of a circle segment. Using this figure as well as the equation

$$r = \frac{1}{2}\sqrt{4R^2 - a^2} \tag{5}$$

Where "r" is the difference between the radius of the pontoons and the depth of the submerged pontoons. The "a" term was then solved for in order to accurately measure the proper location of the turbine. Using this, the turbine was fastened such that the water level is 5.5cm away from bottom face of the plywood. Figure 5 below shows the final design for the 1:13 Froude-scaled tidal turbine deployment platform. To restrict the motion of the simplified turbine design, clevis pins were connected. This prevented the turbine from moving from side-to-side when subjected to a drag force. In addition, zip ties not shown in the image below were added in order to fasten the cardboard tubes to the wooden frame. These zip ties also help the model replicate the prototype as they trip the boundary layer at the same location is it tripped on the prototype. At this point the boundary transitions from laminar to turbulent.

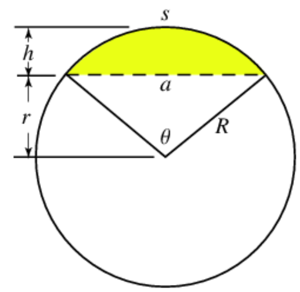


Figure 4- Circle Segment Geometry

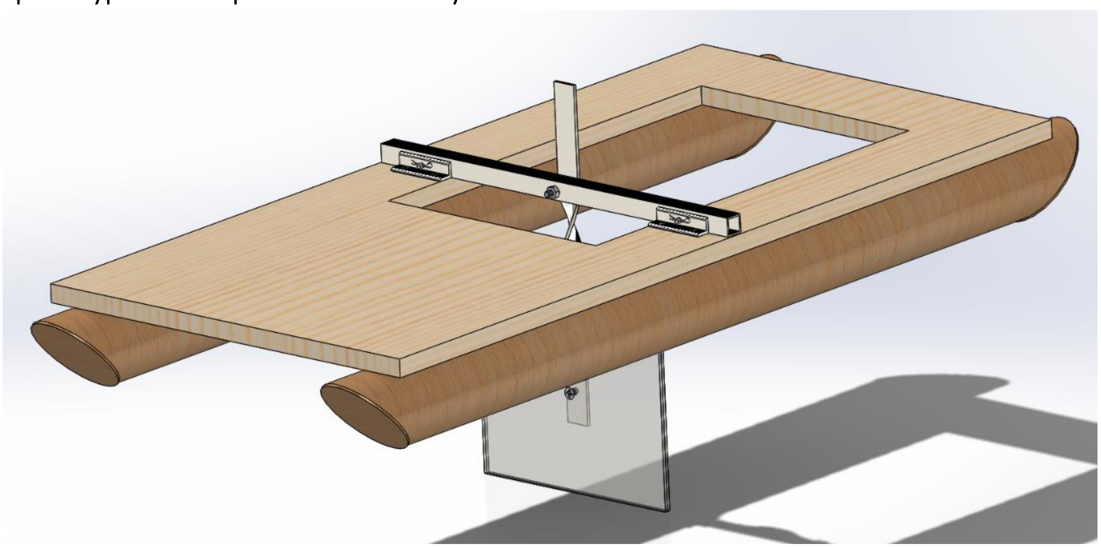


Figure 5- Froude Scaled Model of Tidal Turbine Deployment Platform

When designing the bridge pier, it was only important to length scale because the pier is treated as a fixed body since at full scale it is an immovable structure. Additionally, the pier was included to obtain information about the flow around the edges of the pier (in particular the fenders), thus the forces on the pier are not important and will not be considered. At its widest, the pier was 1.78 m long, 0.76 m wide and approximately 1.1 m tall excluding aluminum extrusions. The model pier was made using ¾" Dryply plywood, pressure treated 2x4s corrugated plastic and 80-20 aluminum extrusions. The plywood was used as footprints for each layer of the pier, to help define the shape. Each layer of plywood was treated with three coats of polyurethane to ensure its longevity. The pressure treated 2x4s helped provide support behind the corrugated plastic screwed to the outside edges of the plywood. Each plywood layer mounted to the two 80-20 extrusions. The aluminum extrusions were used in order to adjust the water level seen by the pier from the top of the tow carriage. By clamping the extrusions at different heights, one could accurately test mooring forces at both high water and low water levels. These 80-20 extrusions were then mounted to a rotator. This rotator allowed the model pier to be tested at varying angles of attack with respect to the flow. The angle of attack was adjustable and range from -5º to 5º in 5º increments. This was done because previously collected ADCP survey data indicates the maximum angle of attack to be ~5º.

Figure 6- Froude scaled Model of Bridge Pier in Progress

The rotator was originally made out of a turn table with a piece of ¾" Dryply plywood mounted to each side. In practice this turn table caused the pier to wobble in the water and therefore was taken out of the design. Attached to all sides of the pier were metal fenders to help protect it from possible boats collisions. These fenders were modeled with ¼" plywood treated with three coats of polyurethane. The joint connecting the model fender plate to the model pier was modeled using a cut to shape pressure treated 4x4. Figure 6 shows the pier during the building process. In addition to current elements of the pier being modeled, the guide posts and brackets were modeled using 1" diameter aluminum piping and 4x4s. The model guide posts extended from the top of the model pier vertically downward. To attach the model guide posts, a 4x4 block was attached to the model pier with a 1" diameter whole through it, the guide posts were then placed through this whole and a metal collar was attached above and below the whole. To also prevent the guide posts from rotating within the 4x4, a screw was driven through the 4x4 and into the aluminum tubing. For purpose of public relations, the model was color coated to show the different elements. The model pier, any concrete element, was painted white, the model fenders were painted grey and elements to the added to the pier, the guide rod brackets, were painted black. Markings were also placed on the side of the pier facing the model deployment platform to portray the different water levels the Piscataqua River experiences as the tides change throughout the day. This can be seen below in Figure 7.

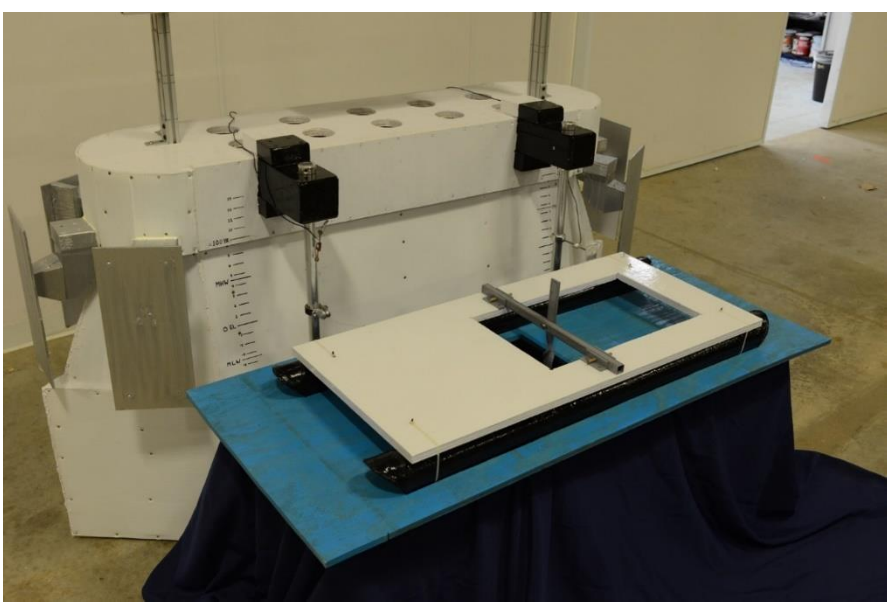


Figure 7- Fabricated 1:13 Froude-Scaled Turbine Deployment Platform and Bridge Pier

The fenders were adjusted to match the surface roughness of the fenders on the bridge pier. When modeling the fenders, plywood was used. This was then spray painted grey, as can be seen in Figure 7 above. This surface roughness did not quite match the surface roughness of the prototype. To match the surface roughness of the prototype a number of steps had to be taken. First the Reynolds number of the prototype was be determined. The equation for Reynolds number is

$$Re = \frac{V*L}{v} \tag{5}$$

Where *V* is the velocity of the flow, *L* is the characteristic length of the turbine, and *v* is the kinematic viscosity of the medium, in this case water. The Reynolds number is the ratio of inertial forces over viscous forces. For the prototype, the maximum velocity is 2.2 m/s, the length is 2.1 m and the kinematic viscosity is 1e-6 m^2/s, which is the kinematic viscosity of salt water at 30 ppt and 10°C. This results in a Reynolds number of 3.42 x 10^6. Next, the location of the transition to turbulence for the prototype had to be determined. This can be found using the equation

$$\delta(x) = 0.37x(\frac{u_p x}{v})^{\frac{-1}{5}} \tag{6}$$

where $\delta(x)$ is the location of the transition to turbulence, u_p is the maximum velocity, x is the characteristic length, and v is the kinematic viscosity. All parameters remain the same values as above, which results in a location of 0.038 m. Next, the relative roughness ratio can be found.

$$\frac{k}{\delta} = \varepsilon \tag{7}$$

δ was determined above and k can be found in an equivalent roughness table. For the bridge pier fenders, it was estimated to be about 0.3 m. This results in a relative roughness ratio of 0.00782. A pipe friction chart (found in the Appendix) can then be used to find an equivalent roughness ratio for the model scale. Next, the parameters for the model scale can be found. The Reynolds number can be found using the Froude-scaling factors discussed above, for a 1:13 scale the equation is

$$Re_{L\,model} = Re_{L\,full} * (\frac{1}{13})^{3/2} \tag{8}$$

This results in a value of 73,640, which is too low, meaning the boundary layer must be tripped. As discussed above, the zip ties connecting the pontoons and the platform accomplish this. Next, the model location of the transition to turbulence can be found. Using the same equation as above, with the model parameters, this can be found to be 0.00640 meters. Based on the pipe friction chart, ε can be assumed to be 0.067. Knowing this, the equivalent roughness k must be determined to match the prototype. Using equation 7 above, with ε equal to 0.067 and δ equal to 0.0064, k can be found to be 0.0043 meters. Comparing this to an equivalent roughness table, this is somewhat rougher than one would expect from a coat of paint, as was used on the fenders. Therefore, 80-grit sand paper was used to roughen the model fenders to match those of the bridge pier. This was done vertically, transverse to the oncoming waves.

Experimental Set-up

All tests required the use of the UNH Tow Tank within the Jere Chase Ocean Engineering Building. The tow tank used has a length, width and depth of 36.6 m, 3.66 m, and 2.44 m, respectively. The towing carriage, which allows for both attaching the scale models and allowing towing tests, can be seen in Figure 8a. The scale model pier connected to the tow carriage through an aluminum extrusion that stretched the length of the carriage. The pier was then clamped to the carriage based on the particular water level that was being tested. The mass of the scale model bridge pier made it difficult to get in and out of the UNH Tow Tank; therefore, the crane system was used to lift the pier into and out of the tow tank. The process of raising the bridge pier into the water can be seen below in Figure 8b.


Figure 8a- UNH tow carriage, **Figure 8b-** Procedure for lifting scale model pier into tow tank

The scale model turbine deployment platform was moored to the pier through the use of two 10 lbf Futek S-beam submersible load cells, seen in Figures 9a and 9b. One load cell measured the mooring forces in tension, while the second load cell measured the compression. These load cells were chosen due to their availability and the magnitude of our expected forces. As shown in both figures, the load cells were mounted onto the length-scaled pier in order to avoid impacting the Froude-scaling of the turbine deployment platform. In Figure 9a, one can see that the tension load cell was connected to the structure holding the guidepost in place, and connected to the deployment platform using fishing wire. The fishing wire passed through a pulley to change its direction to prevent creating additional forces in the upward direction. The pulley was welded to a collar which could be adjusted based on the water level that was being used for testing. Figure 9b shows the set-up for the compression load cell. Similar to the tension load cell configuration, the load cell is connected to a collar which can be adjusted based on the water level. The load cell was placed such that when the turbine deployment platform was subjected to forces, the back of the platform would make contact with the metal plate, obtaining a compression value.

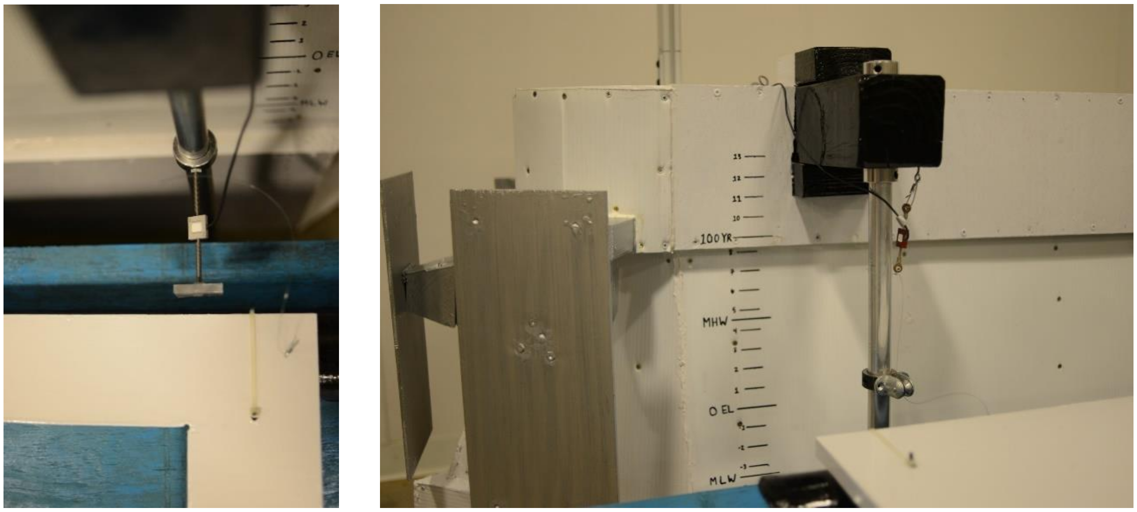


Figure 9a- Compression Load Cell Set-up, **Figure 9b-** Tension Load Cell Set-up

To record the load cell reading in real-time, the load cell was connected to an NI RJ50 Screw Terminal. The load cell wires contain five outputs which connect to the Screw Terminal. These outputs were screwed in to ensure a strong connection. The other end of the NI RJ50 cable connects to the NI 9237 Module of the data acquisition (DAQ) system case located on the tow carriage. This can be found in Figure 10. Both the tow tank and DAQ must be turned on to move the tow carriage and obtain data.

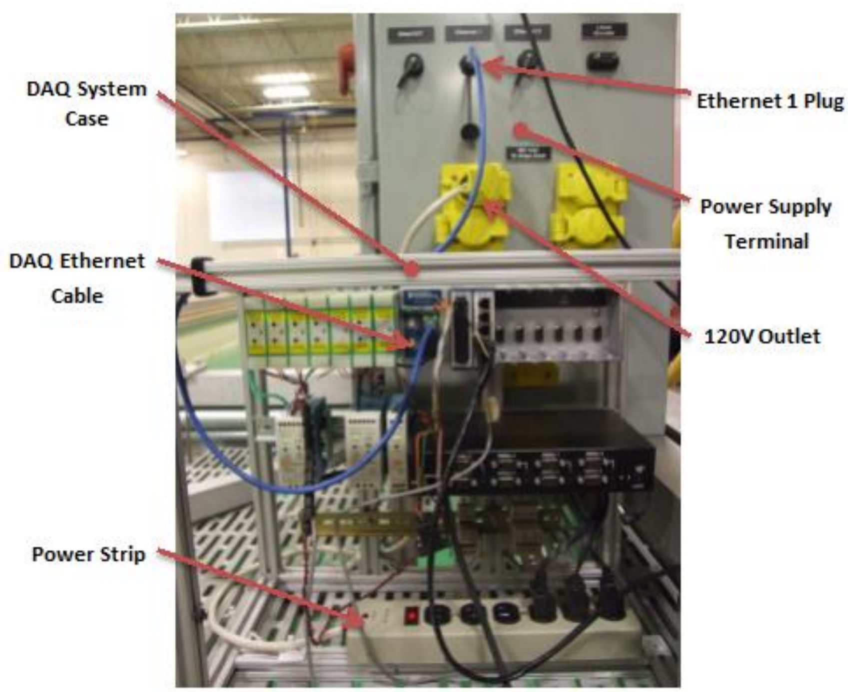


Figure 10- Connected DAQ System Case

LabVIEW was used to obtain drag force data from the NI 9237 Module. To do so, a program called NI MAX can be used. NI MAX scans to the DAQ system for inputs such as load cells or a wave staff. After scanning with NI MAX and changing the input from the NI 9205 Module (for analog signals) to NI 9237, data could be collected. A previously existing LabVIEW program called Tow Tank DAQ.vi was used. Each test result used a different experimental set up. Although the general set-up description has been given, a more specific set-up for each test can be found with the Experimental Results section.

Experimental Results:

Before testing the mooring forces between the scale model turbine deployment platform and bridge pier, several steps were made to ensure that the forces that would be obtained would accurately reflect the prototype scale. The first step of the experimental process involved calibrating both the tension and compression 10 lb_f load cells in order to confirm that the forces that were being read were accurately. Therefore, various weights with known masses were connected to the load cells. The outputs that were obtained using the NI DAQ and LabVIEW were compared to the known masses in order to create a calibration curve. The tension and compression calibration curves can be seen below in Figures 11 and 12. These calibration curves confirm that the readings from the load cells were not exact. However, the calibration curve equations derived allow us to convert all load cell forces read into exact force readings. As seen below in Figure 11, the tension load cell reading had to be offset by approximately .1 lbf, (or .45 N).

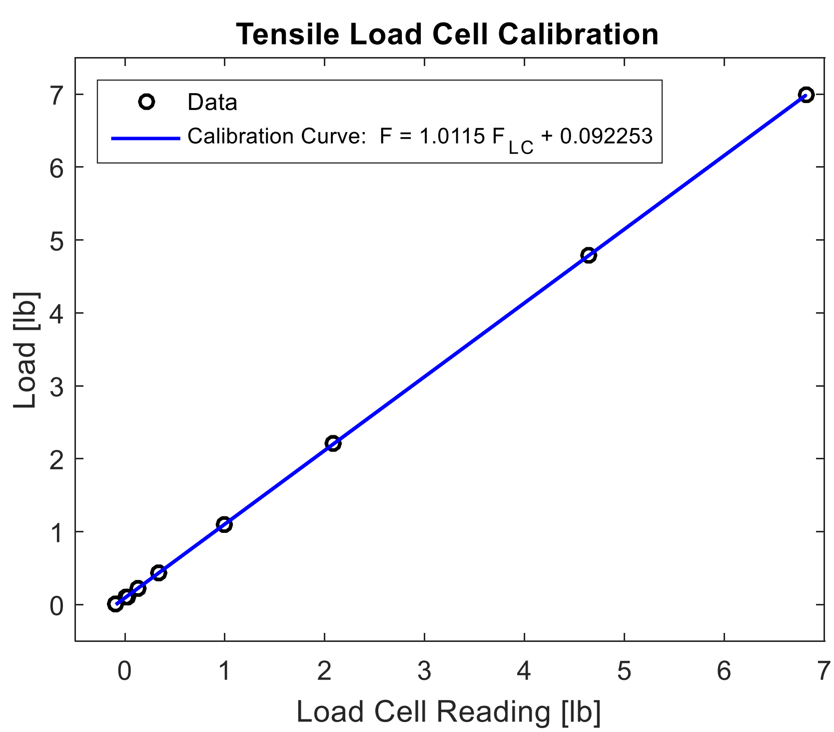


Figure 11- Tension Load Cell Calibration Curve

Similarly, in Figure 12 the compressive load cell calibration curve revealed that the force obtained by the load cell needed to be offset by approximately .1 lbf, (or .45 N).

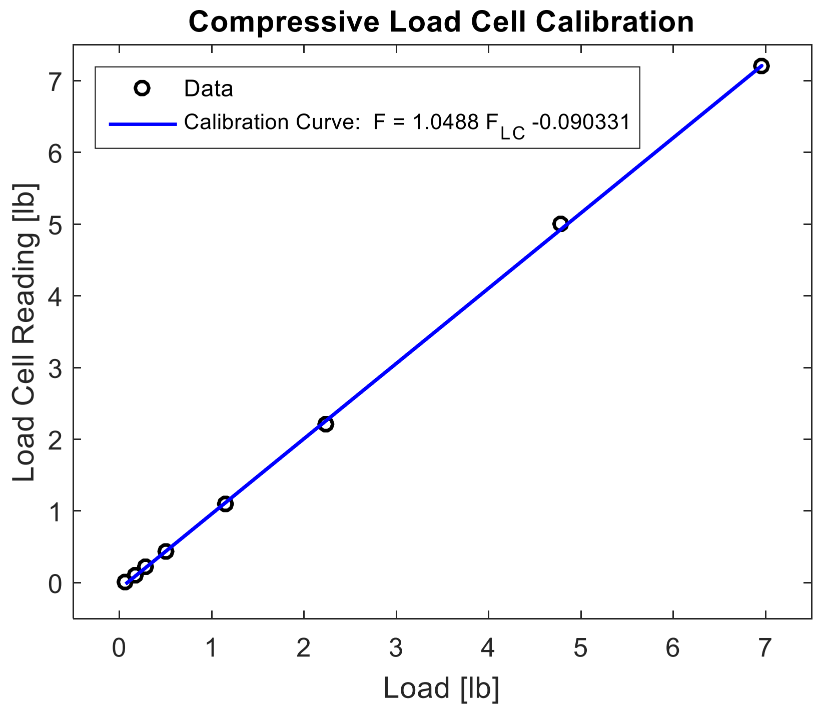


Figure 12- Compression Load Cell Calibration Curve

Prior to testing the mooring forces between the scale model tidal turbine deployment platform and bridge pier, it was important to ensure that the expected drag forces could be obtained from the various components of the scale model. Specifically, tests were done in order to confirm that the drag force on the flat plate would be comparable to that of the drag force of the actual complex turbine. This was completed by calculating the theoretical drag forces on two different sized flat plates and comparing the values to experimental results obtained in the UNH Tow Tank. A schematic of the set-up is shown in Figure 13 below.

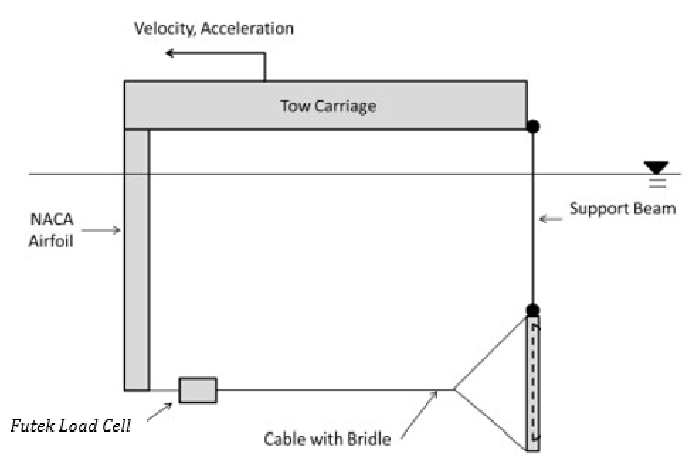


Figure 13- General Test Setup- Analyzing Drag Forces on Flat Plates

The experimental set-up included a hydrofoil arm, a 10lb$_f$ submersible tension load cell, various flat plates, and a supporting shaft, connected as shown in the figure. The system that is being analyzed is a hydrofoil arm connected to a flat plate in which drag forces are measured off of using a load cell. When determining the turbine to obtain an appropriate drag force the Reynolds number must also be taken into account. Froude scaling is automatically satisfied if an object to represent the scale model turbine has the right shape/material and the Reynold's number exceeds 10,000. When this true, the drag coefficient is no longer a function of the Reynold's number and come secondary to the Froude number. The equation for Reynolds Number is given above in Equation 5. Using the following parameters for the model scale turbine, L = 0.23 m, V = 0.6 m/s, v = 1e-6 m^2/s, it can be determined that the Reynolds number is 138,000. With a Reynolds number this large, it is assumed we will have turbulent flow, and the viscosity becomes unimportant. With a Reynolds number this high, the drag force equation can be used to determine the coefficient of drag or the drag force, depending on what is known. The drag force equation is

$$\frac{1}{2}\rho V^2 A C_D = F_D \tag{9}$$

Where ρ is the density of water, V is the velocity at which the flat plate is being towed at, and A is the area of the flat plate, C_D is the drag coefficient, and F_D is the drag force. In this form the equation can be used to theoretically predict the expected drag force on an object, when knowing ρ, V, A, and C_D for the object under the expected towing conditions. ρ, V, and A can be determined by knowing the material properties and selecting a velocity at which to tow the object. C_D for a flat plate can be found using Figure 14 below.

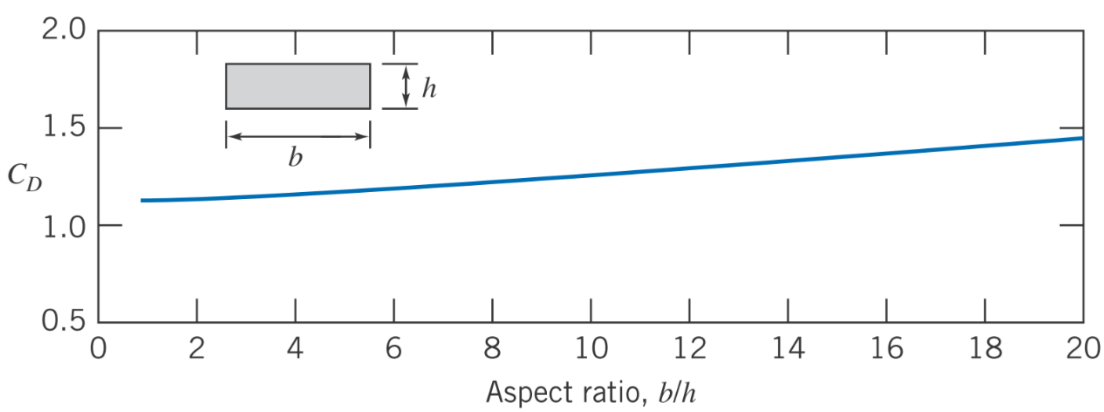


Figure 14- Variation of the Drag Coefficient with Aspect Ratio for a Flat Plate Normal to Flow

By knowing the aspect ratios (b/h) for both plates tested, C_D was determined and substituted into Equation 9 to obtain an expected (analytical) drag force. Equation 9 can also be re-arranged into the following form to solve for C_D when F_D is determined experimentally

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} \tag{10}$$

In this case, ρ, V, and A are known as before. Additionally, F_D has been experimentally determined, through the use of a load cell. Thus C_D can be found and compared to the expected C_D obtained from Figure 14. Likewise, the drag force read by the load cell can be compared to the force drag predicted analytically by Equation 9.

Three tests were run on both a .15m x .15m steel sheet and a .11m x .23m Lexan sheet. They were run at speeds of 0.3 m/s, 0.4 m/s, and 0.5 m/s. Each test was repeated in order to verify the accuracy of the test. The tow carriage pulled the plates from left to right (when viewed from control deck) for 15 meters. After traveling 15 meters the carriage slows down and comes to a complete stop. Figure 15 shows a typical force versus time plot obtained from LabVIEW for the steel sheet, at a tow speed of 0.3 m/s. The general trend of the plot seen in Figure 15 is expected. The transient response is obtained when the tow carriage accelerates, and the steady state value can be seen from approximately 10-50 seconds once the carriage has reached the testing velocity.

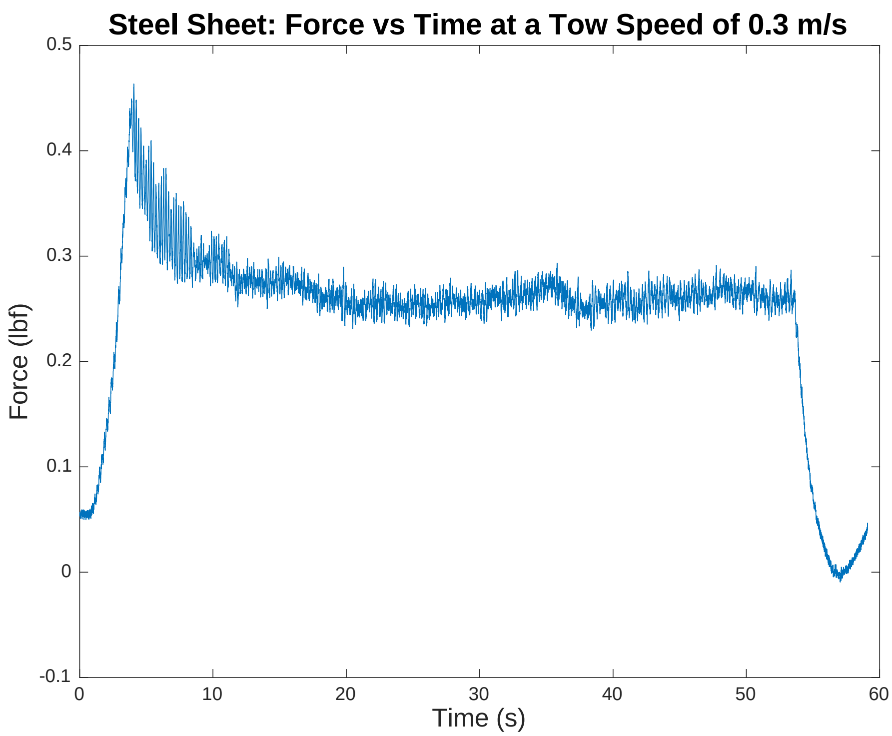


Figure 15- Standard Force vs Time Plot, Steel Sheet

The table of theoretical versus experimental results for both flat plates can be seen below in Table 4. As shown, the experimental values match what is expected theoretically. Therefore, tests involving the rest of the turbine can continue.

Table 4– Drag Forces (Experimental and Analytical) for each Tow Speed

Tow Speed (m/s)	**Steel Plate (.15m x .15m)**		**Lexan Sheet (.11m x .23m)**	
	Theoretically Predicted Drag Force (N)	Experimentally Measured Drag Force (N)	Theoretically Predicted Drag Force (N)	Experimentally Measured Drag Force (N)
.3	1.16	1.20	1.29	1.20
.4	2.05	2.18	2.27	2.14
.5	3.20	3.36	3.60	3.56

It is important to note that all experimental values shown in the tests completed below are expressed in prototype scale. Before conducting experiments, it was important to develop a test matrix with objectives for what was to be tested. The test matrix used, along with the values obtained can be seen in the Appendix. Two types of tests were conducted: Drag force towing tests and wave loading tests. The first and second tests were drag tests, while the third was a wave loading test. The first drag test, validate the model was scaled correctly. The second and third tests help simulate potential resultant forces for the prototype.

It was also important to derive analytical models for each type of test to validate the experimental results. Several assumptions were made to simplify the analysis. First, the turbine was modeled as a flat plate both analytically and experimentally. This is a safe assumption, as at fast rotational velocities the coefficient of drag for the turbine is nearly the same value as for a flat plate with the same dimensions. This mean it appears as a flat plate to the oncoming flow. The second assumption, made analytically, was that the pontoons were fully submerged during the experiments. This a safe overestimation, as in practice the pontoons are only about half submerged. The frontal faces of the pontoons are also analytically modeled as perpendicular to the oncoming flow (similar to cylinders in the flow), when in reality they have been designed at the prototype scale with a 45^o angle. Again this is a safe assumption as it should result in an overstated expected drag force. However, both assumptions for the pontoons are fairly minor, as the turbine domains the total expected drag force. When evaluating experimental drag results, they were compared to a 2D analysis of the system, as shown below in Figure 16.

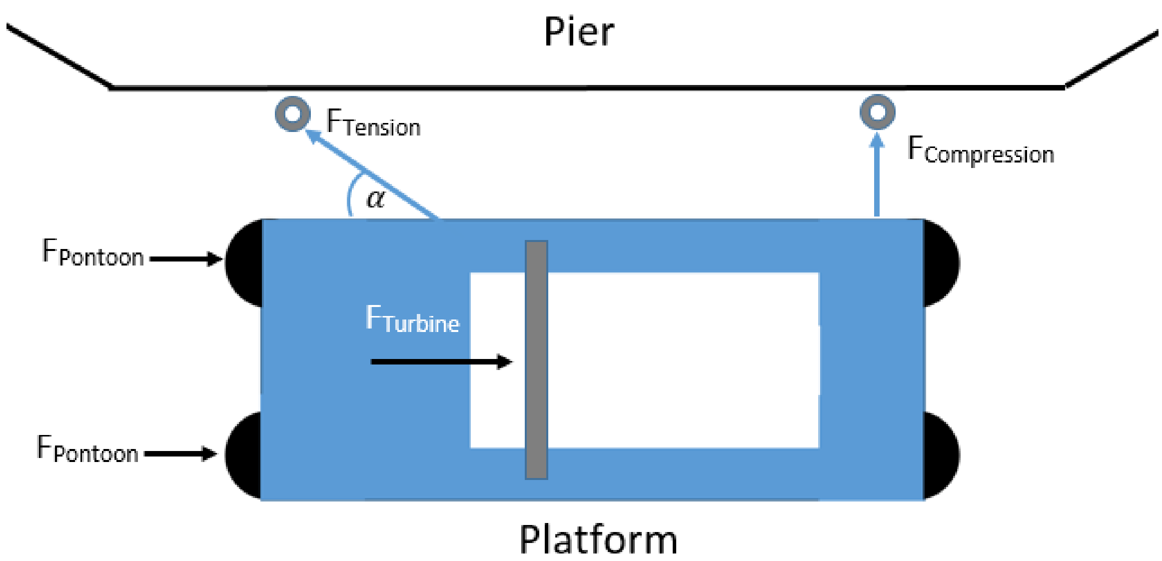


Figure 16- 2D Platform Model used for Analysis

The experimental results were compared to analytically expected results using the drag force equation, Equation 9, where F_D is the expected drag force, ρ is the density of the working fluid (water), C_D is the drag coefficient, A is the frontal area, and v is the velocity of the working fluid. The expected drag force is the sum of the drag force on the pontoons and the drag force on the turbine. In the analytical analysis, ρ was assumed to be 1000 kg/m^3. The turbine was modeled with a coefficient of drag of 1.2, while the pontoons were modeled with a coefficient of drag of 0.82. The derivation for the drag coefficient used for the turbine is discussed above while the C_D for the pontoons was taken from the prototype, as the hydrodynamic similarity between the two models allows the same drag coefficient to be used. The frontal area value for the turbine was simply the base multiplied by the height, as it appears as a flat plate to the oncoming flow. As discussed before, the pontoons are modeled as cylinders with a flat face perpendicular to the flow. This means the frontal area is πr^2.

The first test conducted was a single point tow test, which involved towing of the platform. This was an important test, as it would verify that the model had been Froude-scaled correctly. The platform was towed from 0.1 m/s to 0.7 m/s at the model scale. These tests were completed in 0.1 m/s increments. Once 0.7 m/s tests were completed, previous tests were completed again to ensure that the drag forces obtained were accurate. Using the analytical values discussed, an expected drag value can be obtained for each of the seven tow velocities. A typical force reading response using one submersible tension load cell connected to the front of the platform can be seen in Figure 17 on the next page. As shown, the tension reading oscillates while the tow carriage accelerates, these oscillations lessen in magnitude as the carriage reaches the velocity of interest. Once steady state was reached, the data could be analyzed. It is important to note that the LabVIEW forces have been scaled to the prototype.

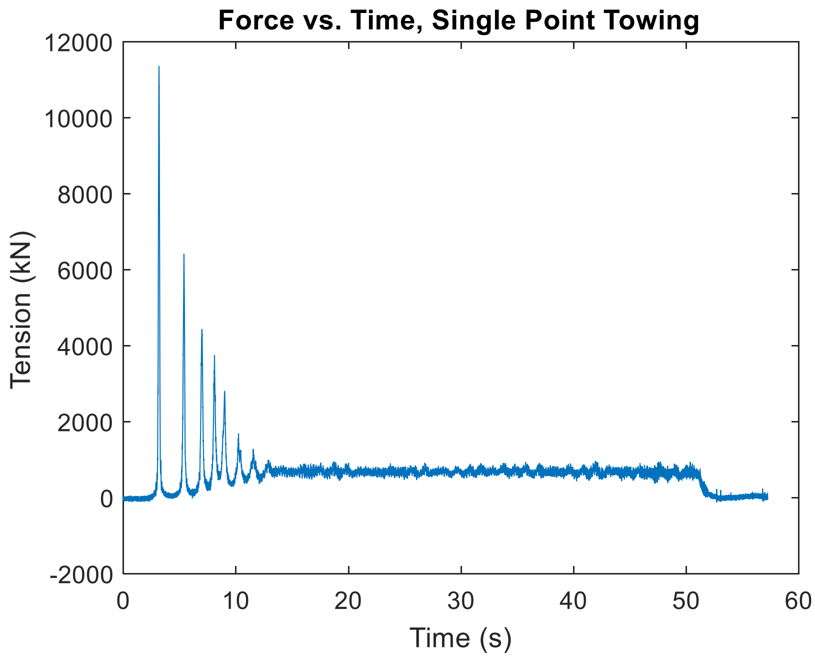


Figure 17- Typical Force vs. Time Plot Obtained with LabVIEW, Single Point Towing

Figure 18 plots the theoretical and experimental values on a single plot. The theoretical line was derived based on the previously stated equations and assumptions. As can be seen, the values correlate quite well, indicating the model was Froude-scaled correctly, as the coefficient of determination (R^2) is 99%. The experimental values should be slightly lowered than the theoretical values, as the theoretical analysis deliberately overestimated several parameters. In the plot, the values are scaled back up to the prototype scale.

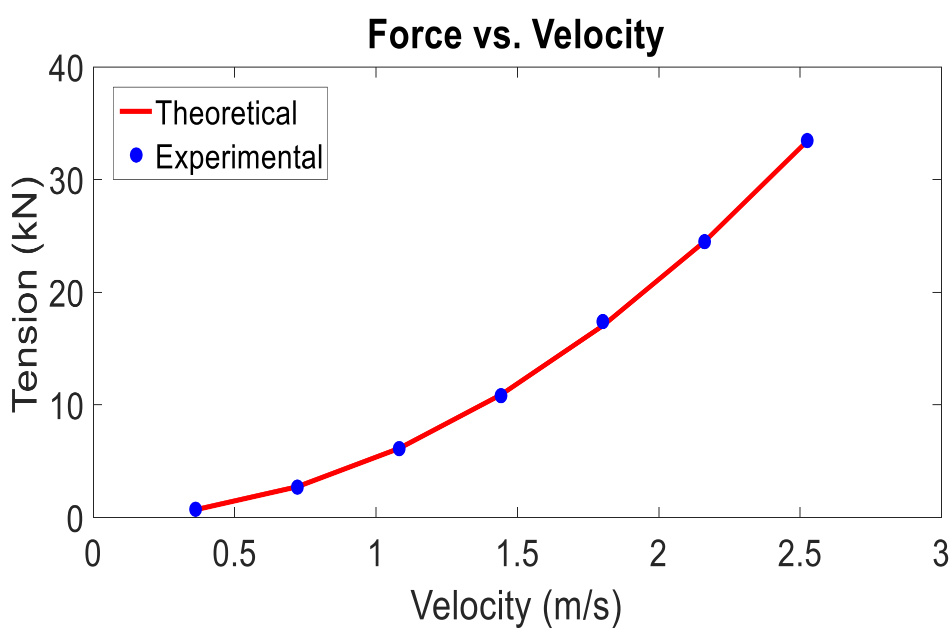


Figure 18- Experimental and Theoretical Force versus Velocity

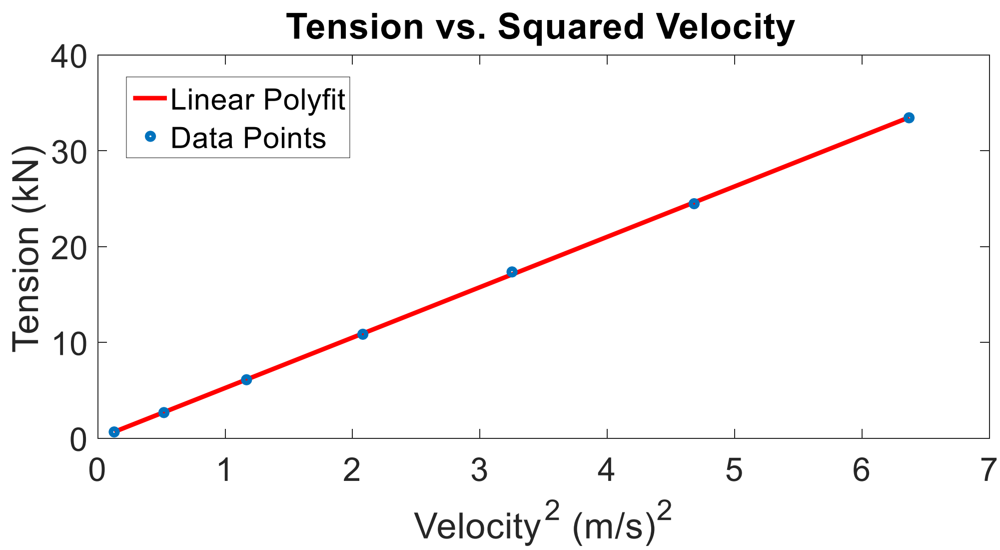


Figure 19- Tension vs. Velocity Squared at Various Flow Speeds

Another confirmation that the Froude-scaling process was completed properly can be seen above in Figure 19 in the force vs. velocity squared. The experimental data points obtained follows a linear trend as shown by the linear polyfit. From here, more complex tests can be completed; such as tests that involve the pier and wave tests. This is because we are extremely confident that the Froude-scaling was completed accurately and that future test results can be applied at the full scale for comparison to design criteria.

The next drag force test, compared angle of attack to measured drag force. In this test both the platform and pier were in the tow tank, and analyzed using the diagram in Figure 16. The angle alpha was measured to be 35^o using a protractor and confirmed using video taken from GoPro cameras mounted on the tow carriage. The compression values read by the compression load cell were compared directly to the analytical compression values, while the analytical tension values were divided by sine α (from Figure 15) to compare them to the read tension values.

Three angles of attack were used: -5^o, 0^o, and 5^o. This test was done only at the maximum expected current (2.2 m/s prototype). A typical angle of attack at 0^o plot is shown below in Figure 20. As the tow carriage accelerates, the tension and compression load cells read increasing values. Once the full desired velocity is reached, the system approaches steady state. Of interest is the slight decline in magnitude recorded by both load cells during steady state. As the tow carriage slows down the magnitudes of the forces decrease. The plots for -5^o and 5^o look similar, with different magnitudes. At each angle, four tests were run and the experimental value shown in Table 5 is the average of these. Table 5 compares the experimental and theoretical tension and compression values at all three angles of attack.

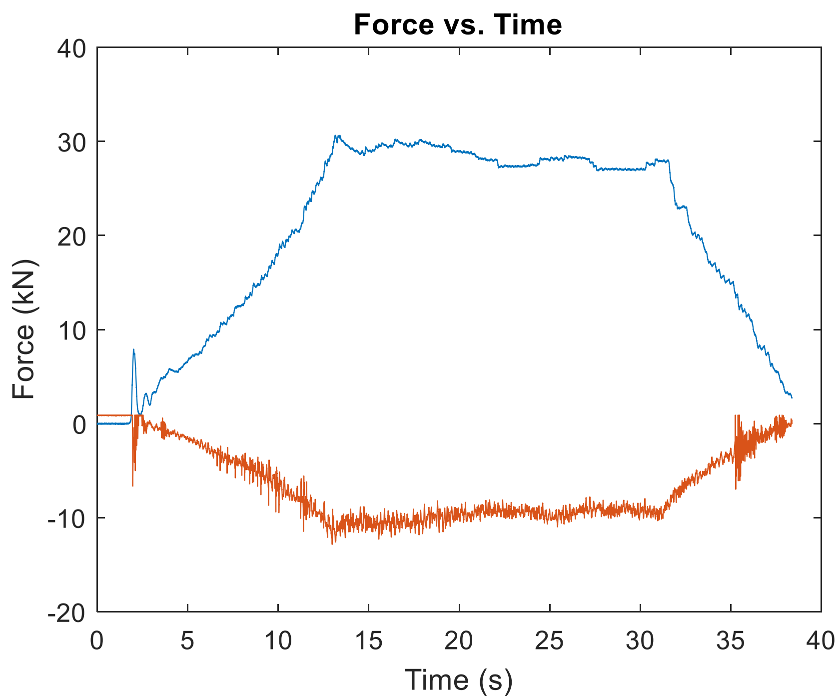


Figure 20- Force versus time at 2.2 m/s and 0^{o} angle of attack

Table 5- Force vs. Angle of Attack with a 2.2 m/s Current

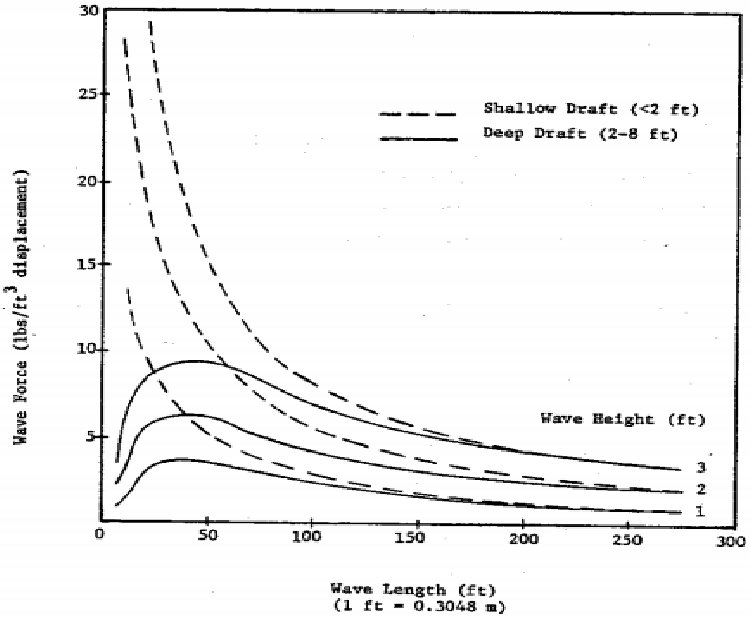
Angle of Attack	Tension		Compression	
	Experimental (kN)	Theoretical (kN)	Experimental (kN)	Theoretical (kN)
-5^{o}	28.1	33.4	-11.1	-13.7
0^{o}	27.9	33.6	-12.0	-13.8
5^{o}	25.9	33.4	-11.5	-13.7

As can be seen from the table, the theoretical values are somewhat higher than the experimental values. This makes sense, as there were a number of overestimations used when modeling the system analytically. Additionally, the system was modeled as 2D when the real system obviously has some forces in the Z-direction (vertical) which are unaccounted for in the 2D model. The model also does not take flow distortion from the fenders and pier into account.

Another topic of interest for the prototype model being deployed underneath Memorial Bridge is how it will fare when subjected to wave loading. These tests are important because the channel between the turbine deployment platform and the next bridge pier is approximately 30m long. This sized channel allows for smaller boats to drive between them, creating waves that could potentially have a significant impact if not considered when designing. Thus it is important to know how the platform responds to various wave loadings and conditions. The first test considered involved placing the platform and pier parallel to the flow. This was the same configuration as the previous drag tests. The wave maker at the back of the UNH Tow Tank was used to create a fixed wave height of 5.8 cm model scale (which is .75 m heights prototype scale). A picture of the UNH Tow Tank created waves with the wave maker can be seen below in Figure 21. While the height of the waves remained constant, the wavelengths varied in order to observe the response from the scale turbine deployment platform.

Figure 21- UNH Tow Tank using Wave Maker

The main interest of this test was to determine if the experimental results that were obtained in the Tow Tank would match the theoretical analysis of what forces should be expected on the prototype scale. When designing the prototype, Figures 22a and 22b were used together as a reference to derive the forces that could be expected. Figure 22a was used in order to determine the wave force expected based on the prototype scale wave length. For this system, the interest is in the deep draft curves. Figure 22b was used to find an adjustment factor (which is a percent value) based on the ratio between the body length of the turbine deployment platform and the wavelength. Both the adjustment factor, and expected wave force from the two figures were multiplied by a constant displacement force of approximately 355 ft^3. Using the tables for each wavelength of interest, a theoretical curve for the full scale model could be created.



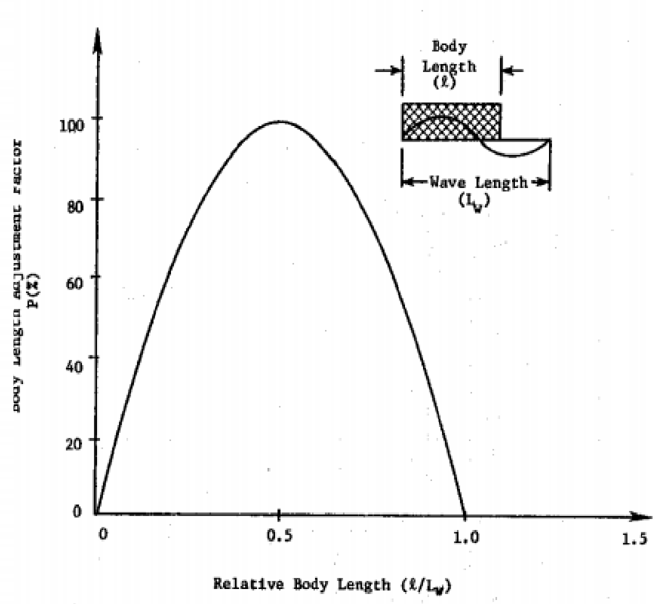


Figure 22a- Horizontal Wave Force on a Floating Object,
Figure 22b- Wave Force Adjustment for Relative Body Length

Mooring forces were then obtained experimentally in the UNH Tow Tank at the various wavelengths. Two Go-Pro cameras were used to capture the behavior of both load cells for the duration of each wave loading test in order to later understand why possible forces were obtained when observing the LabVIEW data captured. Between all tests, it was important to wait several minutes until the water settled to run the next test. This allows the beach located at the other end of the tow tank to absorb the force of the waves, settling them. An example of the type of data captured from the wave loading tests can be seen in Figure 23.

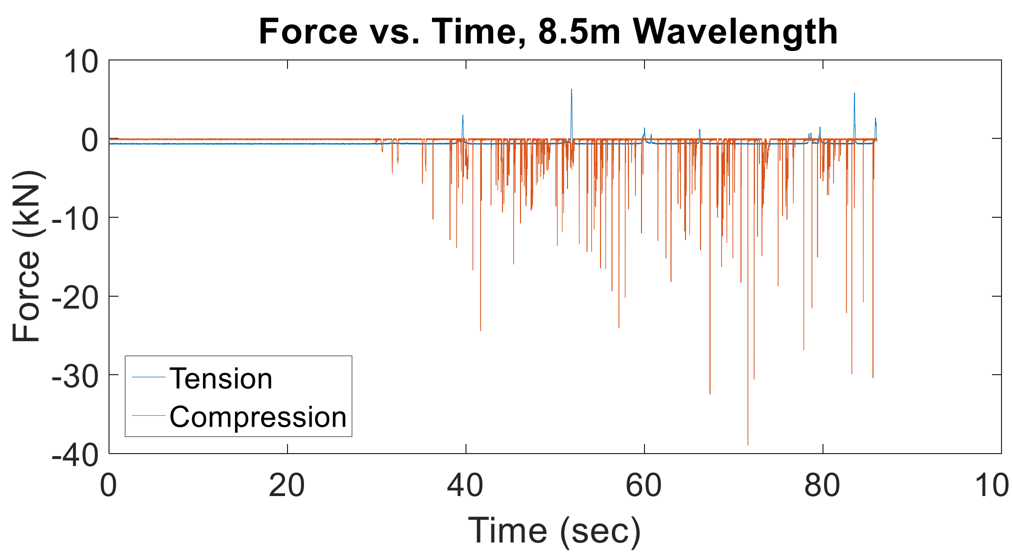


Figure 23- Force versus time, at an 8.5 meter Wavelength

As shown in Figure 23 above, the scale model turbine deployment platform and bridge pier were subjected to waves that have equivalent to 8.5 m wavelengths on the prototype scale. The forces that were obtained through LabVIEW are also expressed with prototype scale values. At this wavelength, there was a high level of compressive forces in the system. The spikes seen for both tension and compression values indicates that there was an impulse on the platform due to wave loading. The Go-Pro footage from all tests allowed us to track why certain spikes occurred in various places. Through various trials, large data spikes would occur primarily from the compression load cell. After video playback, errors that occurred in certain circumstances included the platform getting stuck either on top or underneath the compression configuration, creating a torque on the load cell. For future tests, preventative measures were taken in order to ensure that no damage was done to the load cell by shutting down the wave maker and manually moving the platform out of harm's way in those scenarios.

The experimental and theoretical forces can be seen plot against wavelength below in Figure 24. The wavelengths of interest were obtained from the prototype scale. The tested wavelengths were spaced out evenly along the theoretical curve, with the exception of 70 m wavelengths because that wavelength produces a frequency close to the natural frequency of the wave maker. The plot indicates that the mooring configuration could not accurately capture the experimental data. The two curves do exhibit similar shapes and trends however. The magnitudes of the mooring forces however are off by approximately 5 kN overall.

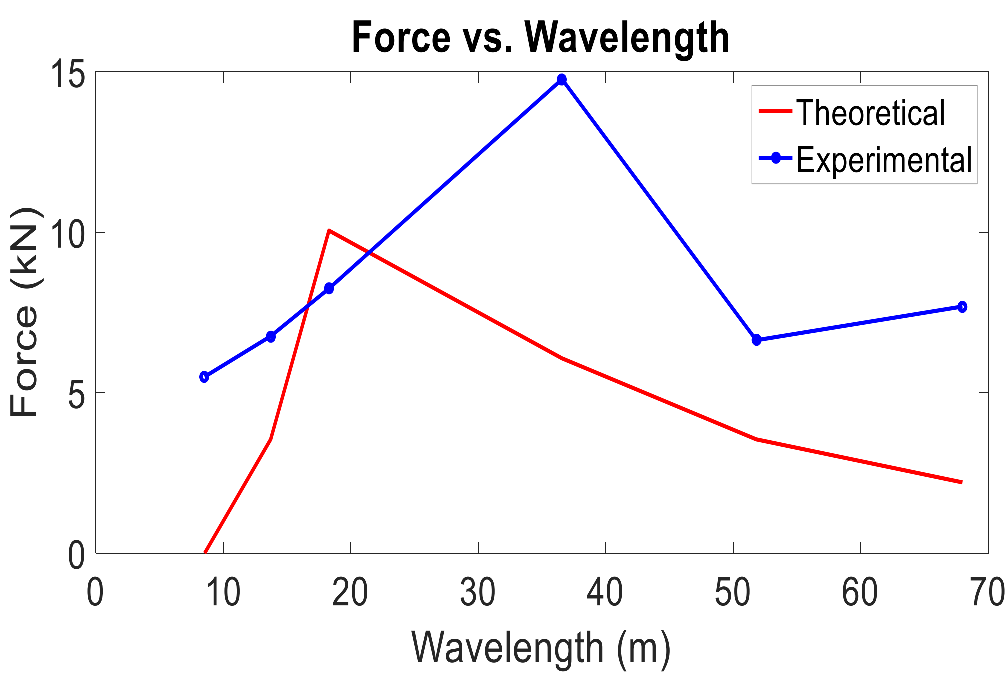


Figure 24- Force versus Wavelength, at Various Wavelengths

We are confident that the lack of accuracy comes from the mooring configuration for the scale model. The current mooring configuration in the tow tank uses fishing line to connect the pier and platform. The use of fishing line in the current setup has slack in the line, which allows the platform to accelerate and intensify the forces read by the load cells. In addition, the errors discussed above can also be an explanation for the larger magnitudes of force. Future work for this project which will carry into the summer will involve the development and implementation of a new mooring configuration for the load cells that can measure forces accurately with various degrees of freedom, as well as implement a stiffer wire material to prevent slack and skewing tension results. It is important to note that the mooring configuration that was used for these tests does not directly imitate what will be implemented at Memorial Bridge.

Another test that was of interest to the design of the prototype turbine deployment platform was transverse wave loading. The deployment platform and bridge pier models were placed in the UNH tow tank perpendicular to the flow in an attempt to collect data for waves created by barges passing alongside the platform. Figure 25 above shows the pier and platform configuration in the UNH Tow Tank when clamped perpendicular to the flow.

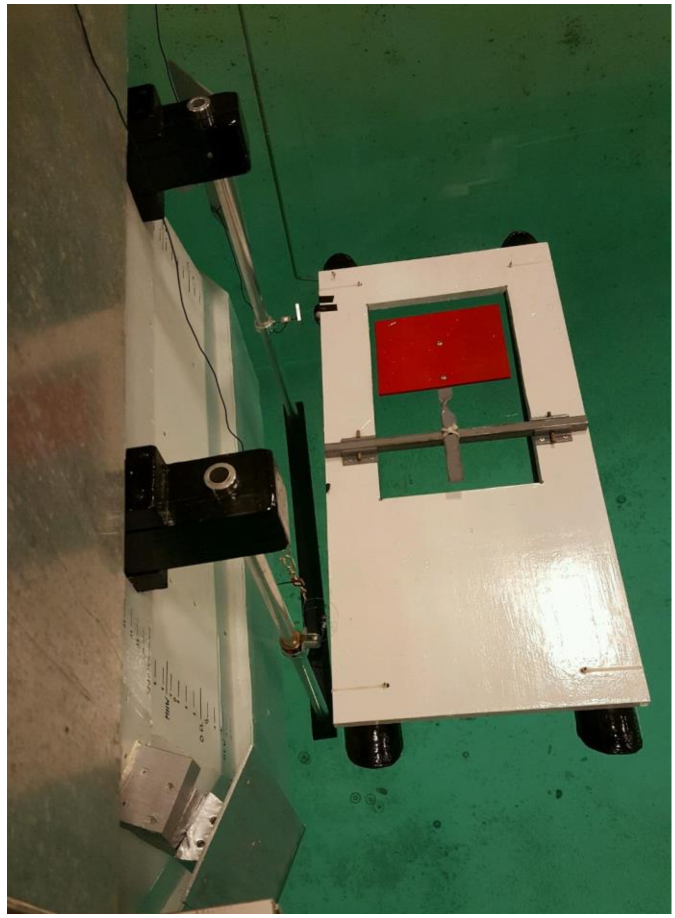


Figure 25- Pier and Platform Perpendicular to Flow

The turbine was lifted out of the water and waves 2.5 meters high were targeted so that the worst case scenario was simulated. The testing was not completed because large drag forces on the pier induced from a larger area exposed to the flow caused the pier to sway dangerously when impacted with waves. The pier and the connections to the tow carriage were designed to resist drag forces from towing the set up parallel to the flow at a maximum of 2.2 m/s. The perpendicular wave test featured an area of approximately 5x the parallel area and the waves created larger forces on the pier than towing did. The worst case scenario was attempted initially with waves of short wavelength. These waves caused the pier to displace several inches in either direction and in addition beam that absorbs most of the forces one the pier bowed significantly. Even at wave heights half the size of the target waves and with long wavelengths the pier swayed more than was acceptable for accurate data collection and avoidance of damage to the pier and platform models. Additional bracketing, clamps, and supports were added to the upper portion of the pier to try and combat the swaying but these methods were unsuccessful. A proposed solution for the resolution of this problem is to attach cross braces from the bottom of the pier back and up to the tow carriage. This will add support to a system that is currently only perpendicularly supported by clamps and threaded rods along one axis.

Conclusion:

The data collected during the course of the project will prove valuable to the Living Bridge Project. Specifically, the work completed on this project will help to verify that the current design work completed by graduate student Ian Gagnon was conservative when dealing with expected forces underneath Memorial Bridge. Over the course of the year, the team was able to successfully Froude-scale the proposed turbine deployment platform, as well as create a length-scaled bridge pier; both of which will be able to continue to be used and tested in the UNH Tow Tank in the future, including this summer and potentially the fall as well. The platform was tested both individually and with the pier, obtaining useful data for the prototype. This summer further testing will continue provide even more data to the designers. In particular single point towing tests and parallel wave tests were successfully conducted. They verified that the model had been Froude-scaled corrected. Though the force measurement system did not ideally replicate that of the prototype, the results of the parallel wave tests were encouraging. Further research will be performed this summer to refine the set-up.

This summer is very important because it will be interesting to see if the forces seen on the prototype are those that were predicted through our scale model testing. The model pier and turbine deployment platform will continue to be used as Kaelin Chancey and Jamison Couture will be continuing this project during the summer of 2016. The testing set up will be modified so that more accurate wave data can be collected. The compression plate will be expanded so that the platform cannot get stuck on top of or below the plate. With this modification the parallel wave testing will be repeated to confirm or rebuke the data reported above. Cross bracing from the bottom of the pier up to the tow carriage will also be added so that the model can be tested with perpendicular waves. In addition to testing with the model further design and analysis of the prototype deployment platform will be conducted. The data collected using the model will be used to assess the guidepost and attachment design and possibly prompt modifications. The sensors that will be featured on the prototype will be mounted on custom brackets to in the coming months.

References:

[1] Fox, Robert W., Philip J. Pritchard, and Alan T. McDonald. *Fox and McDonald's Introduction to Fluid Mechanics*. Hoboken, NJ: John Wiley & Sons, 2011. Print.

[2] "Yakima, Washington." *Instream Energy Systems*. N.p., n.d. Web. 12 Nov. 2015. <http://instreamenergy.com/projects/yakima-washington/>.

[3] Horizontal Wave Force on a Floating Object (Winzler and Kelly, 1979, p. III-16, after Brater, McNown and Stair, 1958)

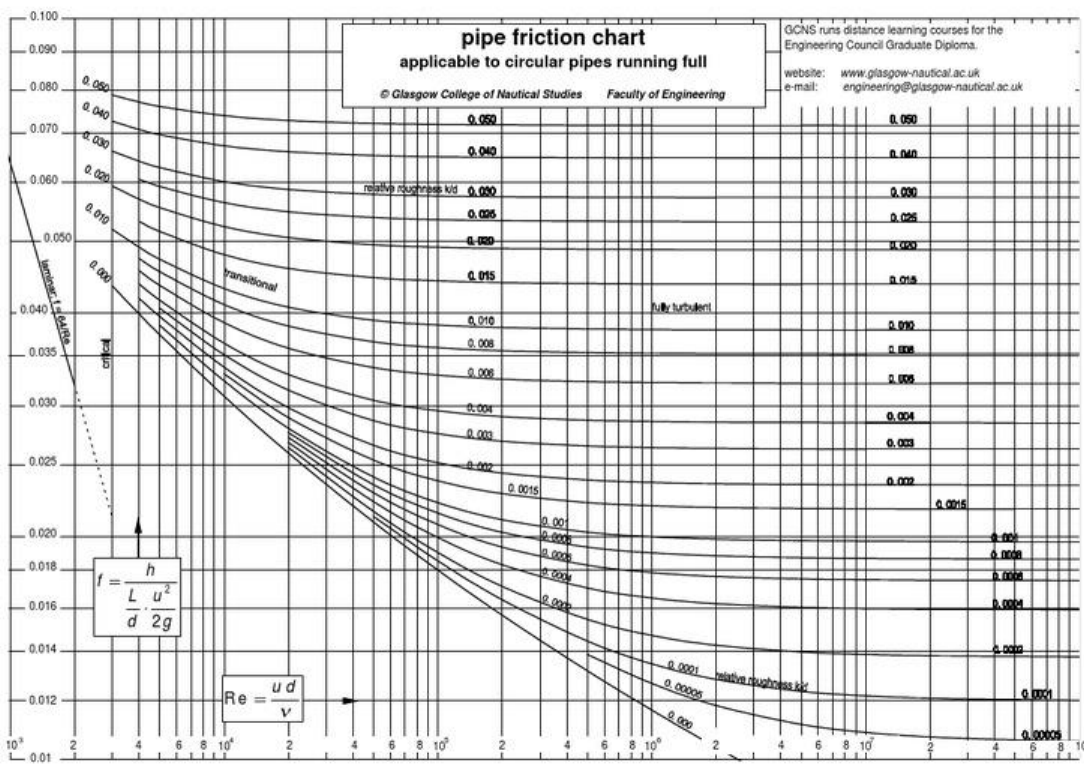
[4] Wave Force Adjustment for Relative Body Length (Winzler and Kelly, 1979, p. III-17).

[5] *Boundary-Layer Theory*. Schlichting, Hermann, 1979

Acknowledgements:

This work is the result of research sponsored in part by the New Hampshire Sea Grant College Program through NOAA grant # NA10OAR4170082, the UNH ME Department, and the UNH Marine Program. Special thanks to Toby Dewhurst, Scott Campbell, Paul Lavoie, John Ahern, Jim Abare, and Hard Core Spiral Tube Winders.

Appendix:



Test Matrix			
Test 1: Drag Qualification of Turbine Deployment Platform			
	Tow speed (m/s)		Prototype Forces (kN)
	Model scale	Prototype	
Test platform	0.1	0.36	.68
Test platform	0.2	0.72	2.69
Test platform	0.3	1.08	6.10
Test platform	0.4	1.44	10.83
Test platform	0.5	1.80	17.39
Test platform	0.6	2.16	24.49
Test platform	0.7	2.52	33.47
Test platform	0.6	2.16	24.31
Test platform	0.4	1.44	17.50
Test platform	0.2	0.72	10.69
Test 2: Towing at Max Speed – 0.6 m/s			
	Angle(°)	Prototype Forces (kN)	
		Tension	Compression
Platform and pier	-5	28.1	-11.1
Platform and pier	0	27.9	-12.0
Platform and pier	5	25.9	-11.5
Test 3: Waves (5.8 cm height) with Pier Parallel			
Platform and pier	Wavelength (Prototype Scale, m)	Wavelength (Scale Model, m)	Prototype Forces (kN)
Platform and pier	8.58	0.66	5.45
Platform and pier	13.65	1.05	7.13
Platform and pier	18.33	1.41	8.27
Platform and pier	36.53	2.81	14.85
Platform and pier	51.87	3.99	7.06
Platform and pier	67.99	5.23	7.41