northwest energy innovations

Azura Full-Scale Design

2017

Test Report
Wave Tank Tests April 2017

Northwest Energy Innovations

5/8/2017

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1. Introduction

This document describes the results of wave tank tests that were performed on a scale model of the Azura preliminary full-scale design on April 24-28, 2017. These tests were performed at the Harold Alfond W^2 Ocean Engineering Laboratory at the University of Maine in Orono (UMO). The primary objective of these tests was to validate NWEI's WEC-Sim simulation model of this design.

2. Test Plan

The NWEI document "Test Plan for Wave Tank Testing" is included in Appendix I of this document. Included in this test plan is a description of the equipment tested, test objectives, test setups, test instrumentation, and detailed plans describing the specific tests performed. Tests were conducted per this test plan except where noted in this report.

See Figure 3-4 and Figure 3-5 for photos of the Azura tank model operating in the UMO tank during the test.

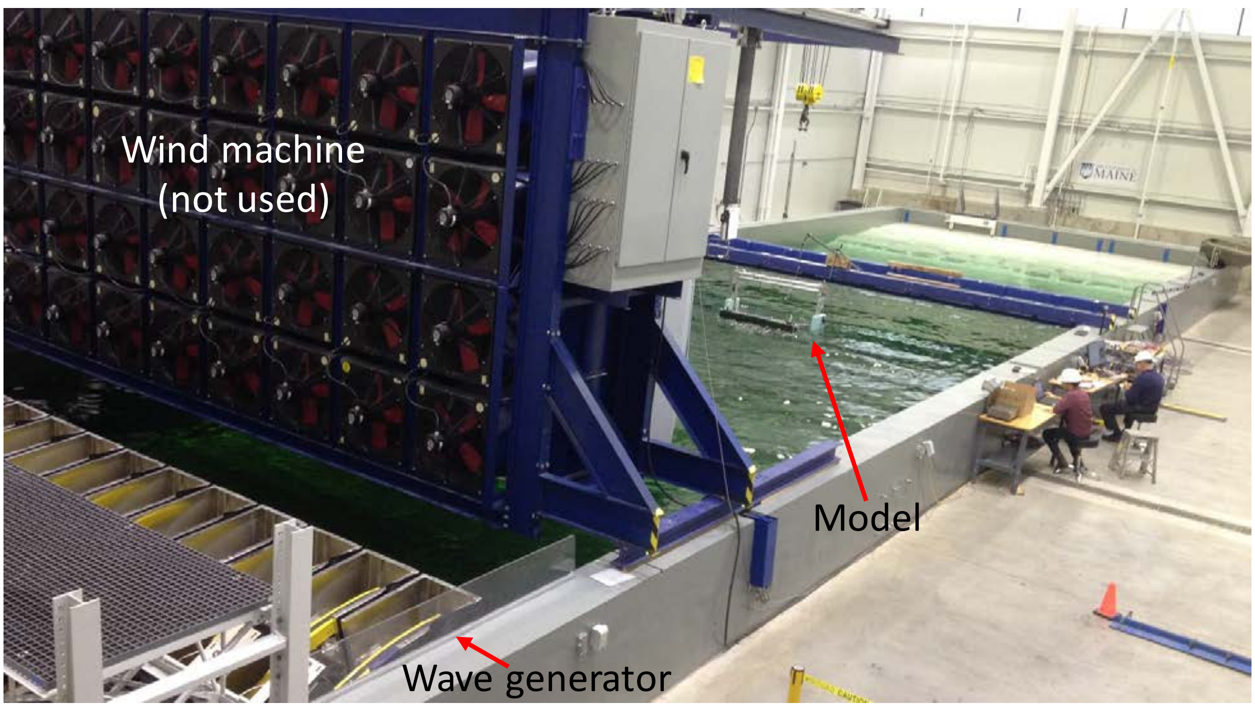


Figure 3-1 UMO wave tank during NWEI test

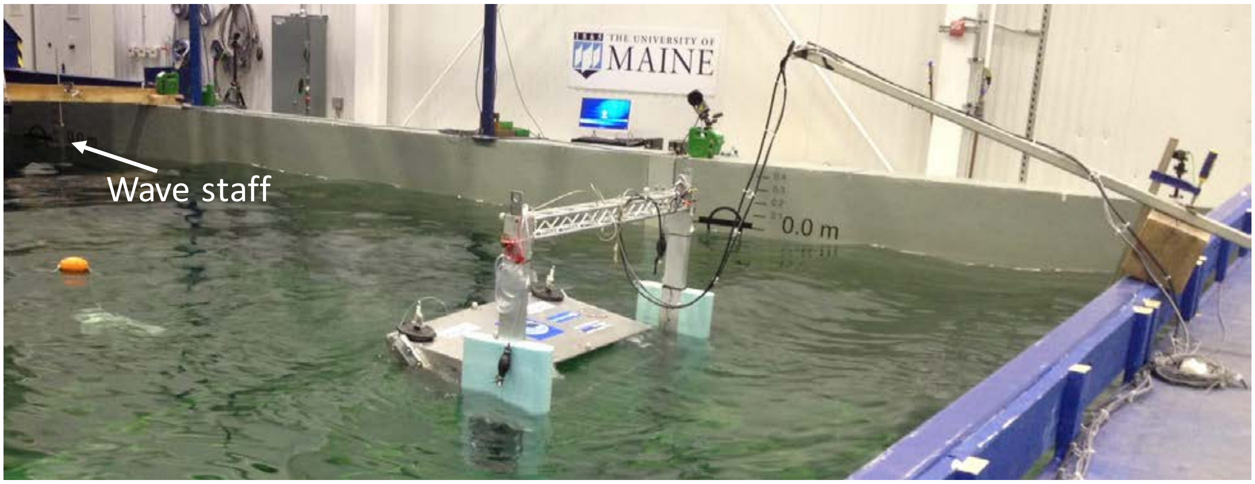


Figure 3-2 Close up of tank model during the tests

3. Test Results

3.1. Mass, center of gravity, and moment of inertia measurements

See Appendix B for the mass, CG, and MOI results. These measurements were made per Sections 7.1, 7.2, and 7.3 of the test plan (Appendix A) respectively.

3.2. Float arm torque measurement calibration check

A calibration check of the float arm torque measurement was performed before the beginning of the wave tank tests and repeated after the tests were complete. To do these checks the float was removed from the float arms. An aluminum bar was bolted to the torque measuring float arm to extend its length to approximately five feet and a clamp was used to keep the PTO shaft from rotating in a horizontal position. See Figure 3-1 for a photo of the setup.

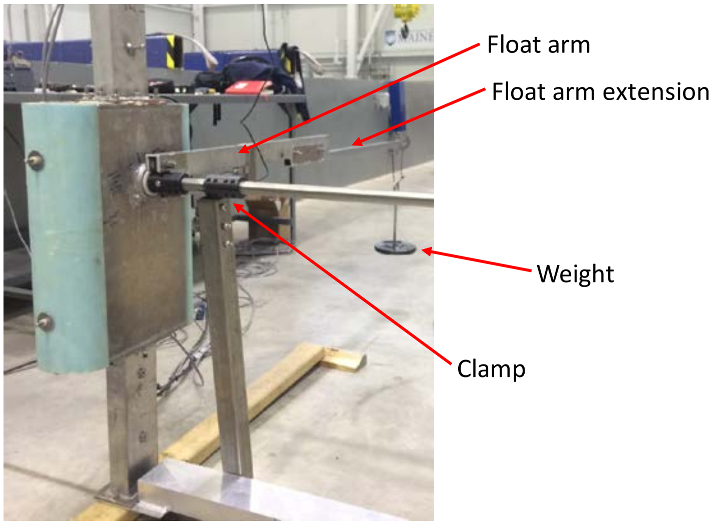


Figure 3-1 Float arm load cell calibration check setup

A check of the torque measurement was made by hanging different known weights from the arm, recording the DAS torque measurements for each weight, and comparing expected torque to measured torque. Note that DAS scaling was per calibration data from the manufacturer of the load cell used to make the torque measurements throughout all tests; these were only rough checks of that calibration. In order to simplify these calibration checks the DAS was temporarily programmed with a secondary torque output that was scaled from the primary output to equivalent lbf at the hang point and zeroed with zero hang weight. The measurements were repeated with the float arm extending horizontal to both sides of the model so that both positive and negative torques were applied. The results are shown in Figure 3-2 and Figure 3-3 for the pre-test and post-test respectively. The results show a change in torque readings of approximately 2.5% from pre-test to post-test with the pre-test measurements approximately 2% low. Some flex in the float arm extension was noted with the higher hang weights during both tests, however, which may have caused measurements to be about 2% low of the hung weights for both tests.

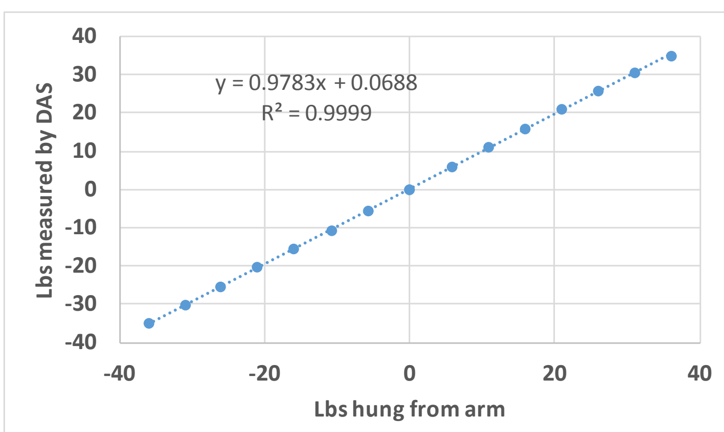


Figure 3-2 Torque load cell calibration check pre-test

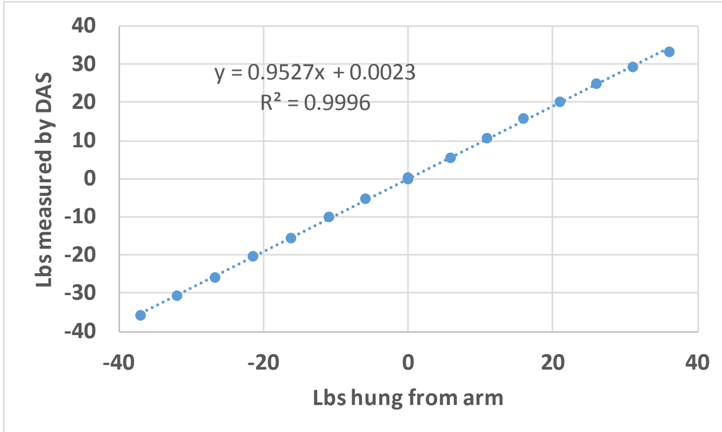


Figure 3-3 Torque load cell calibration check post-test

3.1. Data recorded

The following data was recorded during each 30 minute wave tank run listed in the Test Matrix (see Table 7-2 of the test plan included in Appendix A). Separate 30 minute duration data files were recorded for each test run.

- NWEI cRIO data in LabVIEW .tdms format sampled at 100 Hz for float angle, float velocity, float torque, and UMO synch. The UMO synch signal is a 0-5V signal that transitions high at the beginning of each wave run and low at the end.
  File name format: NWEI_lwf_WC1_D120_100Hz_MMddyy_hhmmss.tdms where "lwf" is only included for runs with low float weight (10 lbs weight removed from baseline), "WC1" refers to wave case #1, "D120" refers to a target damping of 120 Nm-s/rad, and MMddyy_hhmmss is the data and time of the start of the file.
- UMO wave probe data in .csv format sampled at 128 Hz. This includes time series data for water surface elevation recorded by the single wave probe shown in Figure 3-5.
  File name format: WC1_D120_ MMddyy_hhmmss _LFW.csv
- UMO Qualisys motion tracking data in MATLAB .MAT format sampled at 100 Hz.
  File name format: WC1_D120_ MMddyy_hhmmss _LFW.MAT

In addition, wave calibration data was recorded prior to the test runs and saved in two .csv files. Time series water surface elevation data was recorded at 128 Hz sample rate for the reference wave probe (at location device was placed during the test). Data was also recorded for a second wave probe adjacent to the reference probe, and a third wave probe that was left in place for the tests (this is the wave probe shown in the Figure 3-5 photo).

3.2. Relative capture width results

NWEI analyzed the data recorded for each test run to produce the relative capture width (RCW) plots shown in Figure 3-6 through Figure 3-8 with test runs using different PTO damping shown on the same plot. These plots are shown for the tank scale wave periods. The RCW was calculated from the power and wave spectra for each 30 minute data period as follows:

$$RCW(\omega) = \frac{real\left(\frac{P(\omega)}{J(\omega)}\right)}{float\ width}$$

Where P(ω) is the PTO input power spectra of the device and J(ω) is the wave energy flux spectra. The Azura PTO input power spectra were calculated for multiple 30 minute data periods as follows:

$$P(\omega) = \frac{2\,dt^2}{T} * \text{fft}(\text{float torque}) * \text{conj}(\text{fft}(\text{float velocity})),$$

where Fast Fourier transforms (ffts) results were bin averaged to smooth the results.

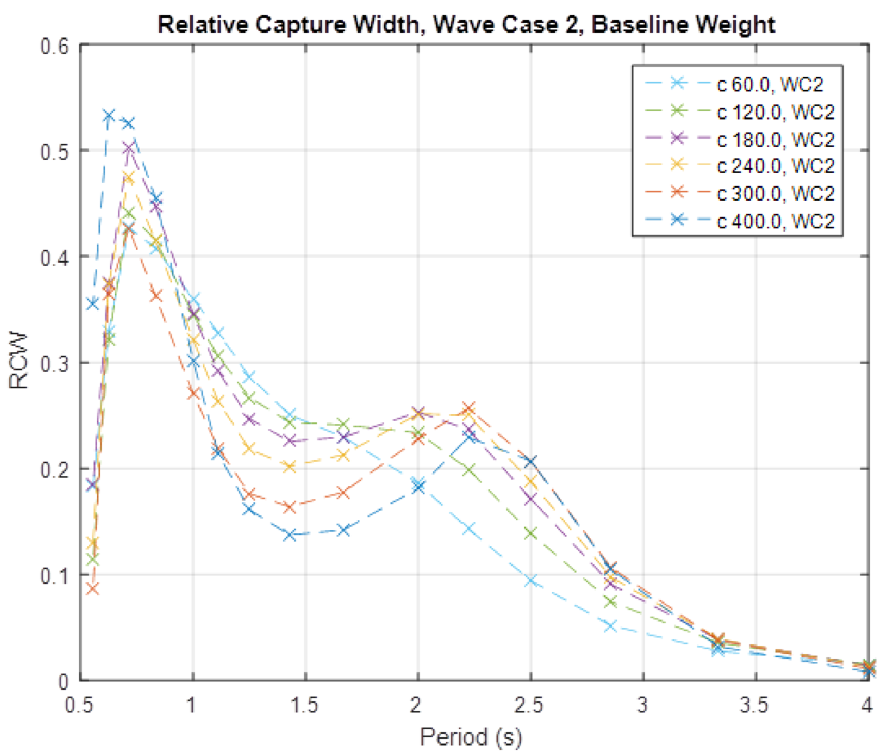


Figure 3-4 RCW for wave case #2, baseline weight

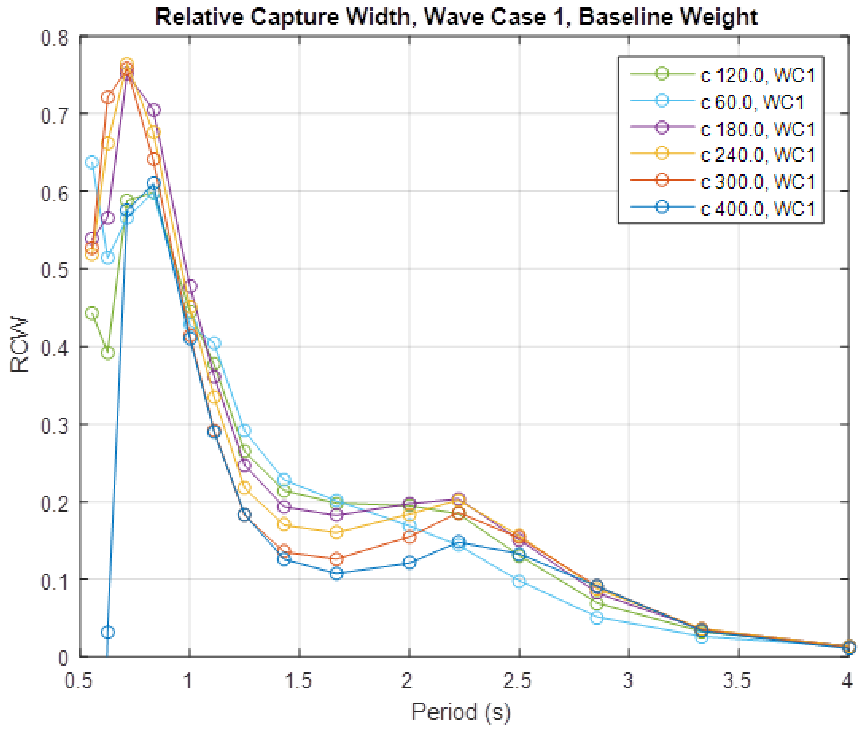


Figure 3-5 RCW for wave case #1, baseline weight

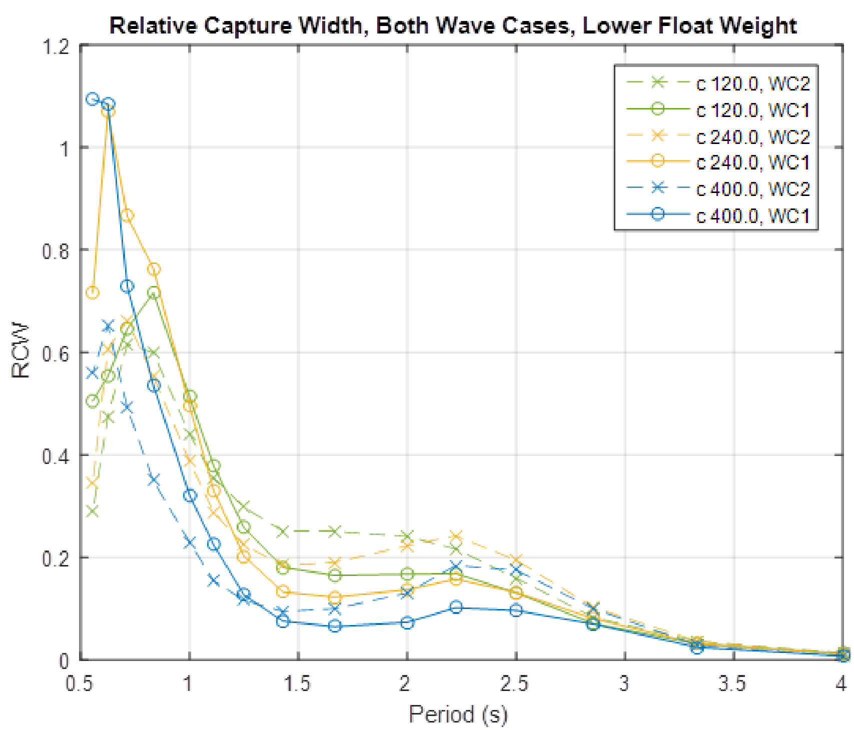


Figure 3-6 RCW for both wave cases, low float weight

3.3. Response amplitude operators

NWEI analyzed the data recorded for each test run to produce the Response Amplitude Operator (RAO) plots shown in Figure 3-9 through Figure 3-17 with test runs using different PTO damping shown on the same plot. The RAO magnitudes shown in each plot were calculated using the following equation, where the RAO is defined as the modulus of H(ω):

$$|H(\omega)|^2 = \frac{S_{yy}(\omega)}{S_{xx}(\omega)}$$

Where $S_{xx}(\omega)$ is the wave spectrum calculated by taking the fft of wave calibration data recorded by UMO for the appropriate wave case and $S_{yy}(\omega)$ is the measured response spectrum of device motion. The device motion spectra were calculated by taking ffts of either NWEI time series float angle data or UMO time series motion tracking data for hull heave and hull pitch. Bin averaging of the fft results was used to smooth the data.

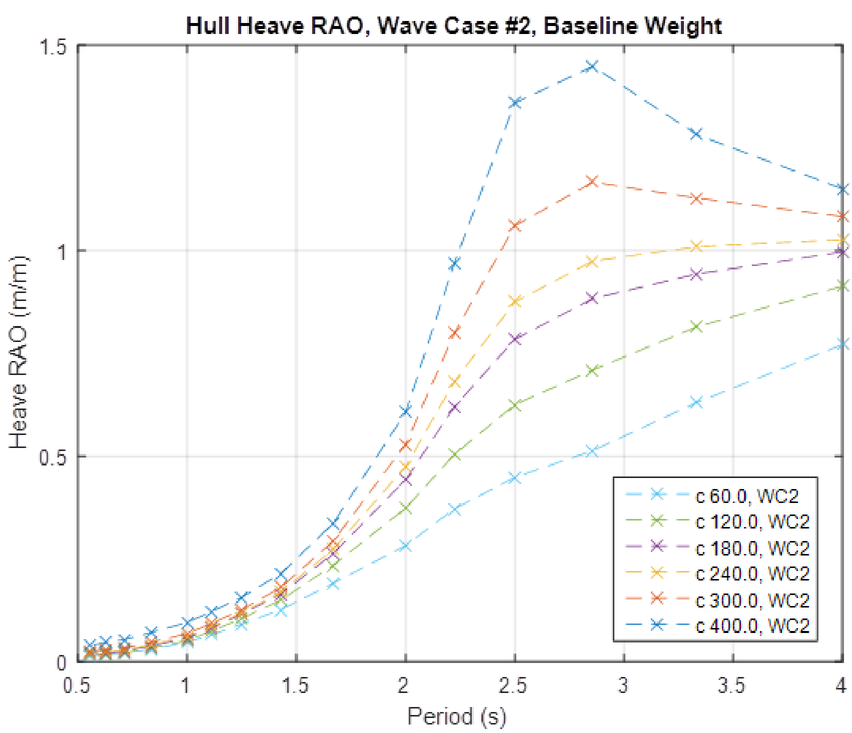


Figure 3-7 Hull heave RAO for wave case #2, baseline weight

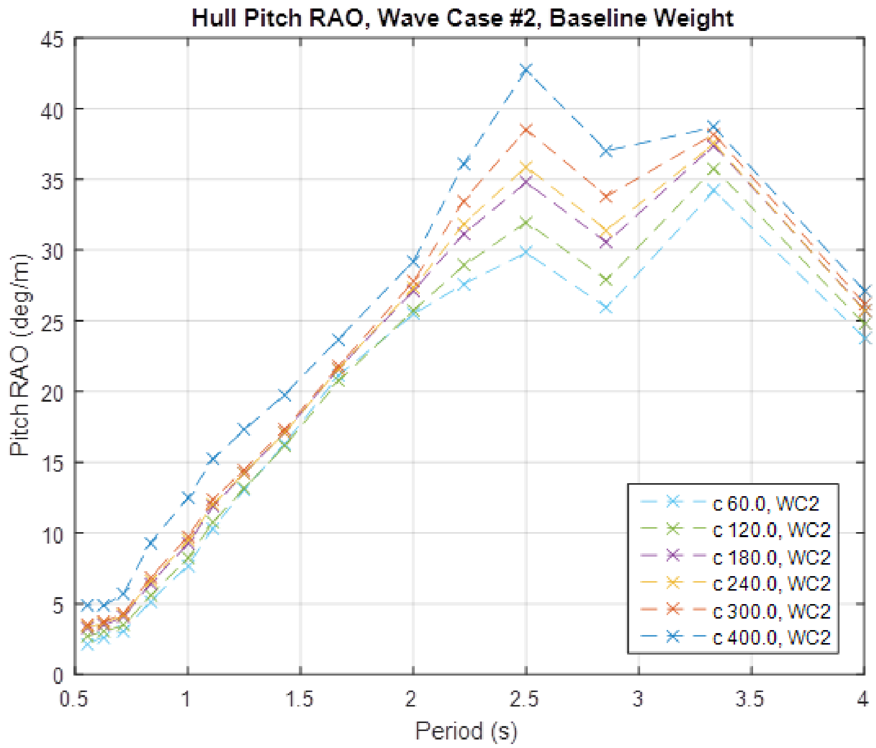


Figure 3-8 Hull pitch RAO for wave case #2, baseline weight

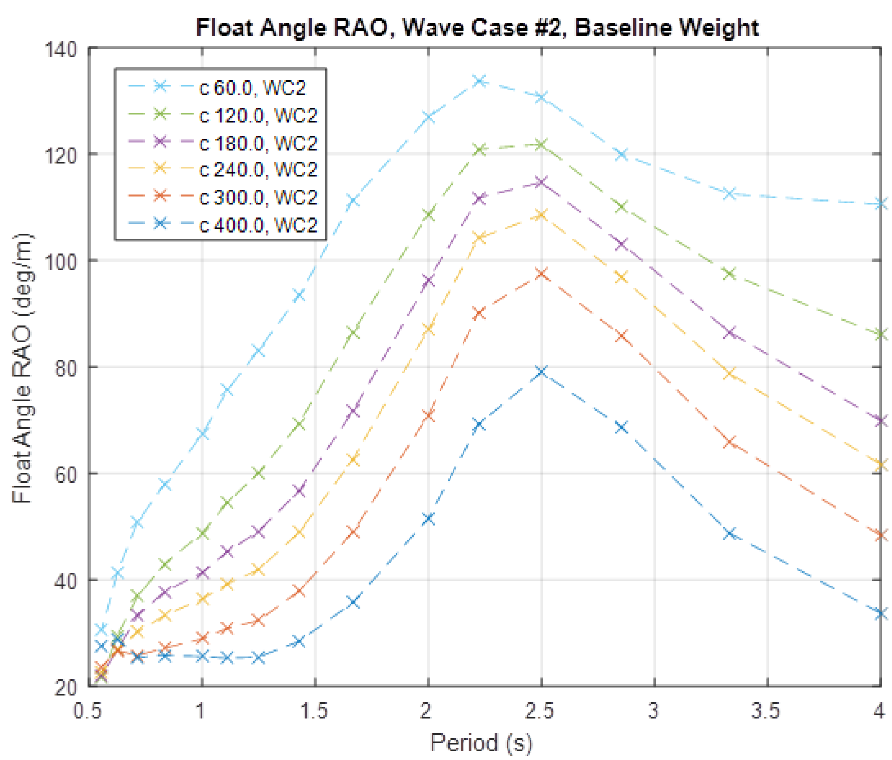


Figure 3-9 Float Angle RAO for wave case #2, baseline weight

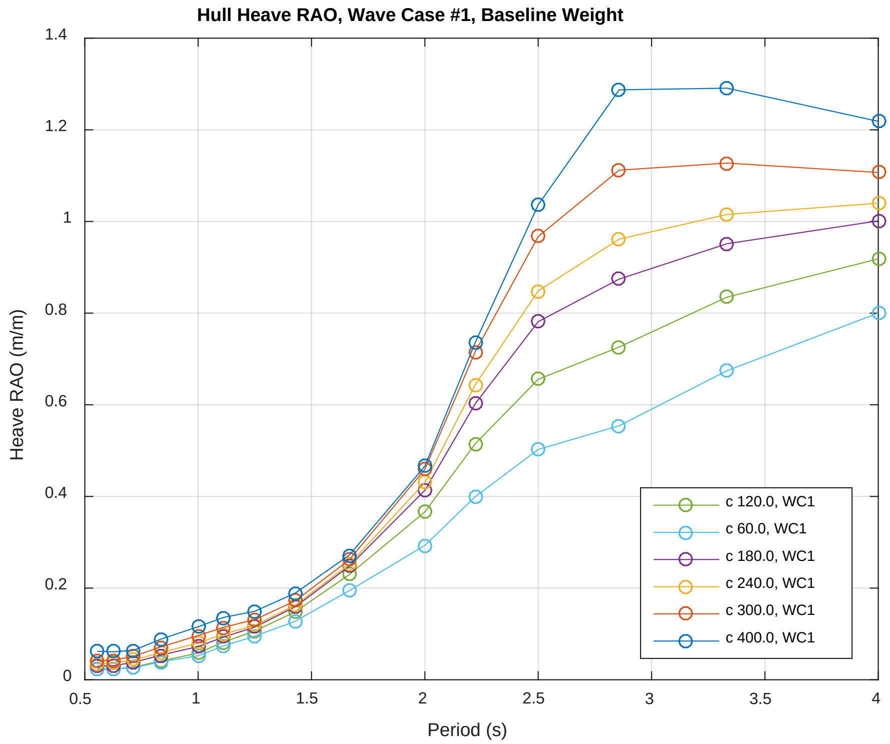


Figure 3-10 Hull heave RAO for wave case #1, baseline weight

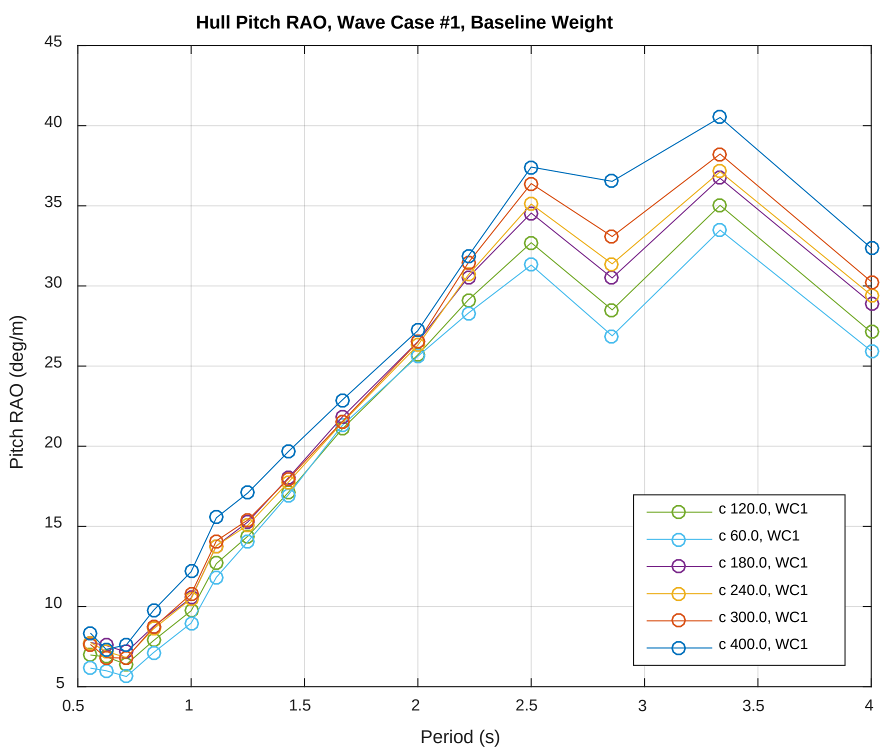


Figure 3-11 Hull pitch RAO for wave case #1, baseline weight

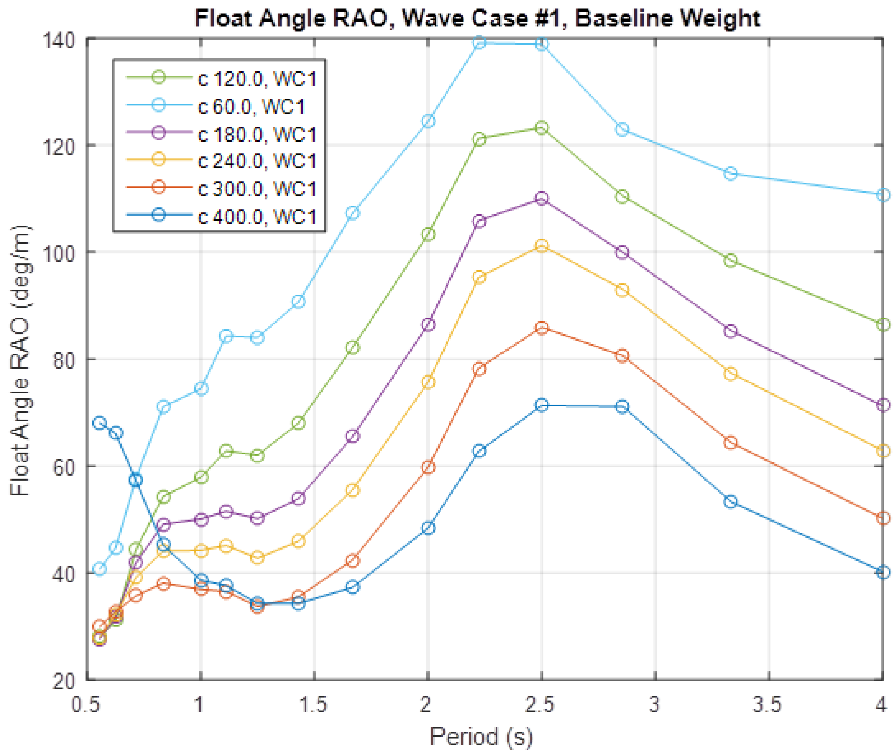


Figure 3-12 Float angle RAO for wave case #1, baseline weight

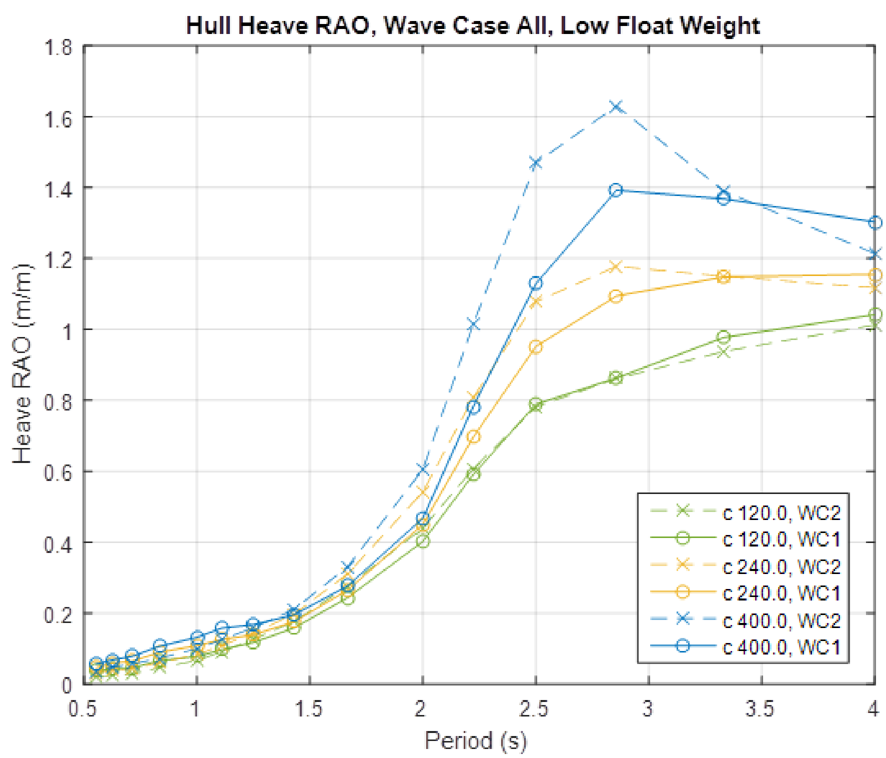


Figure 3-13 Hull heave RAO for both wave cases, low float weight

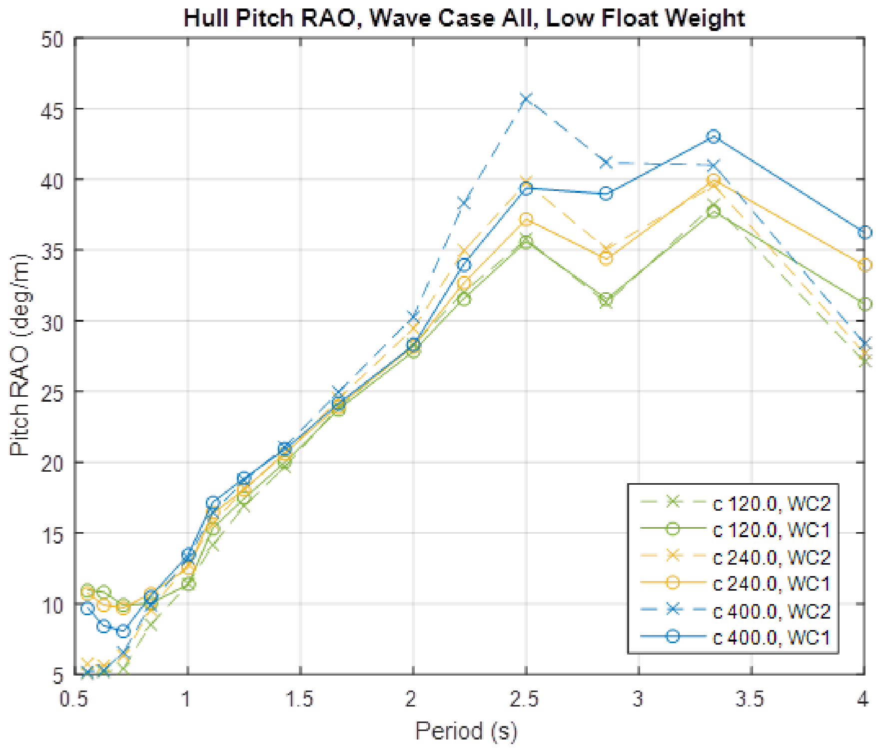


Figure 3-14 Hull pitch RAO for both wave cases, low float weight

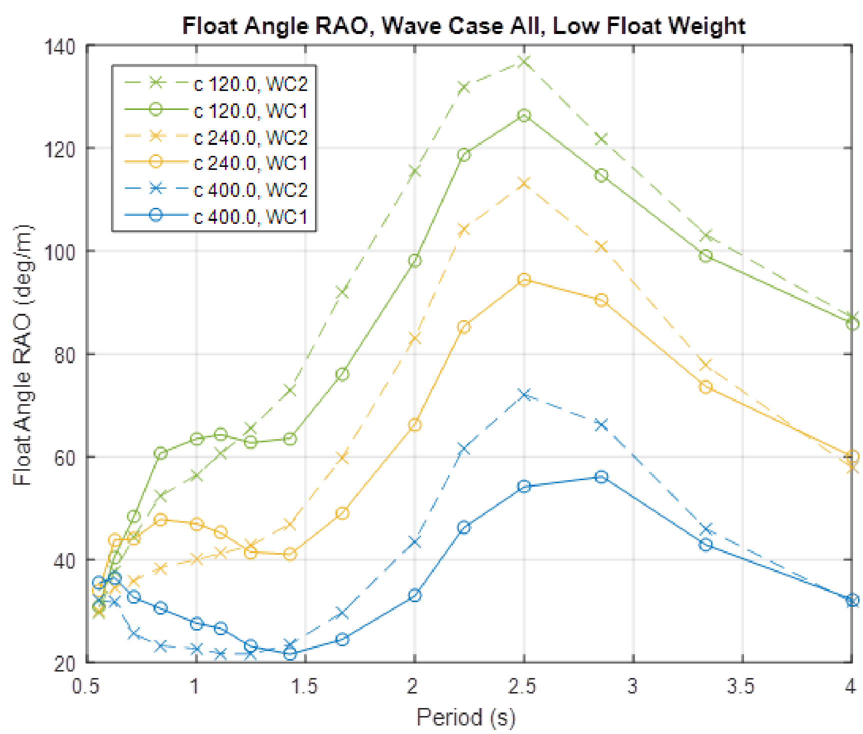


Figure 3-15 Float angle RAO for both wave cases, low float weight

Appendix A

Test Plan

Azura Full-Scale Design

2017

Test Plan for Wave Tank Testing

Northwest Energy Innovations

5/3/2017

TABLE OF CONTENTS

1. Introduction

This document describes wave tank tests that will be performed on a scale model of the Azura preliminary full-scale design in April 2017. These tests will be performed at the Harold Alfond W^2 Ocean Engineering Laboratory at the University of Maine. The primary objective of these tests will be to validate NWEI's WEC-Sim simulation model of this design. Tank tests will consist of approximately two days of broadband irregular wave testing.

2. Objectives

The objective of this test is to collect data that can be analyzed to produce experimental Relative Capture Width (RCW) and Response Amplitude Operators (RAOs) with respect to wave frequency for a scale model of the Azura preliminary full-scale design. RAOs will be calculated for hull heave, hull pitch, and float angle motions of the device. The resulting RCW and RAOs will be used to validate a NWEI WEC-Sim model of this design.

3. Test Article

The test article will be a wave tank model that was built in 2016 by RTI Wave Energy for the Department of Energy Wave Energy Prize (WEPrize) competition. NWEI is collaborating with RTI and adopting its F2QD WEPrize design as the Azura full-scale prototype design. The RTI tank model was previously tested in the Maneuvering and Seakeeping basin (MASK) at Carderock Division, Naval Surface Warfare Center for WEPrize. During those tests the tank model PTO did not function as designed and device performance was degraded. Prior to the planned NWEI test, modifications will be made to correct these PTO problems. No other changes will be made to the RTI tank model for this test.

A diagram of the tank model is shown in Figure 3-1. An elongated float is connected to the hull by two drive arms. A single point mooring system allows the device to self-orient so that the float is always parallel to oncoming waves. The PTO is housed in a compartment on the hull that is below water line.

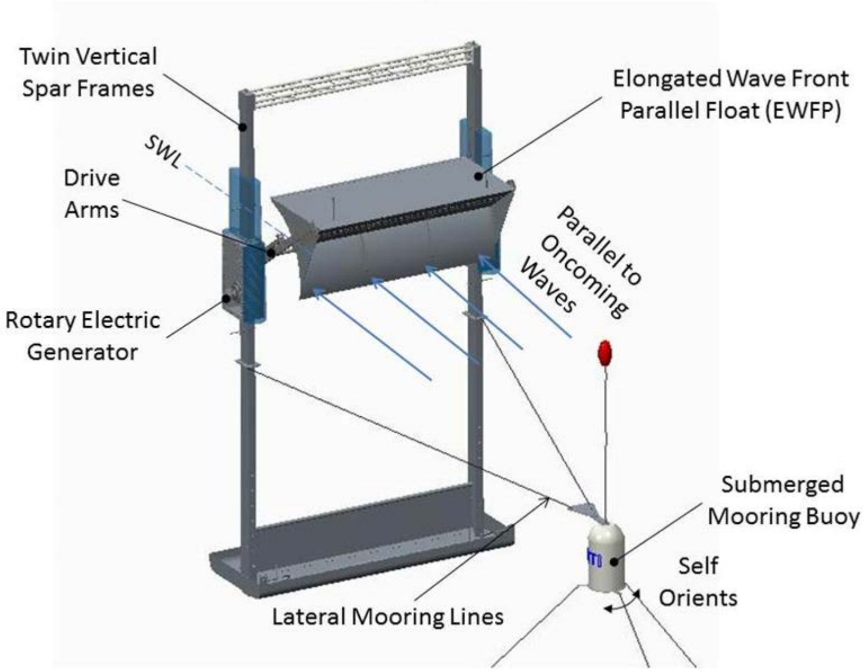


Figure 3-1 NWEI tank model

See Figure 3-2 for a diagram showing the tank model PTO. The tank model has a single PTO on one side of the float that consists of a chain-driven electrical generator with an integral gearhead. The electrical generator is controlled by a custom generator drive developed by RTI. The generator control will be configured for constant damping (torque proportional to rotational speed) for the NWEI tests. The generator control will be configured with different damping constants for different test runs.

Torque is measured in the drive float arm by a submersible tension/compression load cell installed in the split-arm arrangement shown in Figure 3-2. Float arm angle and speed is measured by an encoder on the drive arm.

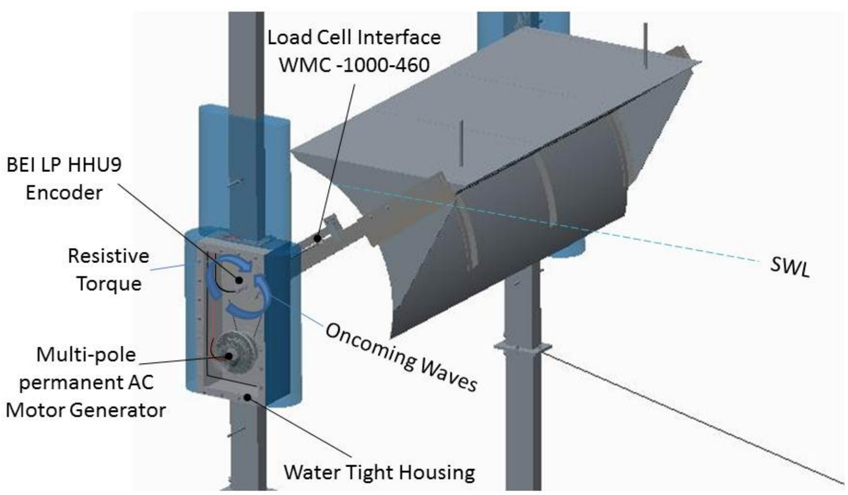


Figure 3-2 Tank model PTO and instrumentation

The torque applied to the float arm by the PTO will be controlled by passive resistor loading of the PTO generator. Because a permanent magnet generator is used, resistive loading causes a generator torque that is proportional to generator speed for constant damping control of the device. The ratio of generator torque to speed, referred to as the damping constant, is determined by the load resistance. A variable resistance load will be adjusted to different settings to provide different damping settings during the test.

4. Test Facility

Testing will be performed at the Harold Alfond W^2 Ocean Engineering Laboratory at the University of Maine Advanced Structures and Composites Center in Orono, Maine. Basic information about this facility is described below; further information is provided at the following web site: https://composites.umaine.edu/key-services/offshore-model-testing/.

Table 4-1 Harold Alfond W^2 Ocean Engineering Laboratory details

Length	30 m
Width	9 m
Max depth	4.5 m
Wave period range	0.5-5 s
Max wave height	0.8 m

This facility is equipped with a high-performance rotating wind machine over a wave basin. The wave basin has a 16-paddle wave generator at one end, a beach at the other end, and an adjustable floor.

5. Schedule

The expected timeline for these tests is shown in Figure 5-1. Tank calibration will be performed prior to NWEI arrival at the wave tank. Center of gravity and moment of inertia tests will be performed at the wave tank facility before the model is installed in the tank. One day is scheduled for setup and installation of the model in the tank, followed by two days of irregular wave testing.

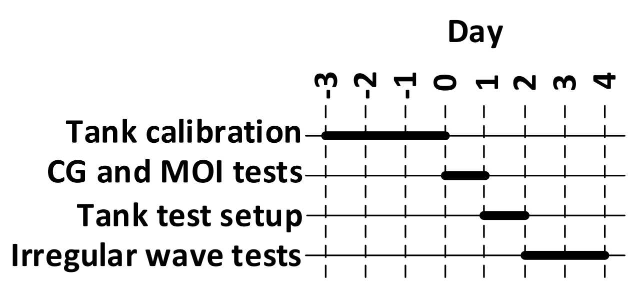


Figure 5-1 Timeline for Azura April 2017 wave tank tests

6. Test Setup

The tests setups described in the following subsections will be used for the test procedures described in Section 7.

6.1. Tank depth

The tank depth will be set to 4.5 m for these tests.

6.2. Mooring configuration

The single point mooring system developed by RTI for the WEPrize tests, shown in Figure 3-1, will be used as-is for these tests. Figure 6-2, Figure 6-3, and Figure 6-4 show the mooring layout used during WEPrize tests, with dimensions corrected for the 4.5 m tank depth that will be used for these tests (WEPrize tank depth was 6 m). The model will be centered in the width of the tank and 12.5m from the wave maker as shown in Figure 5-1. The mooring attachment points on the tank model will be positioned vertically within the "mooring attachment zone" shown in Figure 6-3 so that mooring lines are horizontal while the device is floating statically at still water line. This mooring system successfully provided self-orientation of the RTI tank model during WEPrize tank tests so that the float was always parallel to incoming unidirectional seas.

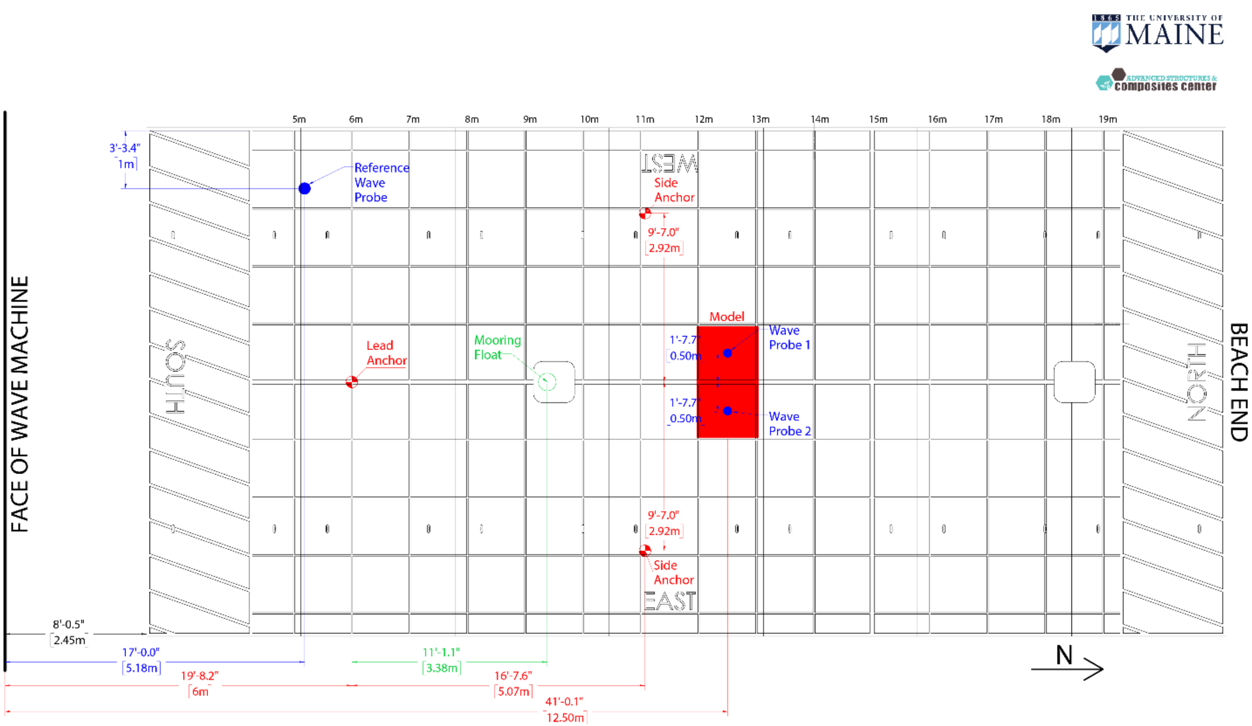


Figure 6-1 Mooring and Model Layout in W2 Basin

6.1. Anchor weights

The anchor weights shall be 500 lb or greater for the anchor in line with the wave direction and 200 lb or greater for the two side anchors.

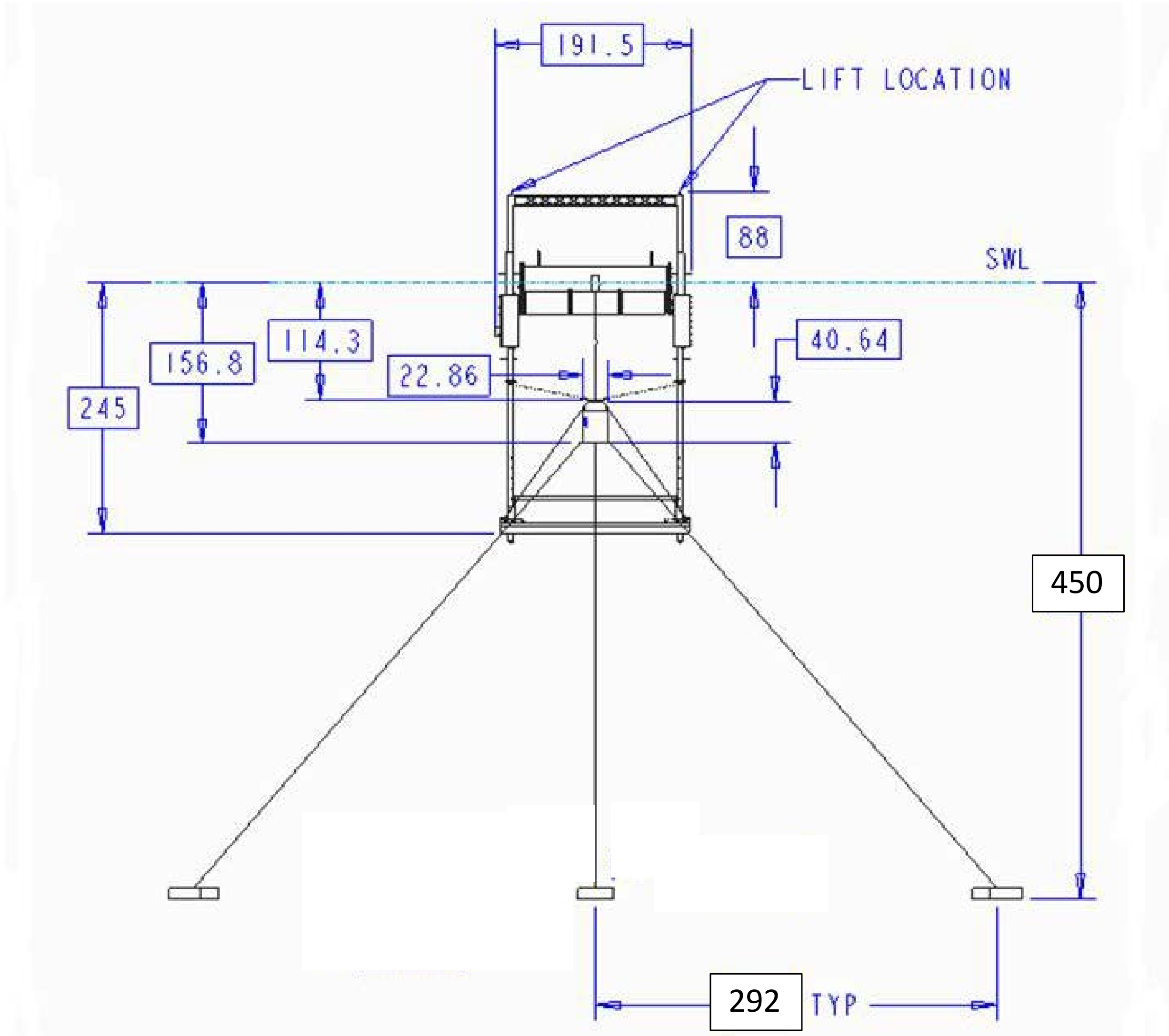


Figure 6-2 Mooring diagram – view from wave generator end

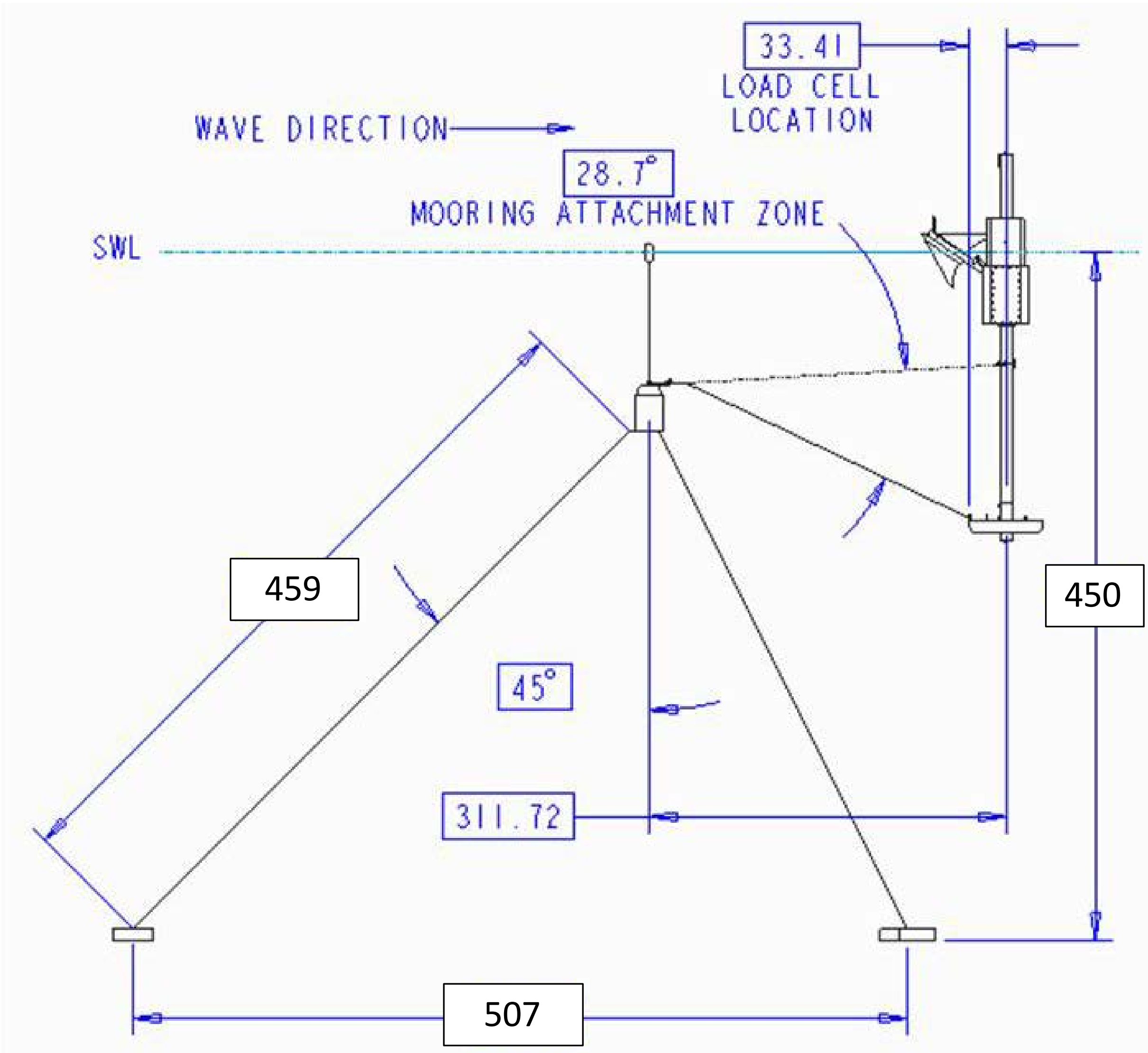


Figure 6-3 Mooring diagram – side view

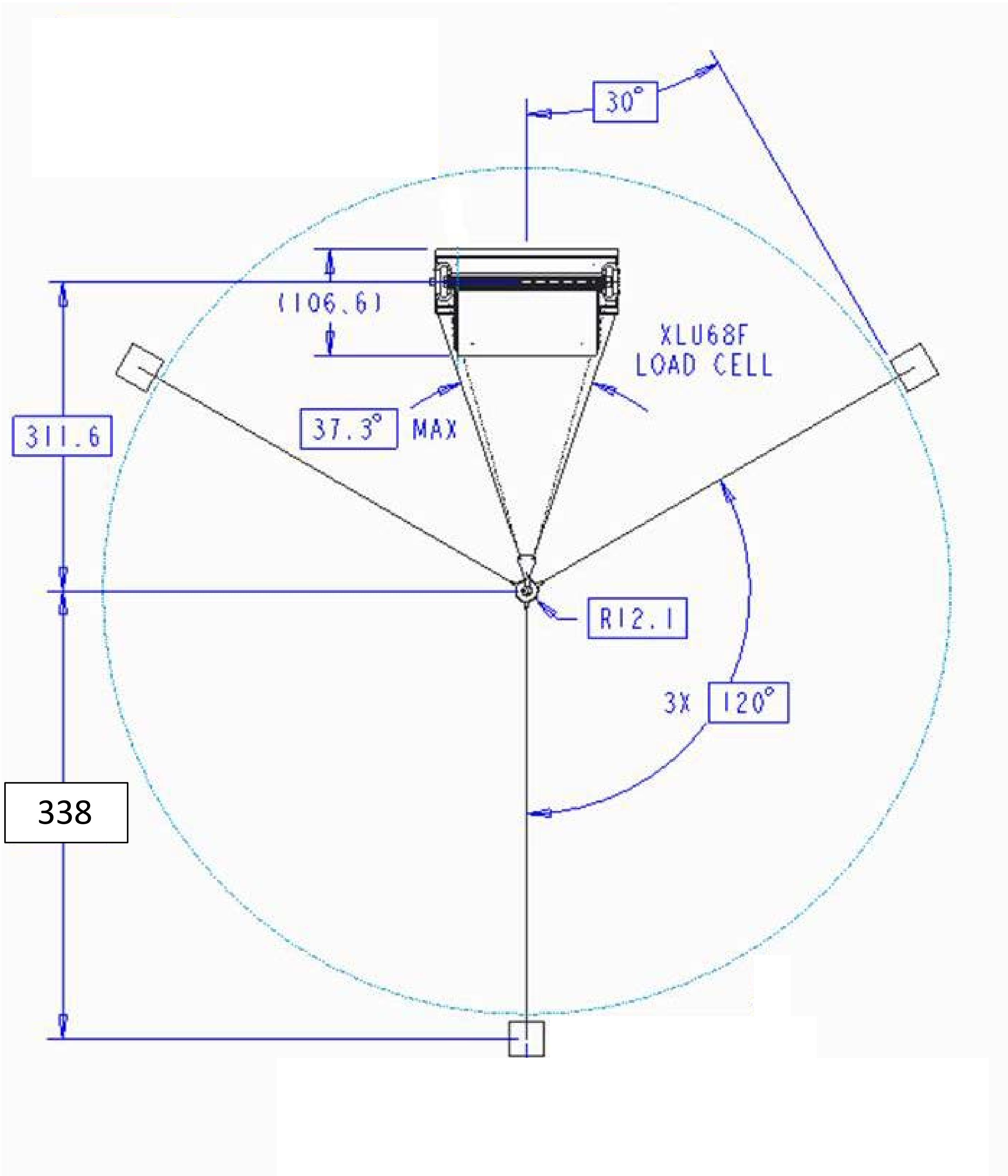


Figure 6-4 Mooring diagram – overhead view

6.2. Wave probe

One wave probe will be provided by the test facility to measure wave elevation at a location shown in Figure 5-1, between the device and the wave generator, during irregular wave tests. These wave probes interface with the DAS described in Section 6.3.

6.3. Data acquisition

Three separate data systems will be used for this test:

1. An RTI cRIO data system will be used to collect float arm torque and speed data. The data sampling rate will be 100 Hz.
2. Wave probe data will be recorded by the wave tank test facility at a sampling rate of 128 Hz.
3. Motion tracking data will be recorded by the wave tank facility at a sampling rate of 100 Hz.

A common time synch signal that will transition high at the beginning of each test run and transition back low at the end of the test runs will be recorded by each data system during the test.

A list of data acquisition channels that will be recorded during the test is shown in Table 6-1.

Table 6-1 Data Acquisition Channel List

<table>
<tr><th>Measurement</th><th>Sensor PN</th><th>Sensor Mfr</th><th>DAS</th><th>Notes</th></tr>
<tr><td>Shaft torque</td><td>WMC-1000-460</td><td>Interface</td><td>NWEI/RTI cRIO</td><td>Load cells in split float arms</td></tr>
<tr><td>Shaft angle</td><td rowspan="2">LP HHU9</td><td rowspan="2">BEI</td><td rowspan="2">NWEI/RTI cRIO</td><td rowspan="2">Encoders interface with cRIO digital input module</td></tr>
<tr><td>Shaft speed</td></tr>
<tr><td>Wave elevation</td><td></td><td>Edinburgh Designs</td><td>Test facility DAS</td><td>Resistance based wave probes</td></tr>
<tr><td>Surge pos. hull</td><td colspan="2" rowspan="12">Test facility Qualisys motion tracking system</td><td rowspan="12">Test facility DAS</td><td rowspan="12"></td></tr>
<tr><td>Sway pos. hull</td></tr>
<tr><td>Heave pos. hull</td></tr>
<tr><td>Roll pos. hull</td></tr>
<tr><td>Pitch pos. hull</td></tr>
<tr><td>Yaw pos. hull</td></tr>
<tr><td>Surge pos. float</td></tr>
<tr><td>Sway pos. float</td></tr>
<tr><td>Heave pos. float</td></tr>
<tr><td>Roll pos. float</td></tr>
<tr><td>Pitch pos. float</td></tr>
<tr><td>Yaw pos. float</td></tr>
</table>

6.4. Tank model damping adjustments

Adjustable load resistors will be used to provide damping control of the PTO described in Section 3 so that float arm torque is equal to a damping constant times float angular speed. Different irregular wave runs will be performed with the generator load resistances configured for the five different target damping values listed in Table 7-1. Generator load resistance settings for each target damping value will be determined experimentally prior to performing test runs by manually moving the float up and down with the model out of the water while recording float arm torque and speed. Torque and speed data will be used to create X-Y scatter plots; trend line slopes will be used to calculate damping. Actual damping may differ from the target damping.

7. Test Procedures

7.1. Mass measurement

The mass of the device will be measured by weighing the unit on the test facility scale. The scale has a 900kg capacity (2,000lb) and graduations of 0.2kg (0.5lb). This measurement will be made by facility staff.

7.2. Center of Gravity Measurement

The CG will be measured by test facility staff using methods outlined below.

The CG for the model will be calculated using a modified string method for irregular shape bodies. The model will be suspended using a single reflective cable and its attitude measured with the Qualisys motion tracking system to calculate the vector passing through the body's CG. The body will be hung from a different pick point for each of the three tests in order to measure the three coordinate dimensions of the CG. During each test, the Qualisys system will acquire the position of the cable and the body. Using an in-house numerical routine, the location of the cable and body will be translated and rotated to the body's local coordinate system. As shown in Figure 7-1, the CG is then defined as the intersection of the projected vectors.

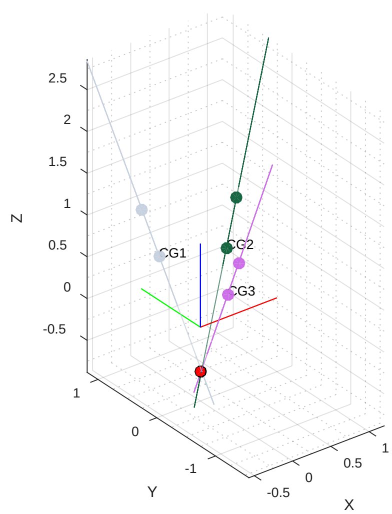


Figure 7-1: Lines are projected with respect to the part to find the center of gravity.

7.3. Moment of inertia measurement

The MOI will be measured by test facility staff using methods outlined below.

The method used to measure the system MOI about the pitch axis will be pendulum testing. In the pendulum test, the body will be hung from a cable running through the calculated CG and swung at small angles. Position data from the Qualisys tracking system will be used to measure the natural period. Then, the body inertia will be calculated using the natural period definition per Equation 1

$$T = 2\pi\sqrt{\frac{l}{g} + \frac{I_A}{mgl}} \qquad \textit{Equation 1}$$

where T is the period, l is the length of the cable to the center of gravity, g is the gravity constant, m is the mass of the object, and I_A is the MOI. Solving for I_A, Equation 2 is used to directly calculate the MOI.

$$I_A = mgl\left(\frac{T}{2\pi}\right)^2 - ml^2 \qquad \textit{Equation 2}$$

7.4. Wave tank calibration

Wave tank calibration will be performed by facility staff before the tank model is installed in the wave tank. Two wave probes will be positioned at the location of the future tank model. Calibrations will be done for the two target wave spectra shown in Figure 7-2. Some trial and error is expected to achieve calibration spectra similar to the target spectra. The final calibration spectra are expected to differ from the target spectra shown in Figure 7-2 to some extent due to practical limitations of the test facility. Surface elevation measurements made with the wave probes for the final calibration spectra will be recorded for use during NWEI data analysis. The same wave generator settings used for these calibrations will be used during the irregular wave tests described in Section 7.6.

7.5. Water line measurement

The water line of the tank model will be measured in still water after the tank model is installed in the tank.

7.6. Irregular wave tests

Time has been budgeted for irregular wave tests using the two different broadband wave spectra shown in Figure 7-2. For both wave spectra, testing will be repeated with the tank model PTO control configured with each of the five damping settings listed in Table 7-1. The following test sequence will be used for the irregular wave runs:

1. Set model damping target setting #1 (this will be done by adjusting the motor resistance)
2. Start data acquisition systems. Record start time, wave spectra, and damping setting
3. Start wave generation with first wave spectra (see Figure 7-2); wait until tank settles to desired condition (< 1 min)
4. Operate for 30 minutes
5. Stop data acquisition
6. Repeat steps 1-5 for the remaining five target damping settings
7. Repeat above steps for the second wave spectra shown in Figure 7-2.

Table 7-1 Target damping values for wave tests

Damping case	Damping value (Nms/rad
1	60
2	120
3	180
4	240
5	300
6	400

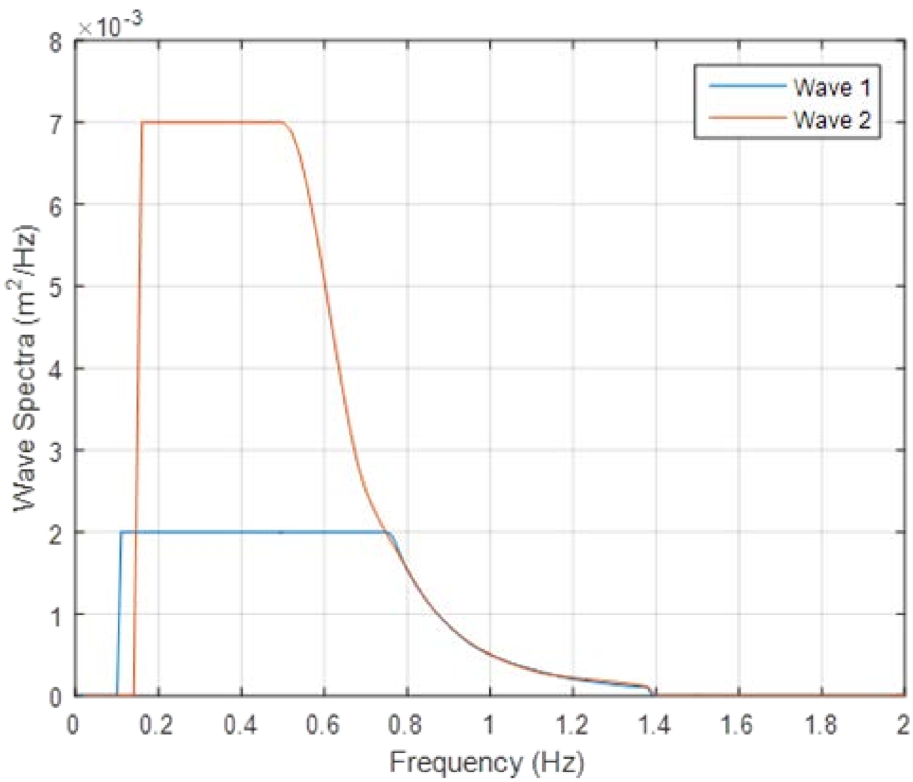


Figure 7-2 Target wave spectra for irregular wave runs

7.7. Test Matrix

See Table 7-2 for the test matrix, which includes all wave tank test runs to be performed. Each test run will be performed with a 15 minute wave train repeated for a 30 minute test.

Table 7-2 Test Matrix

Test No.	Wave	PTO Damping (Nms/rad)	Remarks
-	-	-	Model ballast and trim
-	-	-	Mass measurement
A1	-	-	CG measurement
A2	-	-	Pitch moment of inertia measurement
A4	-	-	Hookup and DAS sync test
B1	Broad Band 2	60	Baseline
B2	Broad Band 1	60	Baseline
C1	Broad Band 2	120	Baseline
C2	Broad Band 1	120	Baseline
D1	Broad Band 2	180	Baseline
D2	Broad Band 1	180	Baseline
E1	Broad Band 2	240	Baseline
E2	Broad Band 1	240	Baseline
F1	Broad Band 2	300	Baseline
F1	Broad Band 1	300	Baseline
G1	Broad Band 2	400	Baseline
G2	Broad Band 1	400	Baseline
	Broad Band 2	120	Low float weight – remove 10 lbs of weight
	Broad Band 1	120	Low float weight – remove 10 lbs of weight
	Broad Band 2	240	Low float weight – remove 10 lbs of weight
	Broad Band 1	240	Low float weight – remove 10 lbs of weight
	Broad Band 2	400	Low float weight – remove 10 lbs of weight
	Broad Band 1	400	Low float weight – remove 10 lbs of weight

Appendix B

Mass, CG, and MOI Test Results

Test Summary Cover Page

Client Name: Azura Wave
Test: 1:10 scale wave energy device
Test Dates: 4/24/2017 – 4/28/2017

Water Depth: 4.4m **Wind:** None **Waves:** Broadband

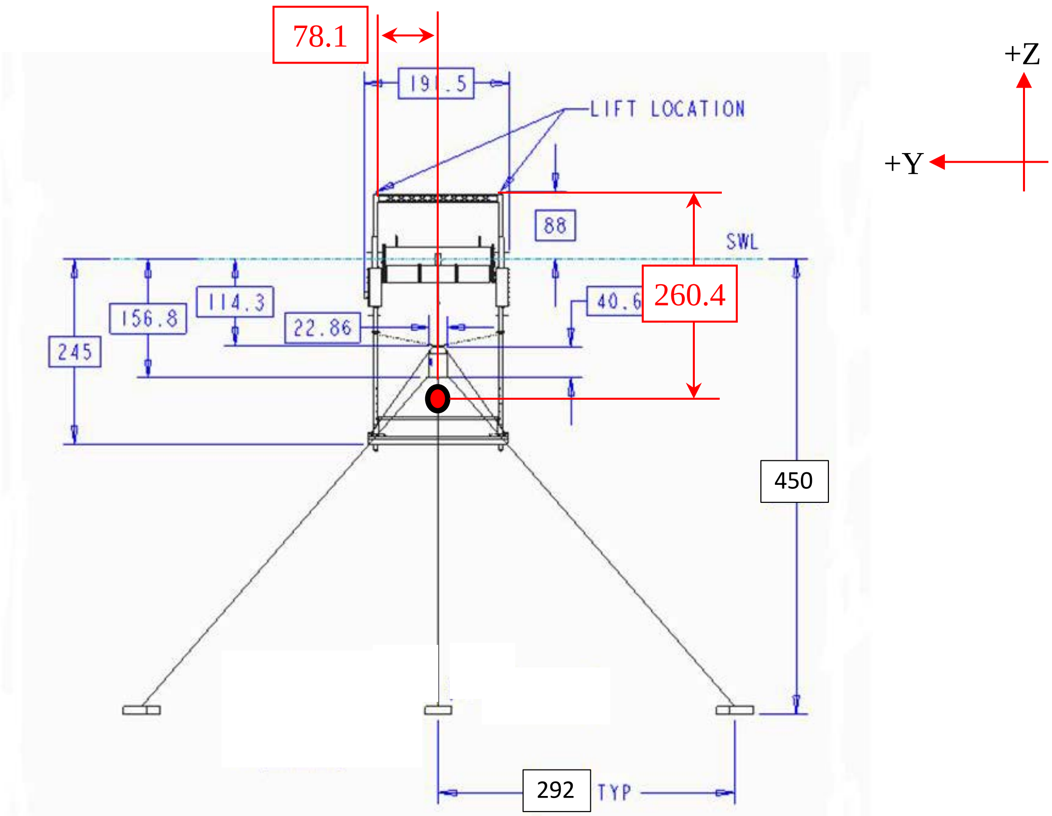
UMaine Data: Qualisys of model and float, Reference wave probe, timestamp video
Sample Rate: 100 Hz Motion Data, 128 Hz Wave Data

Data Report: None

Special Notes: Pitch moment of inertia only – swing model and float separately

Calculated Values

1. Model Mass: 100.8 kg (w/ cable relief and 40lb ballast)
2. Model CG: x: 0.0655 m y: -0.781 m z: - 1.88 m (no water ballast)
   z: - 2.604 m (w/ calc ballast)



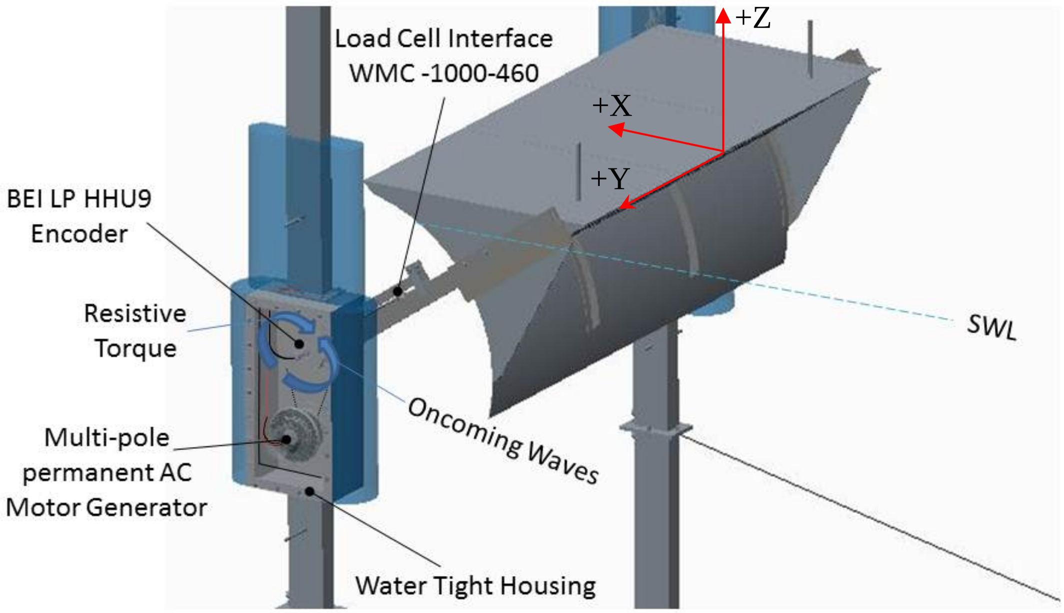
3. Model Pitch Period: 3.28 s

4. Model Pitch Moment of Inertia: 137.5 kg-m^2, about hull CG

Note: All motion data for the hull is given about the CG defined above.

1. Float Mass: 32.4 kg (w/ 20lb ballast)

2. Float CG: x: 0.2295 m y: -0.0018 m z: -0.0967 m



3. Float Pitch Period: 1.34 s

4. Float Pitch Moment of Inertia: 1.56 kg-m^2, about float CG

Note: All motion data for the float is given about the CG defined above.