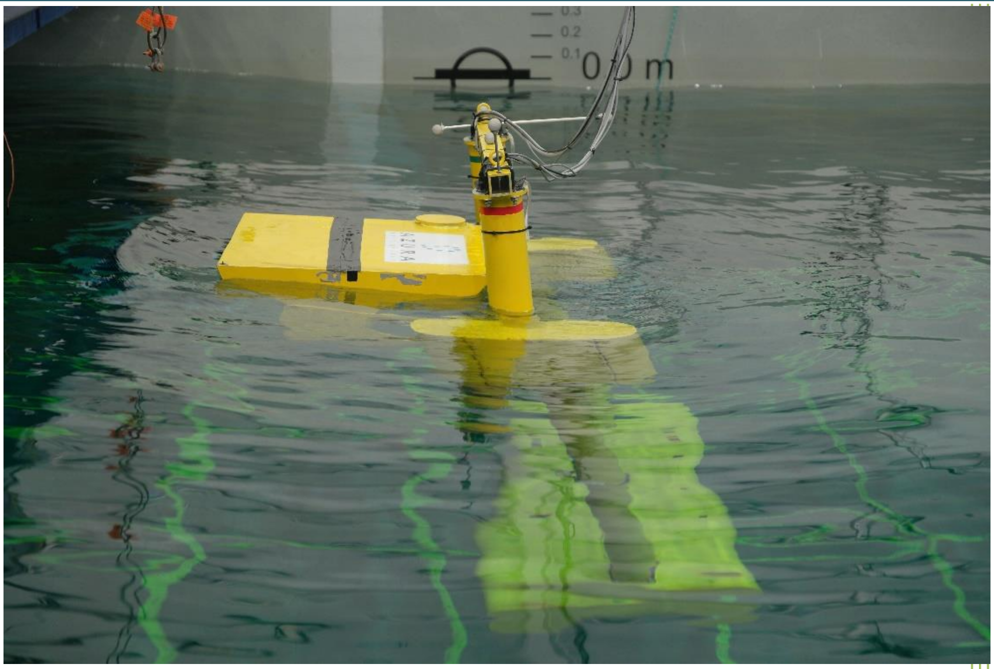
Azura Full-Scale Design

2018

Test Report Advanced Control Wave Tank Tests January 2018



Northwest Energy Innovations

10/24/2018

Project Title: “Advanced Control of the Azura Wave Energy Device”

DE-EE0007693

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1. INTRODUCTION

This document describes the results of wave tank tests that were performed on a 1:15th scale model of the Azura preliminary full-scale design on and January 22-Febraury 2, 2018. These tests were performed at the Harold Alfond W^2 Ocean Engineering Laboratory at the University of Maine in Orono (UMO). The test objectives were to

1. Collect data in irregular waves that can be used to predict full-scale device performance in six representative bins of the device power matrix with MPC control of an ideal direct-drive PTO.
2. Collect data in irregular waves that can be used to predict full-scale device performance in six representative bins of the device power matrix with MPC control of the Azura hydraulic PTO.

In addition to meeting these stated test objectives, additional tests were performed on a preliminary variable force hydraulic PTO design. During design and simulation of the control system, this additional capability was identified as having the potential to further increase power capture. Some testing time was allocated to testing of this preliminary PTO and controller combination.

2. SUPPORTING DOCUMENTS

The NWEI document “Test Plan for Wave Tank Testing Advanced Controls Project” is included in Appendix A 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 unless noted otherwise in this report. This test also utilized procedures and results from the testing of the uncontrolled performance of the Azura commercial design. The test report from these earlier tests, “Test Report: Wave Tank Tests Dec 2017/ Jan 2018”, is included in Appendix B of this document. This attached test report documents much of the work done on characterizing the tank PTO, the Hardware in the loop system, and sensor calibrations. The corresponding test plan and model design report are included in this attached test report. The design of the control systems are presented in the document “Azura Advanced Control Design Report”. Reference the design report for definitions of control system parameters presented in this test report.

Data collected from this test has been uploaded to the MHK Data Repository website.

See Figure 2-1 and Figure 2-2 for photos of the Azura tank model operating in the UMO tank during the test.

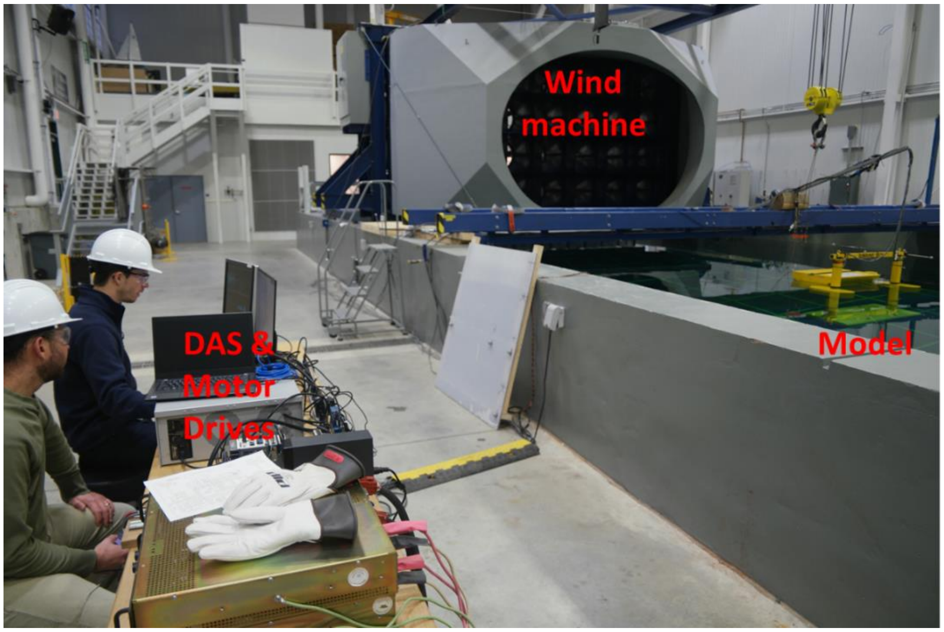


Figure 2-1 UMO wave tank during NWEI test

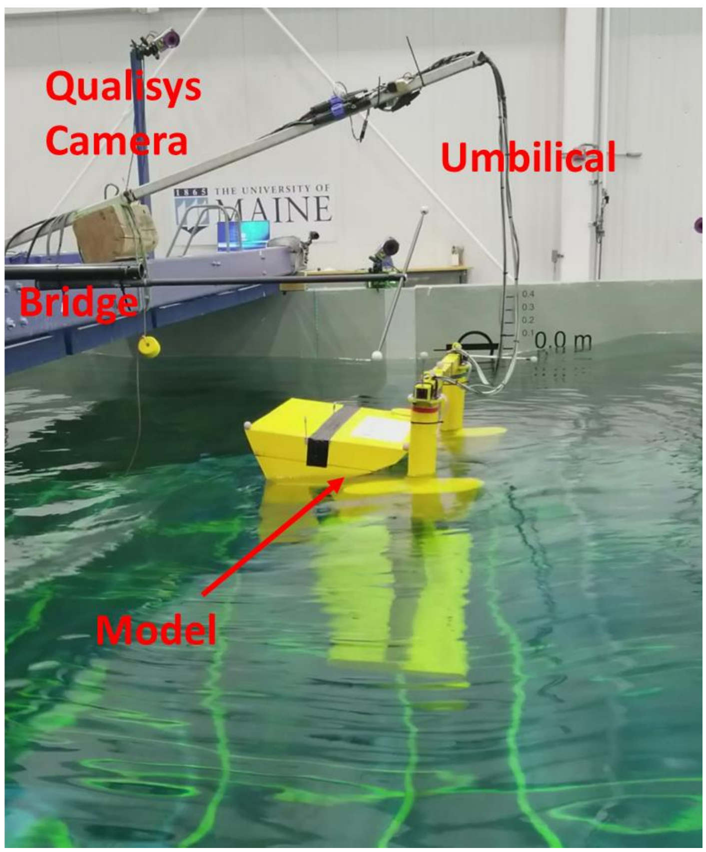


Figure 2-2 Close up of tank model during the tests

3. Test Procedure

The document "Test Plan for Wave Tank Testing: Advanced Controls Project", shown in Appendix A, describes the test procedure that was followed for the test. Supplementary information is supplied below, as observations and challenges arose during testing.

The first three days of testing consisted of tuning the controller and estimator, debugging software, and debugging hardware problems. During this process, one of the strain gaged drive shafts began to fail. It was observed that if any water made contact with any of the strain gages, the output was corrupted. The drive shaft was replaced with the backup shaft, additional tape was added to both shafts to seal the strain gages from water, and the failed strain gage was repaired. After reinstallation of the shafts, the calibration of the strain gages was verified and testing proceeded. Immediately following each test, the correlation between measured and commanded torque was inspected to monitor for any problems with the strain gage data.

Another observation made during this debugging period is the sensitivity of the control performance to the mooring line lengths. The control system utilizes wave prediction from the wave calibration test. If the position of the model deviates too much from the location of the calibration wave probe, the accuracy of this prediction decreases significantly. This decrease in accuracy results in a decrease in absorbed power. During the debugging tests, the mooring line lengths were adjusted multiple times to locate the device's mean surge position at the wave prediction location. This was done visually, by observing the model during the test, and comparing it to a mark on the side of the wave tank indicating the wave prediction location. This process was complicated by the relatively large magnitude, low frequency, surge drift observed during the tests.

3.1. Data File Naming Scheme

As discussed throughout the report, three different controllers and PTO configurations were tested. Various file naming schemes for output files from the NWEI DAS and UMO DAS were used for different configurations. The wave case under test was indicated with the first portion of the filename, "WC#_", where the # corresponds to the wave case. The second portion of the filename included a description of the control configuration, and an increment counter for tests repeated in the same condition. The NWEI tests also included a date-time stamp from the time the test concluded. The full naming methodology is shown in detail in Table 3-1.

Table 3-1. File Naming Methodology

Controller Type	Test Purpose	NWEI Filename	UMO Filename
Ideal MPC	Debugging	WC#_test#_MMDDhhmmss.mat	N/A
Ideal MPC	Final	WC#_MPC#_MMDDhhmmss.mat	WC#_MPC#.mat
Directional Hydraulic	Debugging	WC#_hyd#_ MMDDhhmmss.mat	WC#_HYD#.mat
Directional Hydraulic	Final	WC#_hydf#_ MMDDhhmmss.mat	WC#_HYDF#.mat
Variable Force Hydraulic	Final	WC#_var#_ MMDDhhmmss.mat	WC#_VAR#.mat

Note that during this debugging process, all data systems were not always running. In some tests no data was saved. In other tests data from the NWEI DAS was saved, but data from the UMO motion tracking data system was not saved.

4. Test Results

4.1. Ideal MPC Results

The first controller to test was the ideal MPC controller. This controller does not include a hardware-in-the-loop (HIL) simulation of the hydraulic PTO, making it the most straightforward controller to test. After the tuning and debugging process of the controller described in Section 3, the controller was tested in each of the six wave cases. The time step for the variable force MPC controller was 0.05s. For all wave cases, the Q scale vale was set equal to the time step, 0.05. The other control parameters and resulting mean mechanical power for each wave case is presented in Table 4-1. The power values presented here are mechanical power, which was calculated by taking the product of the measured torque and relative velocity data signals. After the mooring line length was adjusted to achieve the proper results, it was observed that the controller performance was not very sensitive to changes in control parameters. Therefore, some wave cases were only run once, using the optimal controller parameters identified in simulations prior to testing.

Table 4-1. Controller configuration and Experimental mean mechanical power from the ideal MPC controller.

Wave Case	Prediction Horizon	R Scale	Mean Power Controlled (W)
1	150	1.2e-7	1.679
2	150	1.2e-7	3.215
3	150	1.0e-7	3.707
4	120	1.0e-7	5.655
5	140	8.0e-8	4.671
6	90	2.0e-7	10.97

4.2. Directional Hydraulic Control

Results for the directional force control hydraulic PTO are shown here. This PTO had the ability to reverse power, but did not have active control of the magnitude of the force the PTO exerted on the float. The controller included a heuristic which had an additional parameter, a threshold ratio used to determine when to command reverse power. The motor coefficient in the hydraulic PTO was another variable in this configuration. The time step for the variable force MPC controller was 0.05s. For all wave cases, the Q scale vale was set equal to the time step, 0.05. Configuration parameters for the controller and PTO are presented in Table 4-2, along with mean hydraulic power and PTO efficiency. The mean power presented is the hydraulic power, an output of the HIL simulation of the hydraulic PTO. The efficiency was calculated by dividing the mean hydraulic power by the mean mechanical power from each test.

Table 4-2. Control configuration and experimental mean hydraulic power and PTO efficiency for the directional force hydraulic control tests.

Wave Case	Prediction Horizon	R Scale	Motor Coeff (full-scale)	Threshold Ratio	Mean Power Controlled	PTO Efficiency
			Nms/rad		(W)	
1	100	1.0e-8	4	0.6	1.242	0.825
2	100	1.0e-8	2	0.7	2.246	0.853
3	100	1.0e-8	6	0.6	2.716	0.917
4	80	1.0e-8	5	0.4	4.011	0.841
5	80	1.0e-8	6	0.6	3.516	0.937
6	80	1.0e-8	6	0.6	7.732	0.906

In addition to mean power results, an example time series from the directional hydraulic control wave case 3 test is shown in Figure 4-1. This shows the simulated hydraulic pressure, the float velocity, and the PTO torque. All units in the plot are shown at tank scale. The example time domain plot shows some of the force oscillations observed during the test. If the waves could not exert enough force on the float to open the rectifier valves, the compressibility of the hydraulic fluid in the cylinders would cause higher frequency, low magnitude oscillations in velocity and torque.

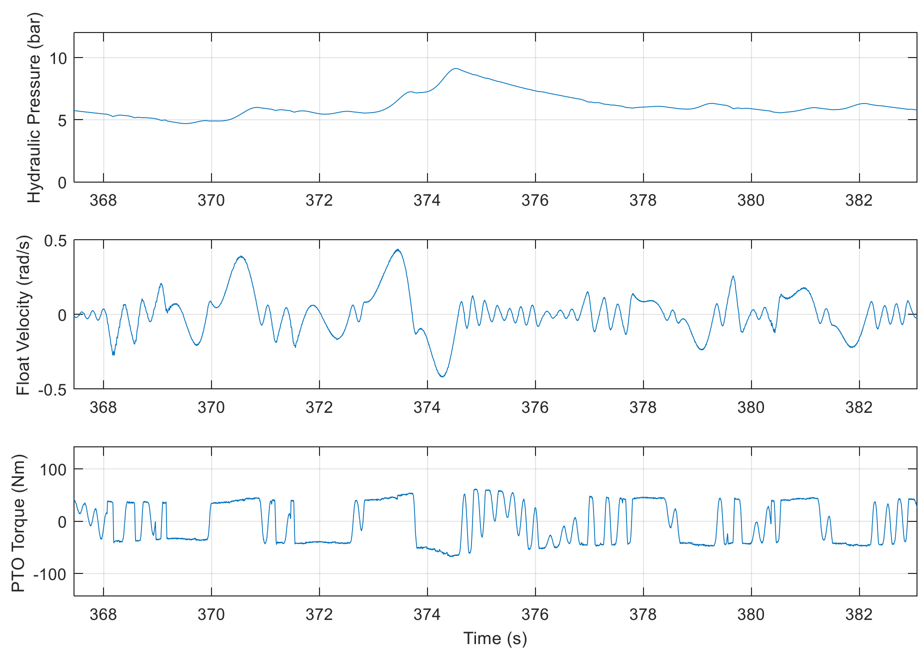


Figure 4-1. Time domain results showing force oscillations caused by hydraulic PTO. Data is a subset of wave case 3 test.

4.3. Variable Force Hydraulic Control

The final controller tested is the variable force hydraulic control. This PTO design is much more preliminary than the directional force control PTO and controller. This hydraulic PTO has the ability to control the magnitude of the force exerted on the float by the PTO, in eight discrete steps. It retained the ability to control the direction of the force exerted on the float. This allowed the hydraulics to more closely track the toque commanded by the MPC controller. The time step for the variable force MPC controller was 0.05s. For all wave cases, the Q scale vale was set equal to the time step, 0.05. For all the variable force hydraulic control tests, the prechargre pressure of the high pressure accumulators was increased to 45 bar, from the 30 bar used in the bang-bang hydraulic control tests and passively controlled hydraulic tests (precharge pressure values at full scale). The wave case 6 tests were not completed due to time constraints. This was an acceptable compromise as the variable force hydraulic control tests were not part of the initial test objectives.

The mean hydraulic power and PTO efficiency for each test, along with the parameters used for the control system, are presented in Table 4-3.

Table 4-3. Control configuration and experimental mean hydraulic power and PTO efficiency for the variable force hydraulic control tests.

Wave Case	Prediction Horizon	R Scale	Motor Coeff (full-scale)	Mean Power Controlled	PTO Efficiency
			Nms/rad	(W)	
1	100	1.0e-8	4	1.348	0.821
2	80	1.0e-8	2.5	2.934	0.829
3	100	1.0e-8	6	3.299	0.887
4	80	1.0e-8	5	4.805	0.821
5	80	1.0e-8	6	4.813	0.851
6	-	-	-	-	

5. Comparison to WEC-Sim Simulations

The experimental control results are compared to the simulation results presented in the Control System Design Report. Comparisons are made with respect to mean power for each wave case. Note the simulations were run using the undisturbed water surface elevation time series from the wave calibration, so the wave conditions are almost identical, subject to the repeatability of the wavemaker system.

A comparison between simulated and experimental mean power for the Ideal MPC is presented in Table 5-1. Note the power data presented are mechanical power. The simulation overpredicts power output compared to the experimental results for wave cases 1 through 5. With the exception of wave case 1, the error between simulation and experimental results is within 8%. Wave case 1 shows a higher percent difference, at 29.1%.

Table 5-1. Ideal MPC mean power, experimental vs. simulation results.

Wave Case	Mean Power Simulation [W]	Mean Power Experimental [W]	Percent Difference
1	2.167	1.679	29.1%
2	3.470	3.215	7.9%
3	3.951	3.707	6.6%
4	5.729	5.654	1.3%
5	5.021	4.672	7.5%
6	10.922	10.969	-0.4%

The comparison of mean hydraulic power between simulation and experimental results for the directional force hydraulic PTO controller is presented in Table 5-2. Values agree within ±11%, with the simulation overpredicting power capture in lower power tests (cases 1 & 2), and the simulation underpredicting power capture in higher power tests (cases 3-6). Note for the hydraulic tests the power values are simulated power output from the hydraulic PTO.

Table 5-2. Directional force hydraulic control, mean power, experimental vs. simulation results.

Wave Case	Mean Power Simulation [W]	Mean Power Experimental [W]	Percent Difference
1	1.378	1.242	11.0%
2	2.379	2.246	5.9%
3	2.462	2.716	-9.4%
4	3.660	4.011	-8.8%
5	3.120	3.516	-11.3%
6	7.175	7.732	-7.2%

The comparison of mean hydraulic power between simulation and experimental results for the variable force hydraulic PTO controller is presented in Table 5-2. There is less agreement between simulated and experimental results for these tests, with errors ranging from 33% to -27%. The same error trend is seen with this controller as the other two controllers, with the simulation overpredicting power for wave case 1, and underpredicting power for wave cases 2-5.

Table 5-3. Variable force hydraulic control, mean power, experimental vs. simulation results.

Wave Case	Mean Power Simulation [W]	Mean Power Experimental [W]	Percent Difference
1	1.795	1.348	33.2%
2	2.910	2.934	-0.8%
3	2.937	3.299	-11.0%
4	4.185	4.805	-12.9%
5	3.485	4.813	-27.6%
6	7.891	-	-

6. Conclusions

Data was collected for all three control algorithms. For the ideal MPC control and the directional hydraulic control, data was collected across all 6 planned wave conditions, meeting the test objectives. The additional tests of the variable force hydraulic PTO was tested in 5 of the 6 planned wave conditions.

Experimental testing showed the control performance was sensitive to the surge position of the model; if the model moved too far forwards or aft of the wave calibration location, the performance of the controller would suffer. This is likely due to the use of a deterministic wave prediction scheme, that does not adapt to the instantaneous surge position of the Azura model. As the surge position deviates further from the calibration location, the accuracy of this deterministic wave prediction will significantly decrease.

The experimental results were compared to the simulation results presented in the "Azura Advanced Controls Report". While a more detailed discussion of the accuracy of the simulation results is presented in the final report for this project, the experimental results generally agree well with the simulation results. There are some discrepancies especially for wave case #1, and larger errors for the variable force hydraulic PTO. Some of the errors can be attributed to the inaccuracies in the deterministic wave prediction caused by the surge drift of the model while under test.

The careful design of the wave tank model PTO, drivetrain, and instrumentation were crucial to the successful test campaign. The PTO was able to accurately track force commands from the controller and hardware-in-the-loop simulation of the hydraulic system. The Speedgoat system made tuning and debugging the control system during testing possible. And the selected instrumentation ensured all necessary data was available both for real-time implementation of control, and proper assessment of the test results.

Appendix A

Test Plan

Azura Full-Scale Design

2018

Test Plan for Wave Tank Testing: Advanced Controls Project

Northwest Energy Innovations

10/24/2018

Project Title: "Advanced Control of the Azura Wave Energy Device"

DE-EE0007693

TABLE OF CONTENTS

1. Introduction

This document describes wave tank testing of advanced control algorithms that will be performed with a 1:15 scale model of the commercial scale Azura wave energy converter in late fall, 2017. These tests will be performed at the Harold Alfond W2 Ocean Engineering Laboratory at the University of Maine - Orono (UMO). The primary objective of these tests will be to measure Azura output power with Model Predictive Control (MPC) implemented. These tests will start soon after the conclusion of baseline tests of the same Azura 1:15 scale model without MPC. Those tests, described in the NWEI document *Test Plan for Wave Tank Testing Fall 2017*, will be performed at the same UMO facility with the same hardware test setup. The results of the MPC tests will be compared to the results of the earlier baseline tests to determine the improvement in output power that results from the addition of MPC.

2. Objectives

1. Collect data in irregular waves that can be used to predict full-scale device performance in six representative bins of the device power matrix with MPC control of an ideal direct-drive PTO.
2. Collect data in irregular waves that can be used to predict full-scale device performance in six representative bins of the device power matrix with MPC control of the Azura hydraulic PTO.

3. Test Article

The test article will be a 1:15 scale model of the NWEI full-scale device. See Figure 3-1 for a CAD rendering of this model. This tank model is described in detail in the NWEI document “Wave Tank Model Specification”. No modifications are planned for this model between the conclusion of baseline testing (per NWEI document *Test Plan for Wave Tank Testing Fall 2017*) and the beginning of these tests.

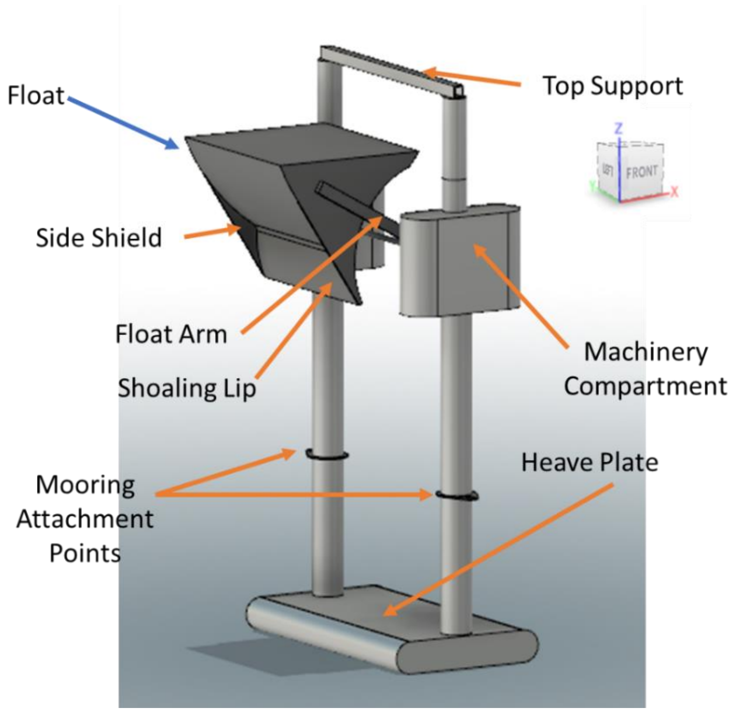


Figure 3-1 Rendering of NWEI tank model

4. Test Facilities

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

NWEI has budgeted for four days of advanced controls debugging and tuning followed by three days of irregular wave testing, then a day for removal. The expected timeline for these tests is shown in Figure 5-1. This schedule assumes that 1) these tests are performed shortly after the conclusion of baseline tests and the test setup is left in place following baseline tests, 2) the test setup is identical to that used for baseline tests, and 3) tank calibration data from baseline irregular wave cases can be used for these tests.

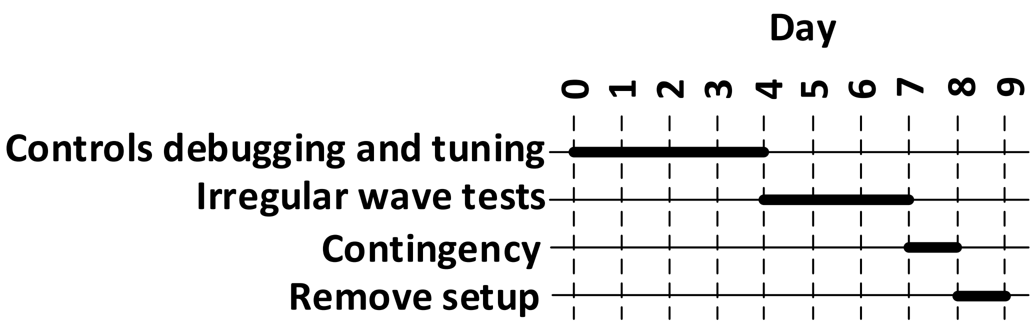


Figure 5-1 Timeline for Azura controls wave tank tests

6. Test Setup

The hardware test setup will be identical to that used for baseline testing and is described in the NWEI document *Test Plan for Wave Tank Testing Fall 2017*. See Figure 6-1 showing the data acquisition and control systems. This diagram is identical to that used for the baseline tests. MPC software and hardware-in-the-loop software simulating a hydraulic PTO will be loaded into the NWEI Speedgoat controller for these tests via the NWEI PC. Several different MPC configurations will be tested.

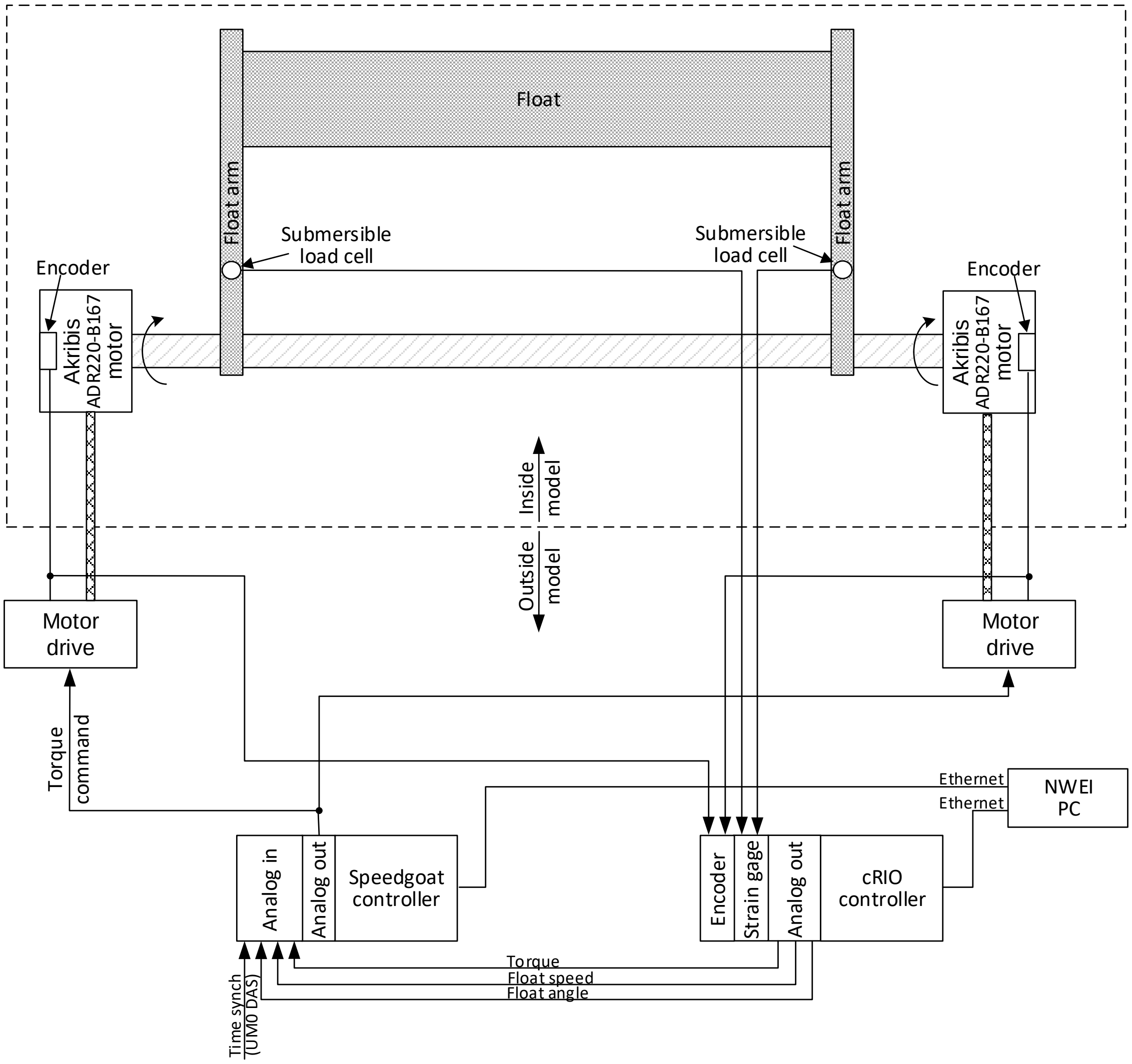


Figure 6-1 Data acquisition and tank model control for NWEI tank test

7. Test Procedures

7.1. Wave tank calibration

Because the wave cases used for these tests will be identical to those used for baseline tests (see NWEI document *Test Plan for Wave Tank Testing Fall 2017)*, baseline calibration data will be used and calibration will not be repeated for these tests.

7.2. Driven PTO test

These tests will be performed during time allocated to controls debugging and tuning to validate PTO performance, and to measure the actuator transfer function between controlled PTO torque and tank model motion.

The Speedgoat controller will be set up to output a white noise torque command to the motor drive (see Figure 6-1) for these tests. Since the tank model PTO is designed for four quadrant control of the PTO generators, the generators are capable of the motoring action needed for this test. A white noise spectra and the corresponding time series torque command will be determined by NWEI prior to performance of the test. The duration of this test is expected to be about 15-30 min. The tank will be allowed to settle before the test is started. While the white noise torque command is applied to the PTO generators, data will be collected from all sensors listed in Table 6-1 of the NWEI document *Test Plan for Wave Tank Testing Fall 2017*, including Qualisys motion data. The resulting data will be analyzed to calculate transfer functions between commanded torque and float arm torque, and commanded torque and device motions.

7.3. Irregular wave tests

See Table 7-1 for a list of irregular wave cases that will be run. These six wave cases are also used for baseline testing (see NWEI document *Test Plan for Wave Tank Testing Fall 2017).* At the onset of testing, tests will be run in various wave conditions and control configurations to debug the control software and real-time instrumentation feedback. Once thoroughly debugged, final runs will be made for each wave case and each control configuration, one with MPC and an ideal direct-drive PTO and one for controlling a hydraulic PTO. The hydraulic PTO will be implemented as a hardware-in-the-loop simulation in Speedgoat controller software. Each controller will utilize parameters from each test that were determined to be optimal from simulations performed prior to testing. Experimental results will be compared to simulation results at the conclusion of each test. Based on observations made during the debugging tests and final tests the test engineer will decide if additional tests with different control parameters are necessary.

Table 7-1 Bulk Wave statistics for Irregular wave runs

Case	Significant Wave Height (m)		Energy Period (s)		Notes
1	1.25	0.083	7.5	1.94	Bretschneider (unidirectional)
2	1.75	0.117	6.5	1.68	Bretschneider (unidirectional)
3	1.75	0.117	9.5	2.45	Bretschneider (unidirectional)
4	2.25	0.150	7.5	1.94	Bretschneider (unidirectional)
5	2.25	0.150	11.5	2.97	Bretschneider (unidirectional)
6	3.25	0.217	8.5	2.19	Bretschneider (unidirectional)

* Note, values in shaded cells are full scale values, unshaded at tank scale.

The following test sequence will be used for the irregular wave runs:

1. Configure Speedgoat software for MPC control of a direct drive PTO.
2. Start data acquisition systems. Record start time, wave spectra, and damping setting.
3. Start wave generation; wait until tank settles to desired condition (< 1 min).
4. Operate for 15 minutes (a single repeat period of the wave elevation time series).

5. Stop data acquisition.
6. Perform basic data quality checks to ensure data was collected and wave tank PTO was functioning properly.
7. Configure Speedgoat software for MPC configuration #1 control of the hydraulic PTO.
8. Repeat steps 2-6 with wave cases #1-6.

Note: The performance of each MPC configuration will be evaluated after testing each wave case; configurations with poor performance may not be tested in all wave cases.

To ensure the model PTO and torque measurements are properly functioning for each test, at the conclusion of each test a scatter plot of the commanded torque vs. measured torque will be displayed on the supervisory computer. A linear regression analysis showing the slope of the correlation and the correlation coefficient will be displayed. If the slope or the correlation coefficient deviates significantly from 1.0, that indicates a problem with either the torque measurement or the model PTO, indicating a problem with the test.

Appendix B

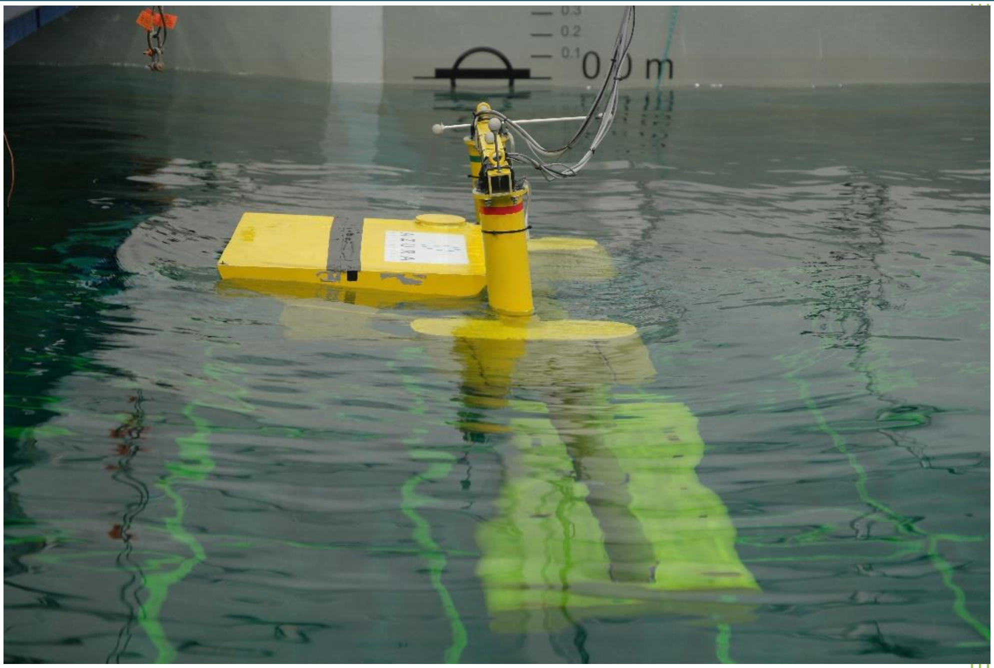
Full Scale Test Report with appendices

northwest energy innovations

Azura Full-Scale Design

2018

Test Report
Wave Tank Tests Dec 2017/ Jan 2018



Northwest Energy Innovations

3/5/2018

TABLE OF CONTENTS

1. Introduction

This document describes the results of wave tank tests that were performed on a 1:15th scale model of the Azura preliminary full-scale design on December 11-22, 2017, and January 22-Febraury 2, 2018. These tests were performed at the Harold Alfond W^2 Ocean Engineering Laboratory at the University of Maine in Orono (UMO). The test objectives were to

1. Record data in a single broadband irregular wave case that can be analyzed to produce experimental Relative Capture Width (RCW) and Response Amplitude Operators (RAOs) with respect to wave frequency for the scale model of the Azura preliminary full-scale design. The resulting RCW and RAOs will be used to confirm validity of the NWEI WEC-Sim model of the full-scale design.
2. Collect data in irregular waves that can be used to predict full-scale device performance at the U.S. Navy's Wave Energy Test Site (WETS) near Kaneohe, Hawaii.

The results of this test are presented in this report.

2. Test Plan

The NWEI document "Test Plan for Wave Tank Testing, Fall 2017" is included in Appendix A 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 2-1 and Figure 2-2 for photos of the Azura tank model operating in the UMO tank during the test.

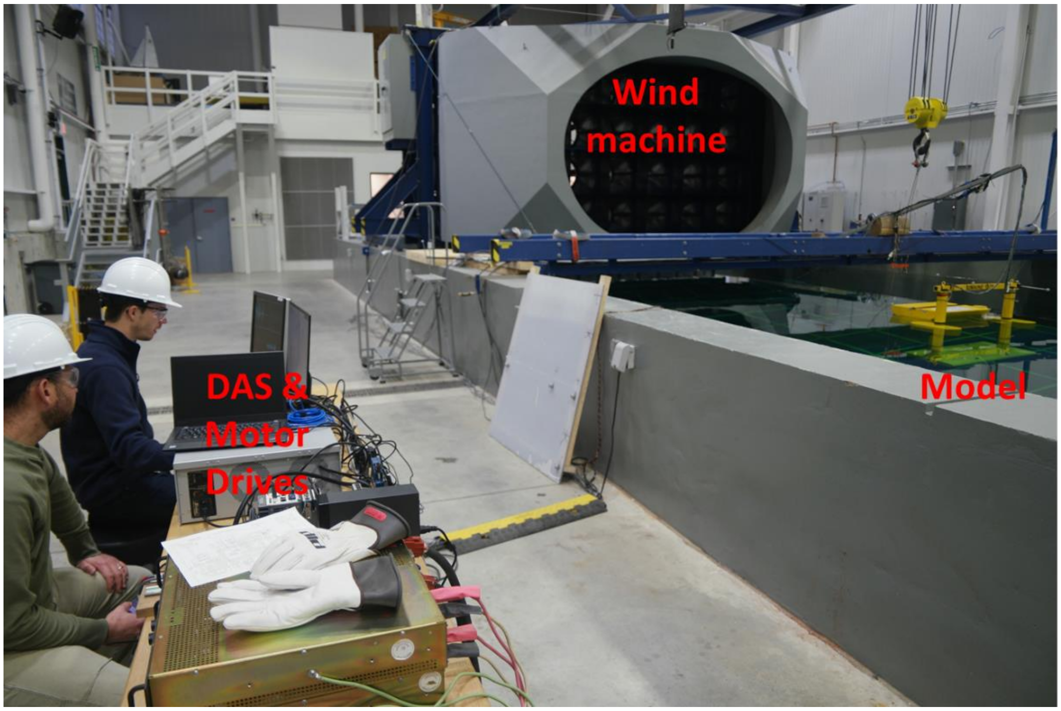


Figure 2-1 UMO wave tank during NWEI test

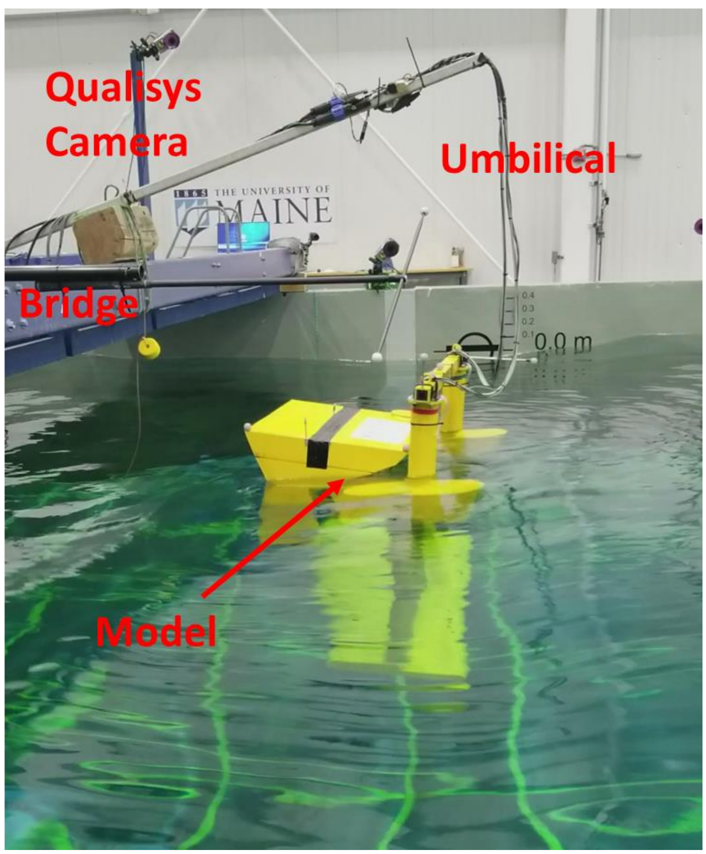


Figure 2-2 Close up of tank model during the tests

3. Test Results

3.1. Motor Drive Verification Tests

A series of tests were performed to characterize the motor and motor drive subsystems. A staged testing approach was taken, gradually adding complexity to the test. First, each motor drive was tested separately with no load attached to the rotor. A small magnitude, band limited white noise torque command was passed to the motor. The motor drive performance was evaluated by looking at the frequency response of the measured motor current vs. the commanded motor current. This process was used to tune the motor drive control loop. The final bode plot of the frequency response of each motor drive is shown in Figure 3-1. Note the measured current used for this was measured by the motor drive, and corresponds to the RMS current of the three motor phases.

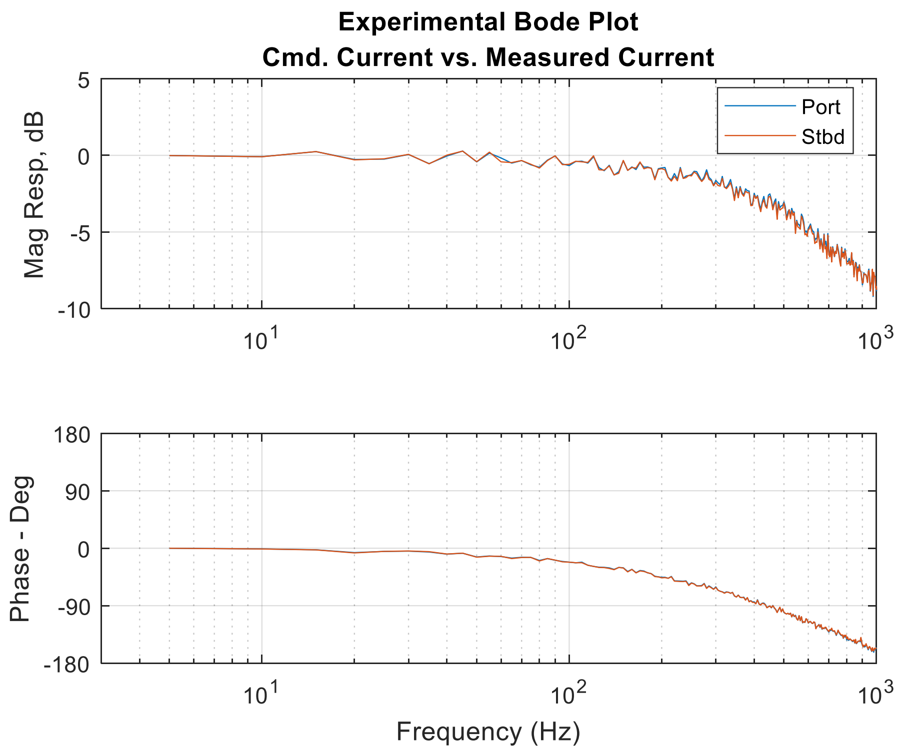


Figure 3-1. Experimental Bode plot with commanded motor current input and measured motor current output. Each motor drive response is plotted separately.

After the motor drives' frequency response were tuned, the motor torque coefficients were verified. This was done by installing the motor, torque sensor, and float arm into a fixture that allowed the float arm to be pinned, preventing rotation. A photo of the fixture used for testing the motor torque coefficients is shown in Figure 3-2.

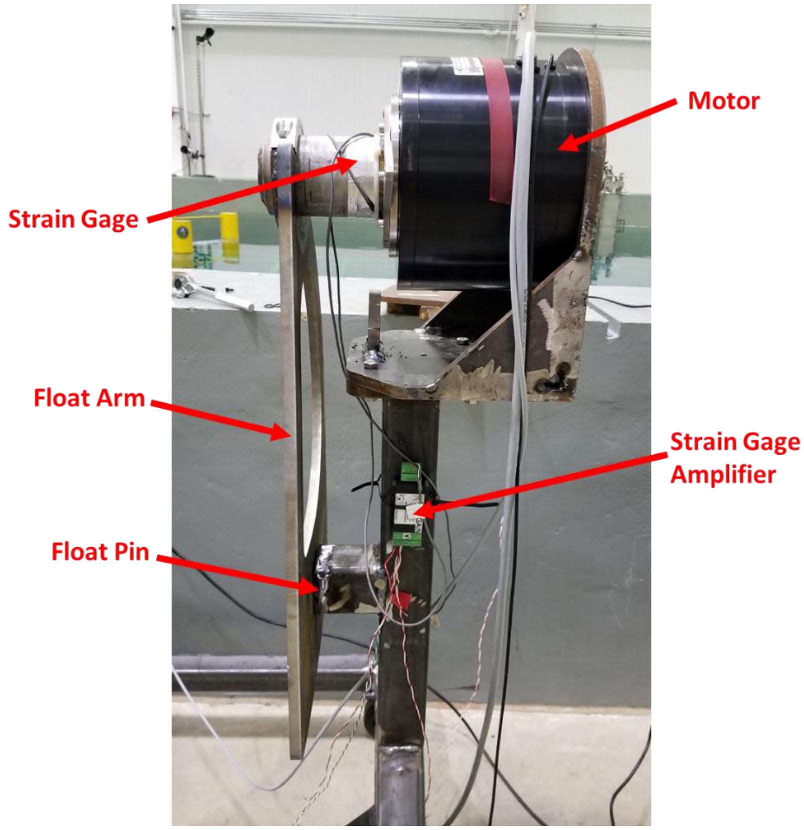


Figure 3-2. Photo of motor torque calibration fixture.

Once the steady state gain motor gains were verified, the next step was to check the frequency response of measured torque vs. commanded torque. This test will be influenced by the dynamics of the WEC, and its hydrodynamics, so the test was run with the model fully assembled and free floating in the wave basin. This is required because it is possible the float arm structure or the WEC dynamics couple with the motor dynamics to change the overall frequency response of measured torque at the drive shaft. The test was performed by commanding a band-limited white noise torque command from 10-1000 Hz. A low frequency, larger magnitude torque command was also included into the command at 0.5 Hz to break the shaft seal, ensuring the shaft had a non-zero velocity during the test. The bode plot of total measured torque vs commanded torque is shown in Figure 3-3. Note this test was run with both motors operating in parallel. This bode plot shows a possible resonant mode at 700 Hz.

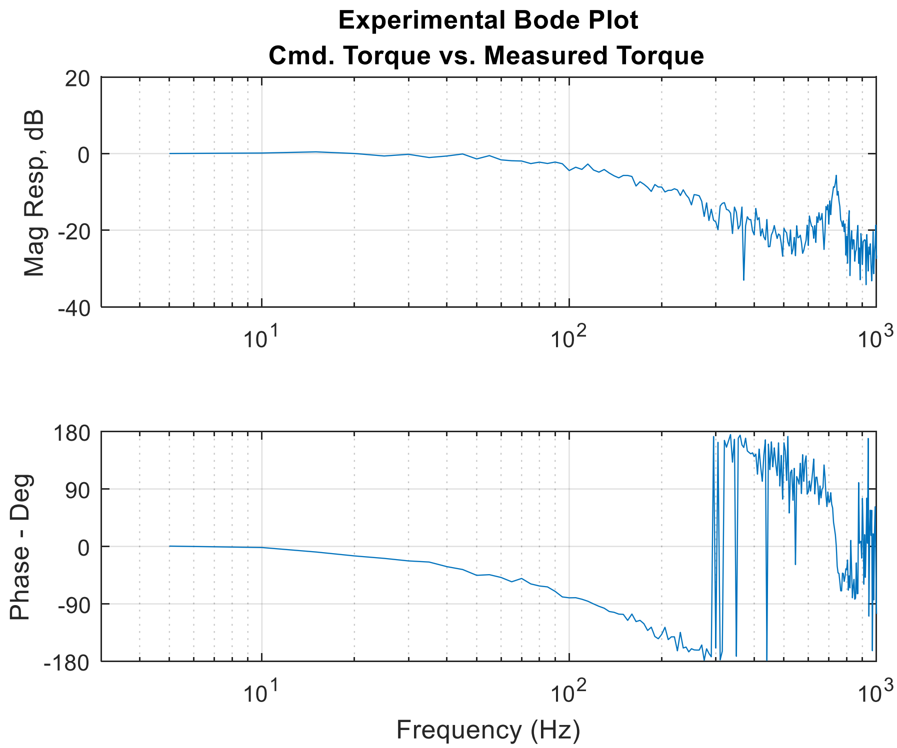


Figure 3-3. Experimental Bode plot with commanded torque input and measured torque output.

The final motor drive verification test was to look at the frequency response of the measured velocity vs. commanded torque. This response was taken from the same test data performed to measure the commanded torque vs. measured torque frequency response. This frequency response represents the open loop response of the closed loop system when damping control is applied to the model. Damping control will be feeding back measured velocity, applying a gain value, and using that to command torque. Since this is closing a control loop, a stability analysis is required to ensure the system remains stable during the test.

To ensure this loop is stable, the damping coefficient must be less than the gain margin of the open loop frequency response, which is the difference between the magnitude and 0 dB at the frequency where the phase is equal to 180˚. The highest anticipated damping coefficient anticipated during the test is 700 Nms/rad, which corresponds to approximately 57 dB. Initial tests showed the gain margin was not sufficient to maintain stability at this gain, so a second order low pass filter was added to the loop. This filter was applied to the torque command in software, and was a Butterworth filter with a corner frequency of 100 Hz, bode plot shown in Figure 3-4. This filter proved to be sufficient to stabilize the closed loop system without significantly detracting from the low frequency performance of the motor drive control loop. The final experimental bode plot of the open loop response of measured velocity vs commanded torque is shown in Figure 3-5. This bode plot shows a crossover frequency of 350 Hz, with a gain margin of 62 dB, which is greater than the required 57 dB. The stability of the system was then verified by closing the loop and applying the maximum damping coefficient to show system stability.

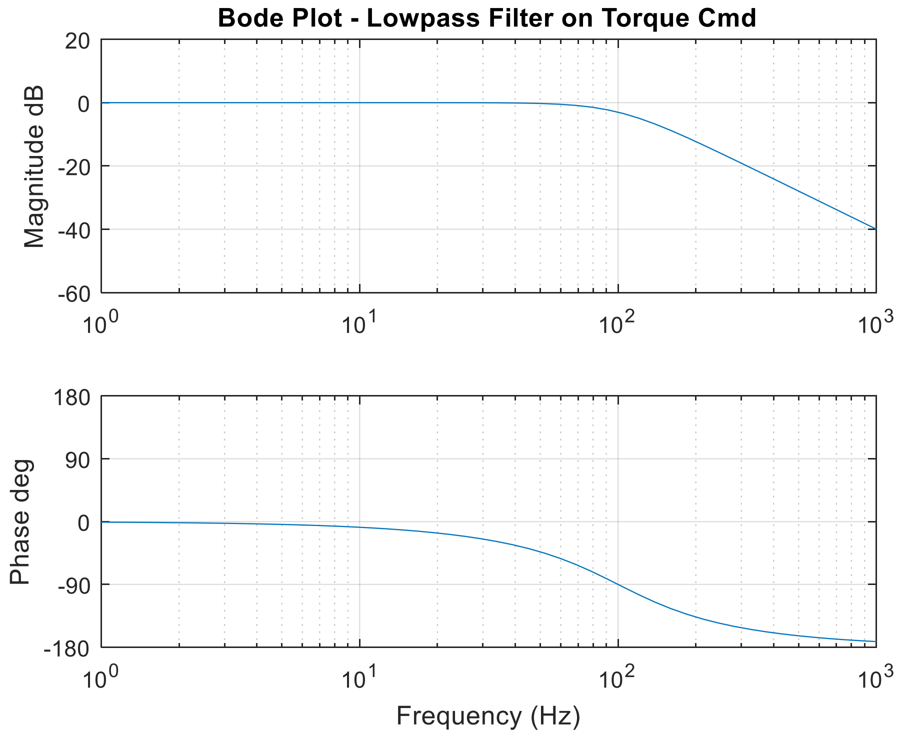


Figure 3-4. Bode plot of second order lowpass filter applied to torque command.

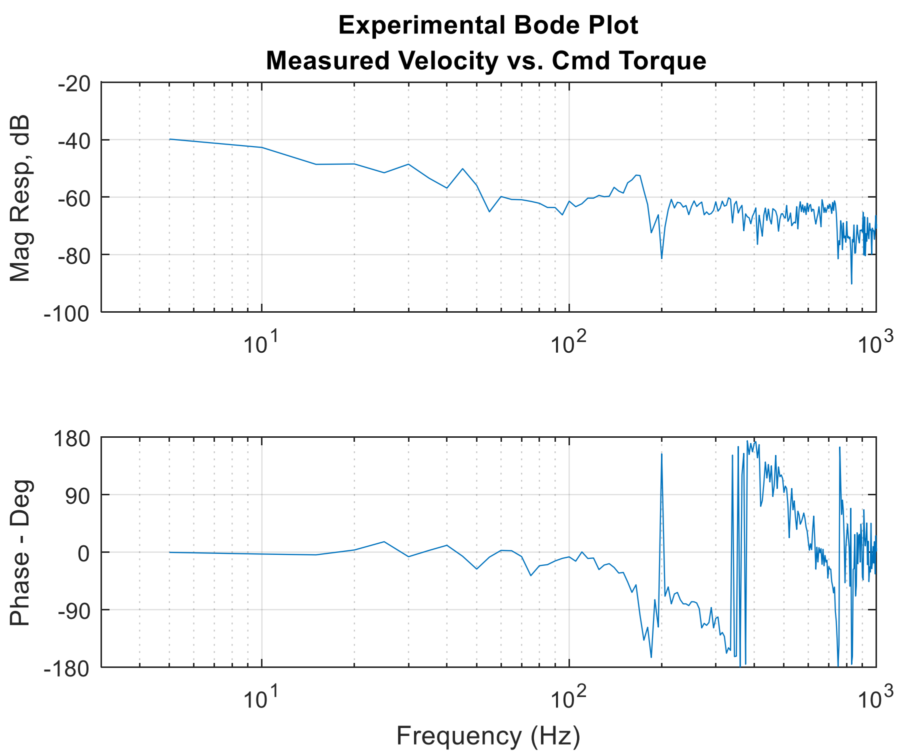


Figure 3-5. Experimental Bode plot with commanded torque input and measured velocity output.

3.2. Float Arm Torque Measurement Calibration Check

A description of the float arm torque calibration process is provided Appendix B: the UMO Report "Design, Construction, and Measurement Report for the NWEI 1:15 Scale Model Wave Energy Converter". Appendix B of the report describes the process used to calibrate the strain gages' torque response.

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

See Appendix B, the UMO Report "Design, Construction, and Measurement Report for the NWEI 1:15 Scale Model Wave Energy Converter" for the mass, CG, and MOI results. Table 2 and Table 3 in the report summarize the mass property measurement results. These measurements were made per Sections 7.1, 7.2, and 7.3 of the test plan (Appendix A) respectively.

3.1. Wave Calibration

For all wave environments, the waves were calibrated so the measured wave spectra matched the specified spectra. Wave runs were made with no model in the basin, and an array of wave probes placed at the location of the model. A drawing showing the location of the wave probes is shown in Figure 3-6.

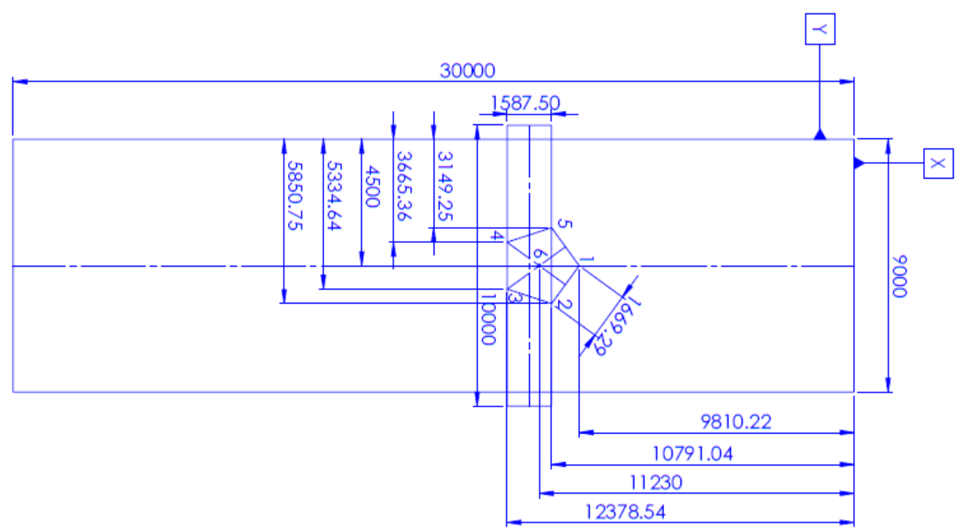


Figure 3-6. Calibration wave probe location drawing. Wave probe #6 is located at the model location. The wave maker is located along the X datum. Dimensions are in mm.

The wave calibration data was processed and compared to the specified wave spectra. Plots comparing the measured and specified wave spectra are shown in Figure 3-7. Spectral parameters significant wave height (H_{m0}), Energy Period (Te), and incident wave energy flux (J) were calculated for all specified and measured wave spectra. A comparison of these parameters is shown in Table 3-1. No deep-water approximation was made when calculating wave energy flux, the wave number for each frequency component was calculated using the dispersion relation. Note that for all wave spectra, the incident wave energy flux was lower than the specified values by between 5-20%. This necessitates using capture width instead of mean power to extrapolate results to Kaneohe.

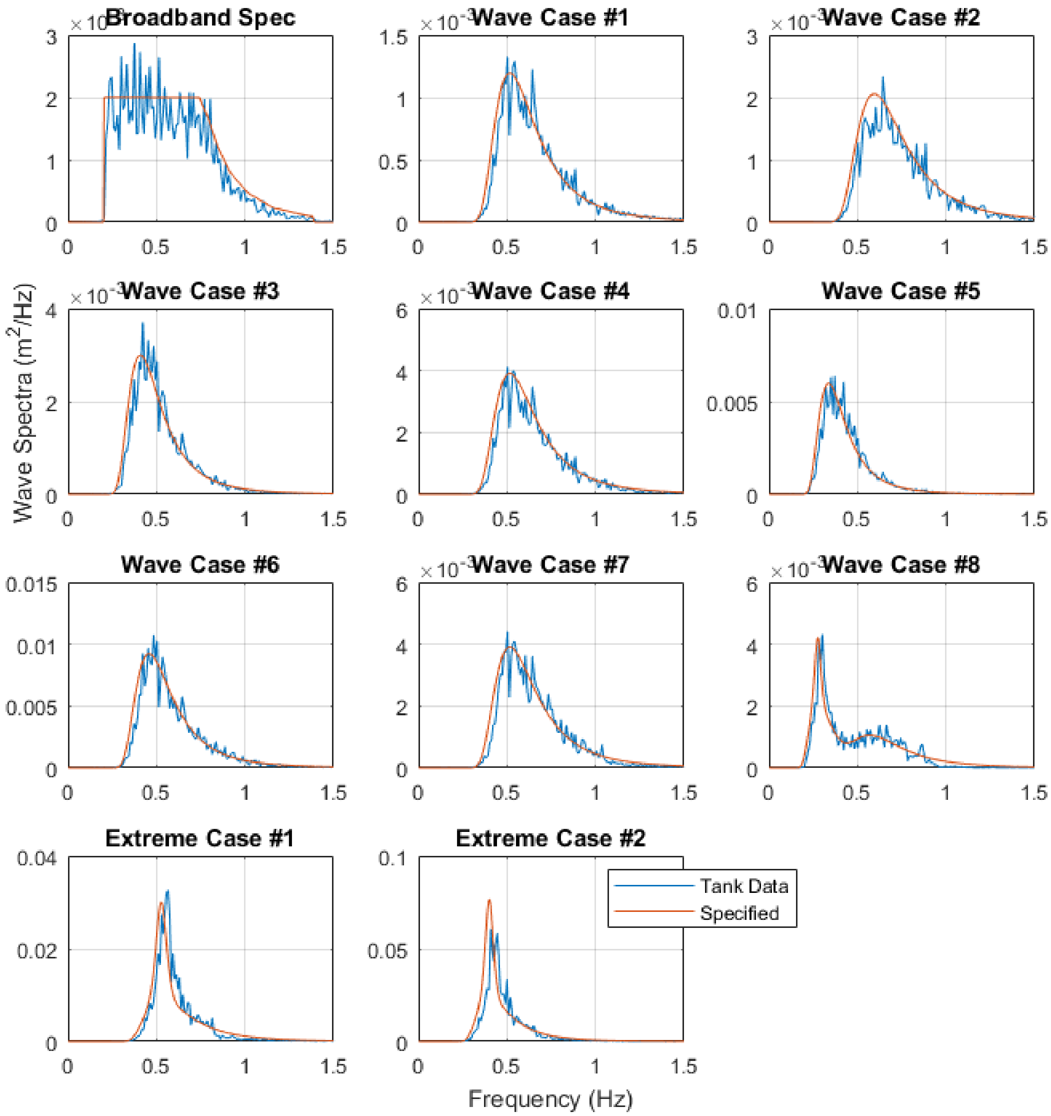


Figure 3-7. Comparison of calibration wave spectra and specified wave spectra.

Table 3-1. Spectral parameters, measured vs. specified.

Wave Case	H_{m0} Target	H_{m0} Actual	Te Target	Te Actual	Energy Flux Target	Energy Flux Actual	Energy Flux Pct Diff
	m	m	s	s	W/m	W/m	
Broadband	0.153	0.142	2.074	2.15	24.883	22.257	-10.6%
1	0.083	0.08	1.663	1.659	5.506	5.069	-7.9%
2	0.117	0.107	1.44	1.436	9.434	7.943	-15.8%
3	0.117	0.114	2.1	2.078	14.16	13.275	-6.3%

4	0.15	0.14	1.663	1.66	17.983	15.569	-13.4%
5	0.15	0.147	2.546	2.504	29.405	27.635	-6.0%
6	0.217	0.208	1.877	1.863	42.875	38.94	-9.2%
7	0.15	0.143	1.663	1.659	17.983	16.306	-9.3%
8	0.118	0.112	2.446	2.52	17.831	16.567	-7.1%
EX1	0.28	0.274	1.716	1.743	64.621	62.649	-3.1%
EX2	0.39	0.355	2.258	2.229	169.898	137.013	-19.4%

3.2. Data recorded

The following data was recorded during each 30 minute wave tank run listed in the Test Matrix (see Table 6-1 and 6-2 of the test plan included in Appendix A). Separate 15 minute duration data files were recorded for each test run.

- NWEI speedgoat data in Matlab .mat format sampled at 250 Hz for float angle, float velocity, float torque, wavemaker enable, motor current, and commanded torque. The wavemaker enable 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:

Ideal Damping Tests	WC#_D###_#_MMDDhhmmss.mat
Hydraulic PTO Tests	WC#_H###_#_MMDDhhmmss.mat
Extreme Wave Tests	WC#_EX###_#_MMDDhhmmss.mat

  WC1_D120_MMddyy_hhmmss.mat where "WC#" refers to wave case #, "D###" refers to a target damping of ### Nm-s/rad, the "_#_" is an index for repeated cases, and MMddyy_hhmmss is the data and time of the end of the file.
- UMO Qualisys motion tracking data in MATLAB .MAT format sampled at 100 Hz.
  File name format matches the NWEI format, but does not include the time stamp.
- Qualitative observations of each test and preliminary mean power results were recorded in an excel spreadsheet. This was used for making decisions in real-time about what damping values to test next during testing.

In addition, wave calibration data was recorded prior to the test runs and saved in .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 five other wave probes, with locations shown in Figure 3-6.

3.3. Relative capture width results

NWEI analyzed the data recorded for each test run to produce the relative capture width (RCW) plots shown in Figure 3-8 through **Error! Reference source not found.** with test runs using the broadband wave case and 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 15 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 15 minute data periods as follows:

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

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

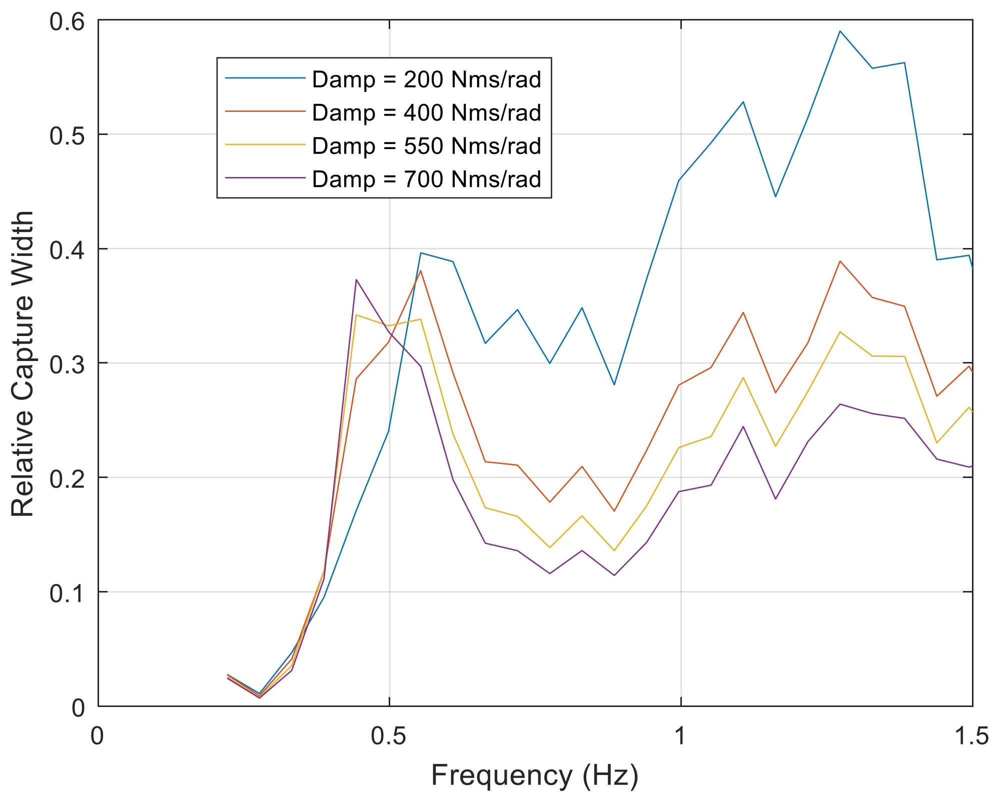


Figure 3-8 RCW for the broadband wave spectra, wave case #0.

3.4. 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 3-11 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):

$$H(\omega) = \frac{S_{yy}(\omega)}{S_{xx}(\omega)},$$

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.

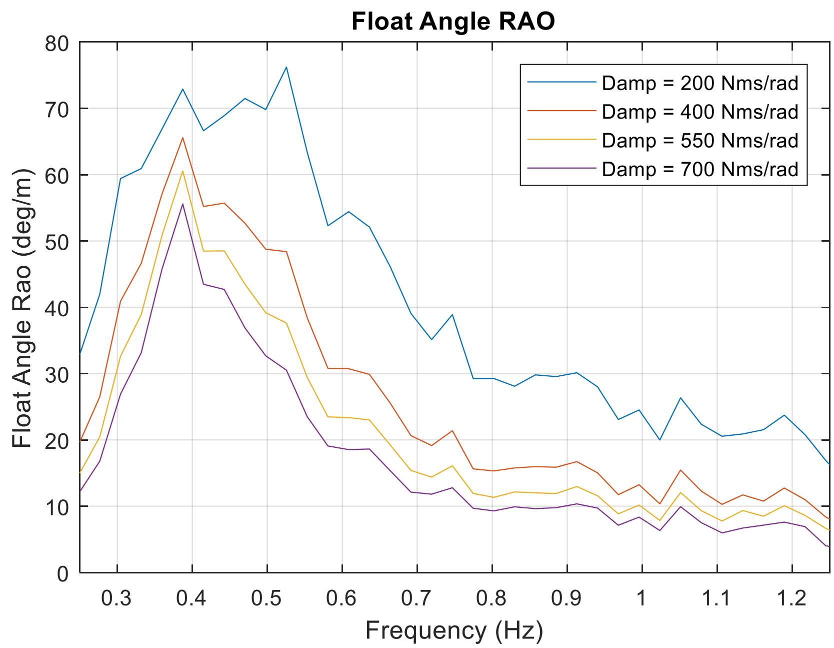


Figure 3-9. Float angle RAO from broadband wave spectra tests.

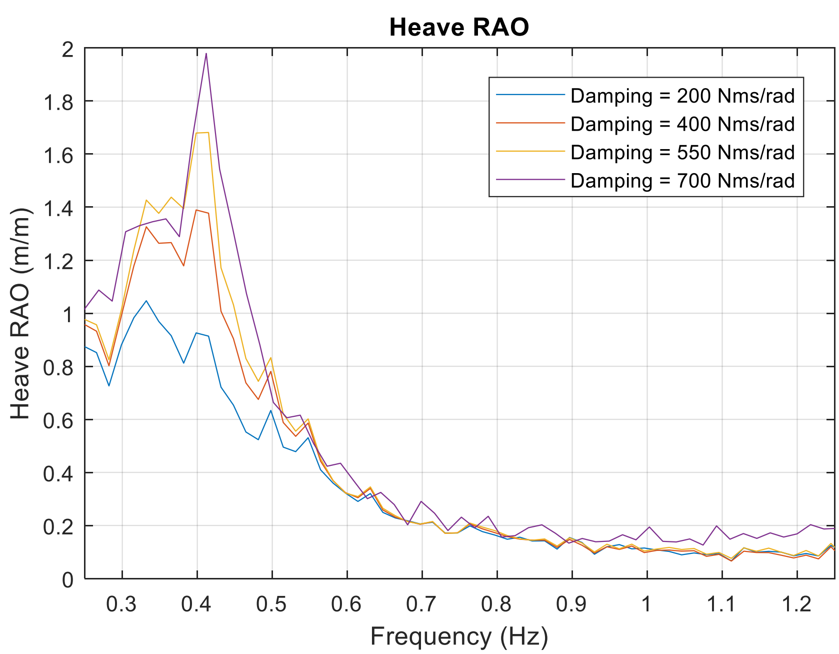


Figure 3-10 Hull heave RAO from broadband wave spectra tests.

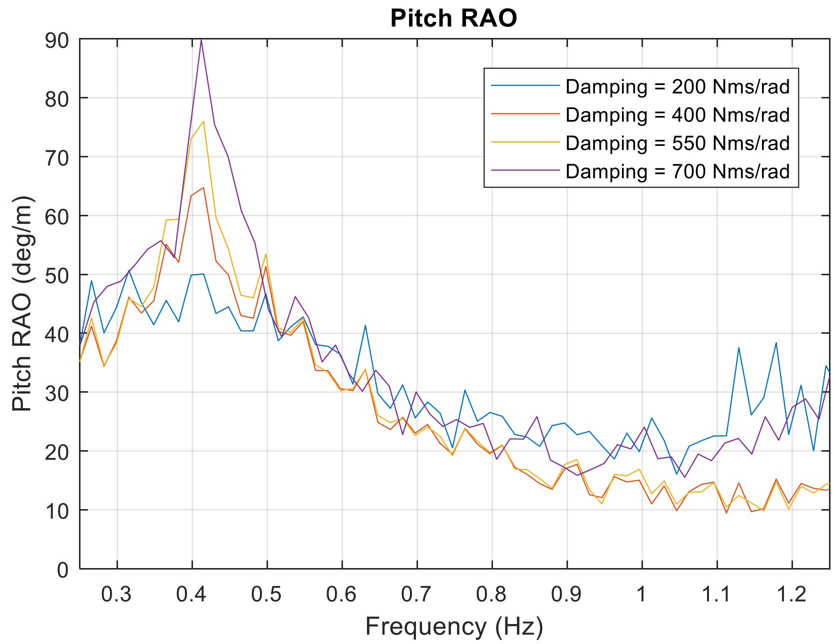


Figure 3-11 Hull pitch angle RAO from broadband wave spectra tests.

3.5. Linear Damping Results

Linear damping tests were run per the test plan by cycling through damping coefficients near the predicted optimal damping coefficient until a local optimal damping coefficient with respect to mean power was identified. This process was repeated for each of the eight wave cases. The results for the maximum produced power for each wave case is listed in Table 3-2. Along with the optimal damping coefficient and mean power, the capture width and motor torque correlation coefficient (R^2) are listed. The correlation coefficient shows how well the motor drives tracked the commanded torque, a value of 1.0 would indicate perfect torque tracking. Mean power is calculated from the product of measured total torque and float velocity. The mean of this product of these signals was then taken for all time values when the wavemaker was on.

Table 3-2. Ideal damping tests mean power and damping coefficient. Only the setting with the maximum power output is listed.

Wave Case	Damping	Mean Power	Wave Energy Flux	Capture Width	Motor Torque R^2
	Nms/rad	W	W/m	m	
1	100	1.2104	5.07	0.24	0.991
2	100	2.3126	7.94	0.29	0.994
3	450	2.7731	13.28	0.21	0.994
4	220	3.7252	15.57	0.24	0.996
5	375	3.9482	27.64	0.14	0.996
6	150	8.4417	38.94	0.22	0.996
7	150	4.0917	16.31	0.25	0.996

8	400	1.4702	16.57	0.09	0.995

3.6. Hydraulic PTO Results

Hydraulic PTO test results were run in the same manner as the linear damping tests. Hydraulic motor damping coefficients were cycled through near the simulated optimal coefficient until the local optimal coefficient was identified. The results for the optimal setting for each wave case is shown in Table 3-3. For this test, the hydraulic PTO was simulated using a hardware in the loop simulation. The dynamics of the hydraulic system were simulated in real-time on the speedgoat computer. The speedgoat then commands a motor torque to the motor drives that emulates the dynamics of the hydraulic PTO. Figure 3-12 shows an example time series of the motor commanded torque and measured torque for a hydraulic test. The figure shows good torque tracking, which is confirmed numerically during each test by looking at the correlation coefficient of commanded vs measured motor torque listed in Table 3-3.

The motor coefficient listed in the table is the torque coefficient applied to the hydraulic motor. The mean power is the mean simulated hydraulic power produced by the PTO during the test, taken for all times when the wavemaker was on. PTO efficiency was determined by first calculating mechanical absorbed power, from the product of measured torque and measured float velocity. The mean hydraulic power was then divided by the mean mechanical power, yielding efficiency. Note that the HIL simulation included all hydraulic losses, but did not include electrical efficiencies from the inverters and electric generator.

Table 3-3. Hydraulic tests mean power and damping coefficient. Only the setting with the maximum power output is listed.

Wave Case	Motor Coeff.	Mean Power	Wave Energy Flux	Capture Width	PTO Efficiency	Motor Torque R^2
	Nms/rad	W	W/m	m		
1	2.8	1.081	5.07	0.21	0.899	0.996
2	1.8	2.032	7.94	0.26	0.887	0.997
3	5.4	2.389	13.28	0.18	0.930	0.998
4	5	3.403	15.57	0.22	0.935	0.998
5	6	3.260	27.64	0.12	0.947	0.998
6	6	7.117	38.94	0.18	0.956	0.997
7	5	3.673	16.31	0.23	0.941	0.997
8	5	1.236	16.57	0.07	0.925	0.996

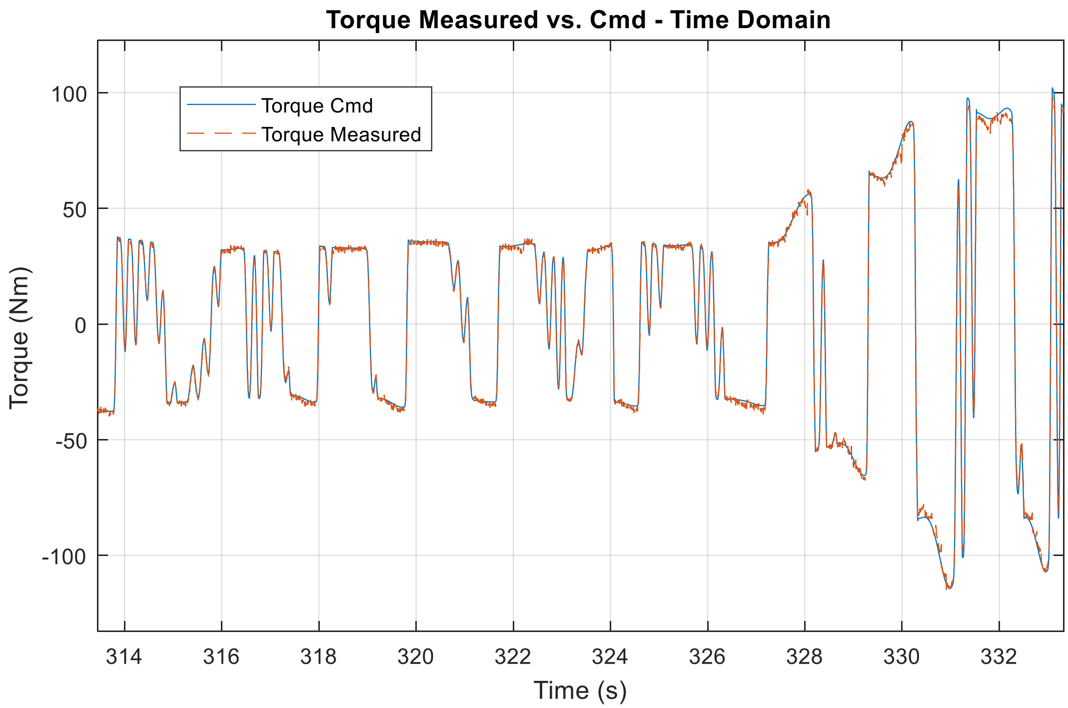


Figure 3-12. Example time domain data showing commanded and measured torque.

3.7. Extreme Event Tests

For the extreme wave tests, additional weight was added to the float, and ballast weight was removed from the hull. This simulates the ballast control that is planned for the full scale design. A few tests were run in the extreme wave configuration with sea state #6 before proceeding into the extreme wave cases, EX1 and EX2.

During the extreme wave tests, a few times the model yawed greater than 90˚ from the oncoming wave directions, and ended up pointing in the reverse direction as intended. When this occurred, the test was immediately stopped to prevent damage from occurring to the model. The tests were repeated multiple times, and the behavior was repeatable, occurring at the same point in time during the test. It appeared that the mean drift forces on the device were not enough to maintain tension in the mooring lines at all times, and this caused the mooring system to fail to weathervane the device into the waves before it yawed past 90 degrees.

After experimenting with different PTO settings, the wind machine was run during the tests. The wind direction was in line with the wave direction for all the tests. The addition of wind loads on the model eliminated any problems with the yaw stability of the model. The additional wind speed pushing on the device maintained tension in the moorings, and the model weathervaned into the mean wave direction as anticipated. Extreme wave events do occur during storms, and would be accompanied by wind, so the addition of the wind to the extreme waves likely creates a more accurate survival test. That being stated, additional mooring design and analysis will be required to ensure this cannot occur to the Azura commercial prototype when deployed at the Kaneohe test site.

Table 3-4. Extreme wave test matrix. Tests that were cut short due to the model yawing past 90˚ are indicated by orange shading. The listed wind speeds are the full scale equivalent wind speeds.

Wave Case	PTO Setting	Wind Machine	Comments
6	Damping, 500 Nms/rad	Off	
6	Hydraulics, 4 Nms/rad	Off	
EX1	Damping, 500 Nms/rad	Off	
EX1	Hydraulics, 4 Nms/rad	Off	Model yaw past 90˚
EX1	Hydraulics, 4 Nms/rad	Off	Model yaw past 90˚
EX1	Hydraulics, 3 Nms/rad	Off	Model yaw past 90˚
EX1	Hydraulics, 3 Nms/rad	Off	Model yaw past 90˚
EX2	Damping, 500 Nms/rad	Off	Model yaw past 90˚
EX2	Damping, 500 Nms/rad	Off	Model yaw past 90˚
EX2	Damping, 250 Nms/rad	Off	Model yaw past 90˚
EX2	Damping, 250 Nms/rad	On, 7 m/s Full scale speed	
EX2	Damping, 350 Nms/rad	Off	
EX2	Hydraulics, 4 Nms/rad	On, 7 m/s Full scale speed	
EX1	Hydraulics, 3 Nms/rad	On, 5.5 m/s Full scale speed	
6	Hydraulics, No Load	Off	
EX2	Hydraulics, 4 Nms/rad	On, 5.5 m/s Full scale speed	

The model exhibited good stability in all other modes of motion, except for yaw, during all tests. The largest waves would overtop the float, which reduced the response of the float to the large waves. Significant pitch angles were observed during the tests, but the model would always revert back to its equilibrium position. No significant wave slamming events were witnessed on any part of the structure. A few times during extreme wave case #2 the water surface would briefly overtop the top of the hull uprights. One case was run simulating a loss of PTO functionality in wave case #6. The model showed good stability during this test as well.

APPENDIX A
TEST PLAN

Azura Full-Scale Design

2018

Test Plan for Wave Tank Testing Fall 2017

Northwest Energy Innovations

3/5/2018

Table of Contents

1. Introduction

This document describes wave tank tests that will be performed on a 1:15 scale model of the commercial scale Azura wave energy converter in the fall of 2017. These tests will be performed at the Harold Alfond W2 Ocean Engineering Laboratory at the University of Maine - Orono (UMO). The primary objective of these tests will be to collect data that will use to predict full-scale device performance at the U.S. Navy's Wave Energy Test Site (WETS) near Kaneohe Bay, Hawaii. These tests follow earlier wave tank tests that NWEI performed at the UMO facility in April 2017 using an earlier version of its design. During those tests a limited number of broadband irregular wave cases were run to validate NWEI's WEC-Sim simulation model of its design; that simulation model has since been used to optimize performance of the current Azura design.

2. Objectives

1. Record data in a single broadband irregular wave case that can be analyzed to produce experimental Relative Capture Width (RCW) and Response Amplitude Operators (RAOs) with respect to wave frequency for the scale model of the Azura preliminary full-scale design. The resulting RCW and RAOs will be used to confirm validity of the NWEI WEC-Sim model of the full-scale design.
2. Collect data in irregular waves that can be used to predict full-scale device performance at the U.S. Navy's Wave Energy Test Site (WETS) near Kaneohe, Hawaii.

3. Test Article

The test article will be a 1:15 scale model of the NWEI full-scale device. See Figure 3-1 for a CAD rendering of this model. This tank model is described in detail in the NWEI document "Wave Tank Model Specification", which is included in Appendix A of this document.

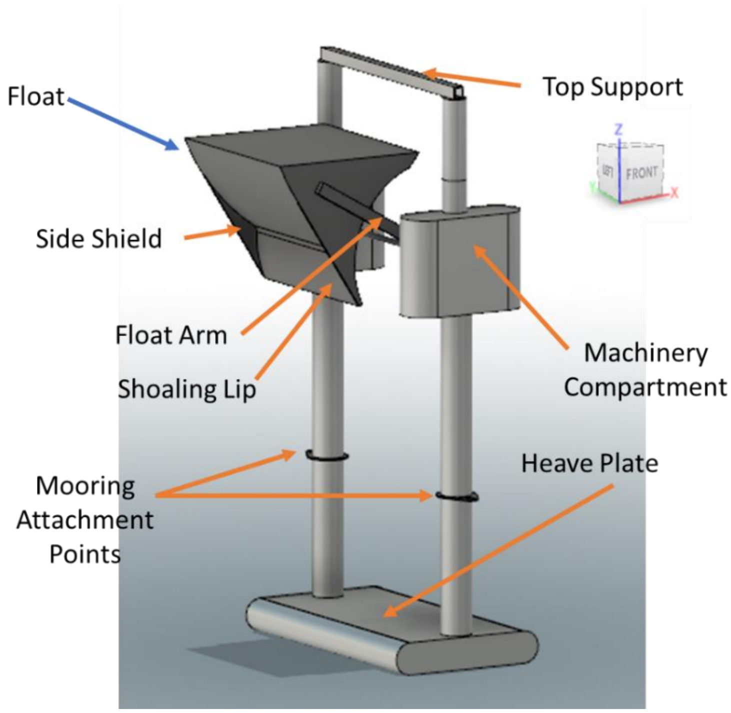


Figure 3-1 Rendering of NWEI tank model

4. Test Facilities

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

NWEI has budgeted for seven days of wave tank calibration followed by nine days of test setup, wave tank testing, and removal. The expected timeline for these tests is shown in Figure 5-1. Three days is allocated for tank model setup after tank calibration is complete, followed by five days of tank testing and a day to remove the setup. Tank model setup includes instrumentation and data acquisition setup, testing, and troubleshooting, and running test wave cases to verify correct operation. Center of gravity and moment of inertia tests will be concurrent with the tank model setup. Hydrostatic tests to verify waterline and tilt of the tank model float and hull will be conducted prior outside the wave tank, prior to these tests.

One day is included in the schedule for extreme wave testing. Extreme wave testing is an option to be decided on as budgets are established.

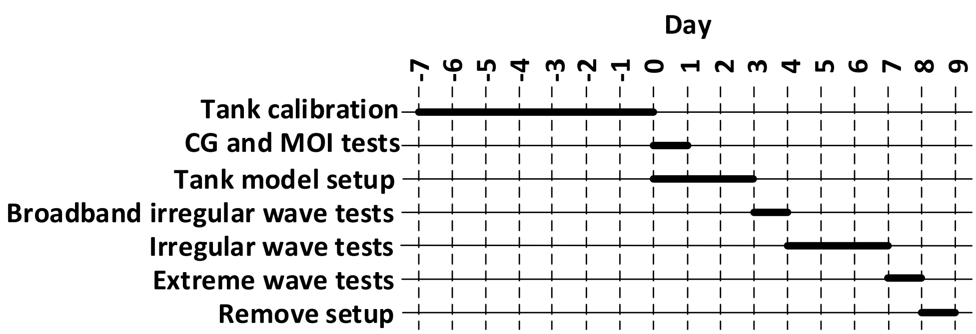


Figure 5-1 Timeline for Azura Fall 2017 wave tank tests

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

A single point mooring system will be used for these tests. Figure 6-2, Figure 6-3, and Figure 6-4 show the mooring layout. The model will be centered in the width of the tank and 12.5m from the wave maker as shown in Figure 6-1. 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 tank model during NWEI’s April 2017 tank tests so that the float was always parallel to incoming unidirectional seas.

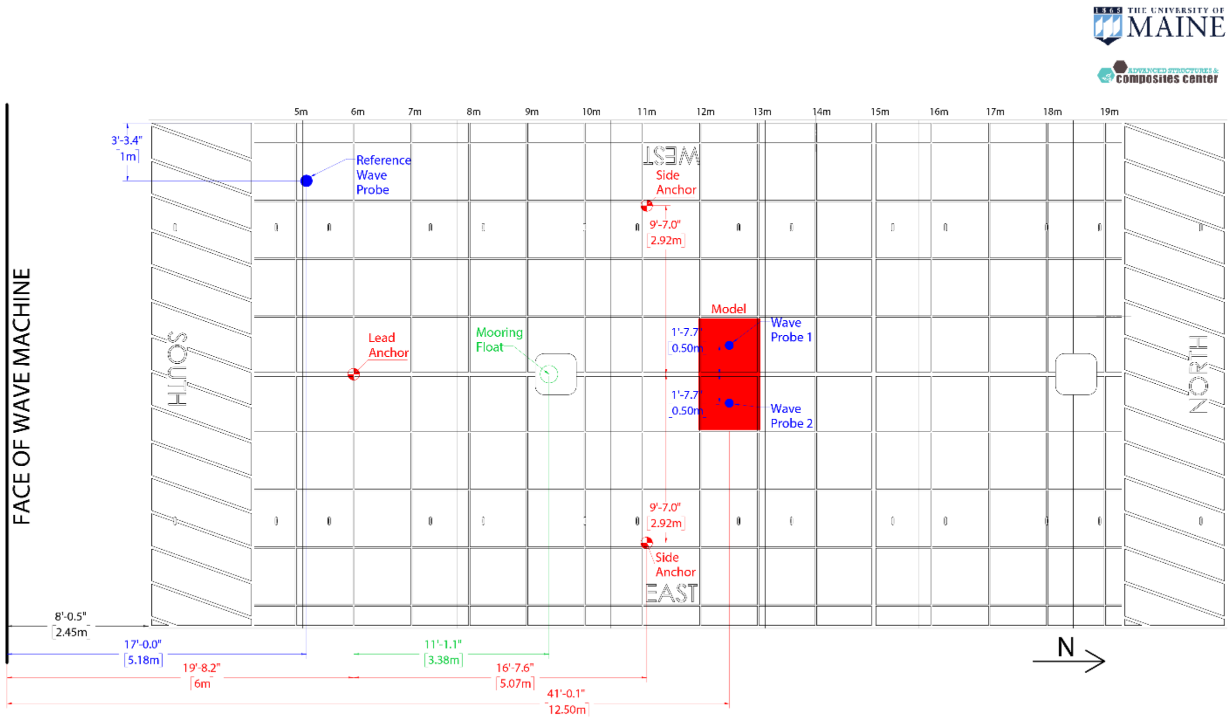


Figure 6-1 Mooring and Model Layout in W2 Basin

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.

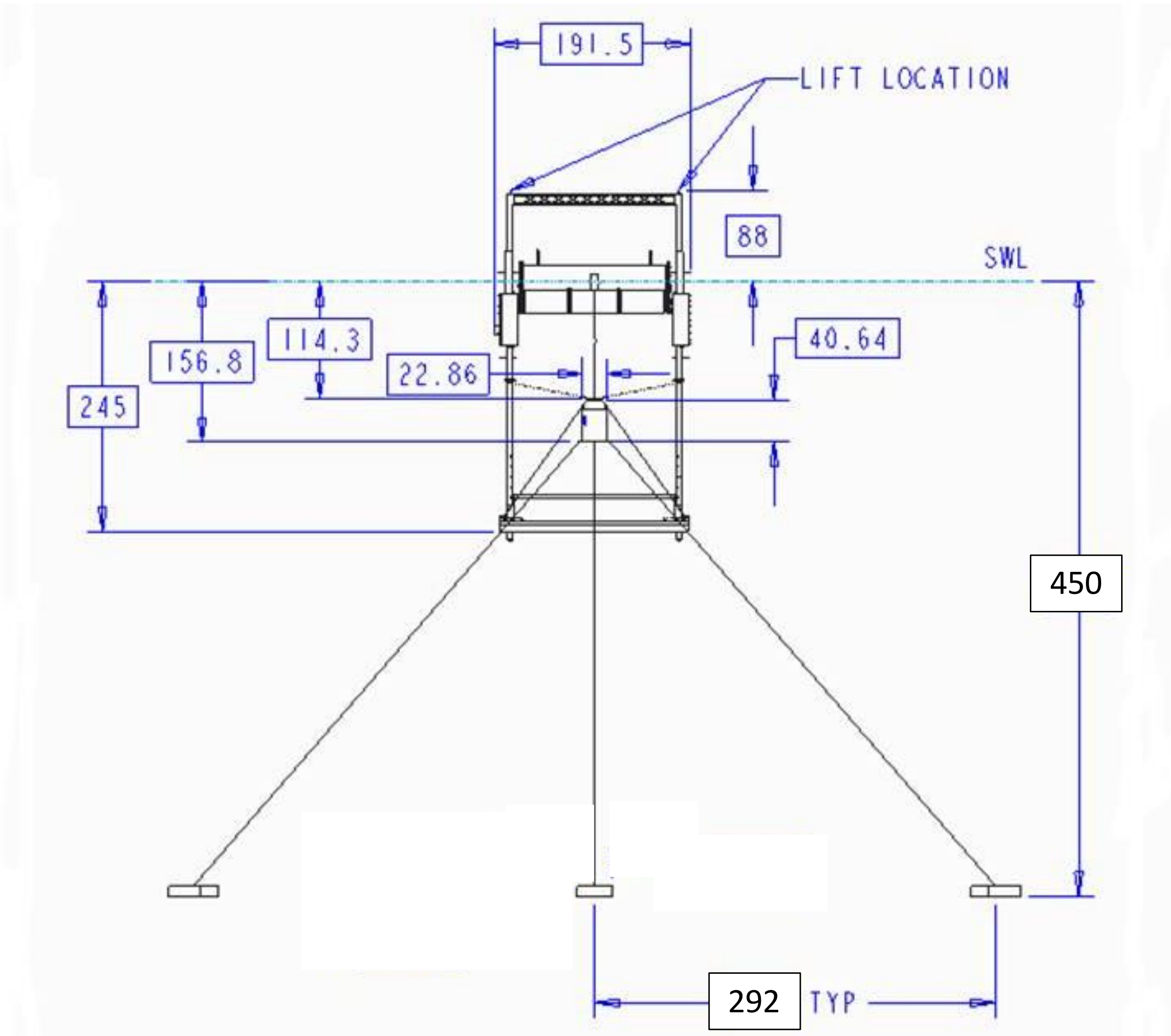


Figure 6-2 Mooring diagram – view from wave generator end (preliminary)

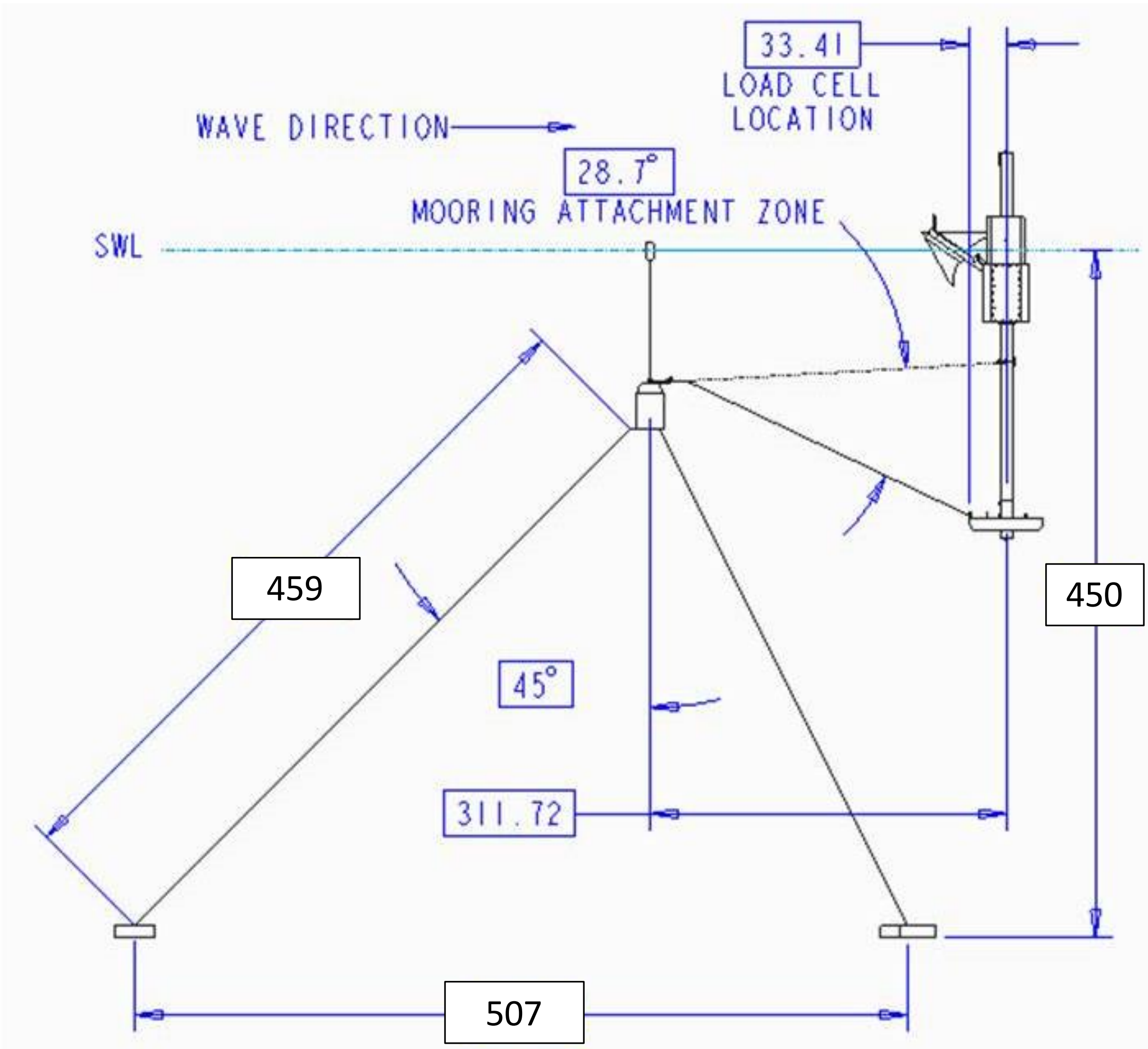


Figure 6-3 Mooring diagram – side view (preliminary)

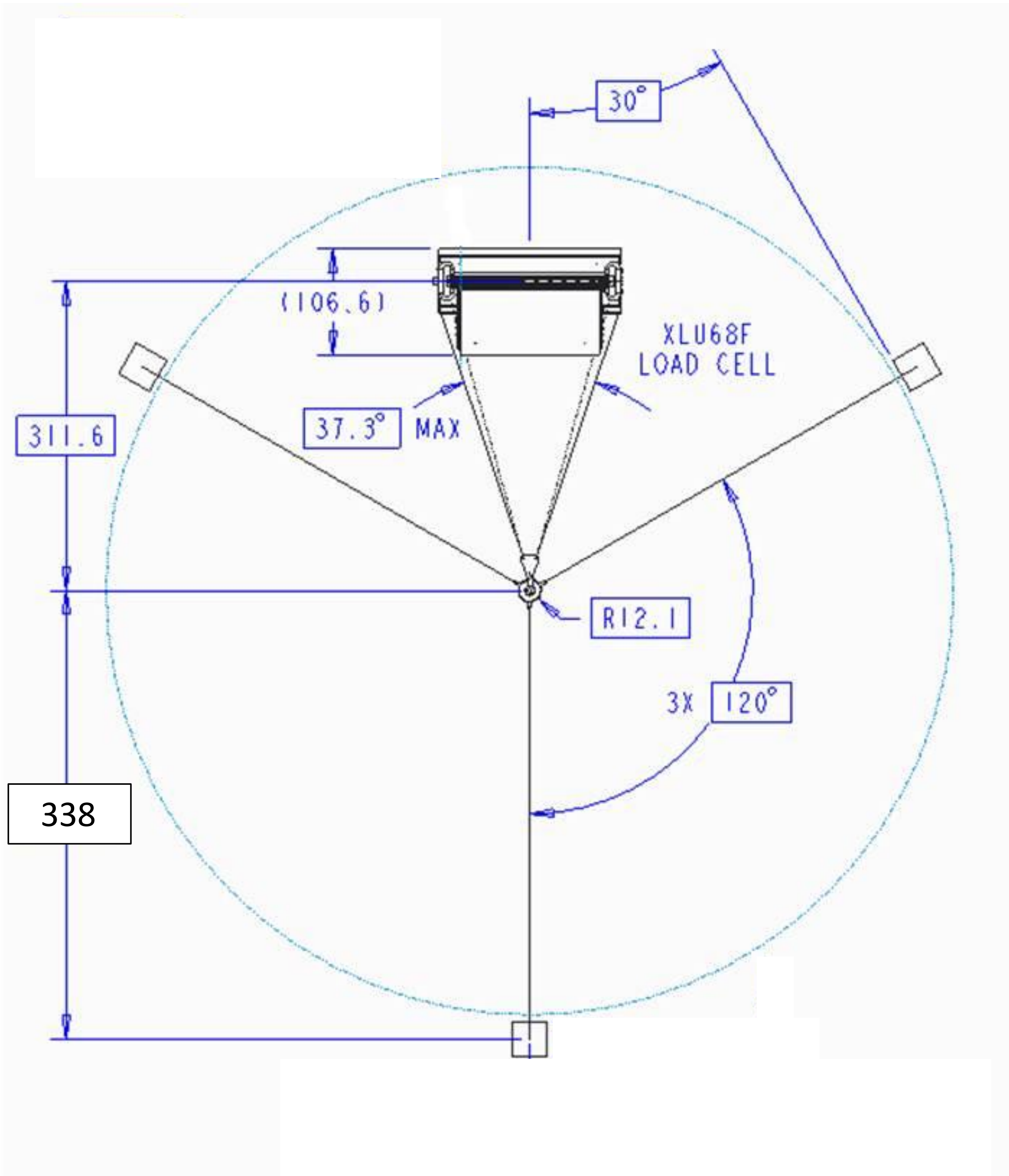


Figure 6-4 Mooring diagram – overhead view (preliminary)

6.2. Wave probe

One wave probe will be provided by the test facility to measure wave elevation at a location shown in Figure 6-1, between the device and the wave generator, during irregular wave tests. This wave probe will interface with the test facility DAS per Section 6.3.

6.3. Data acquisition

Three separate data systems will be used for this test:

1. A NWEI Speedgoat controller will be used to collect float arm torque, speed, and angle data. The data sampling rate will be 250 Hz. This controller will also include control algorithms that will produce the torque command for the motor drives that interface with the PTO generators.
2. Wave probe data will be recorded by UMO at a sampling rate of 128 Hz.
3. Motion tracking data will be recorded by UMO at a sampling rate of 100 Hz.

In addition, NWEI will use a National Instruments CompactRIO (cRIO) controller to interface with the torque sensing load cells and the generator encoders in the PTO tank model. The cRIO controller will include strain gage and encoder input modules for this purpose. The cRIO controller will provide real-time analog outputs for float arm torque, speed, and angle that will be input to the NWEI Speedgoat controller. Data will be recorded by the Speedgoat controller and not the cRIO; the cRIO will be used to reduce processing on board the Speedgoat controller and to eliminate the need for Speedgoat encoder and strain gage input modules.

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, and a diagram of the NWEI Speedgoat and cRIO controllers is shown in Figure 6-5. Additional hydraulic simulated signals recorded during the hardware in the loop tests are shown in Table 6-2. Recorded hydraulic simulation signals from hardware in the loop tests.Table 6-2.

Table 6-1 Data Acquisition Channel List

Measurement	Sensor PN	Sensor Mfr	DAS	Notes
Float arm 1 torque	NA	NA	NWEI Speedgoat	Custom Strain Gages on motor drive shafts.
Float arm 1 torque				
Shaft angle	TBD	TBD	NWEI Speedgoat	Encoders interface with cRIO digital input module; encoder on one side monitored and other is a spare
Shaft speed				
PTO control setting	NA	NA	NWEI Speedgoat	Damping or simulated hydraulic pressure setting; produced by Speedgoat
Motor Current 1	AB50A100	Advanced Motion Controls	NWEI Speedgoat	Motor current sense from motor drive
Motor Current 2	AB50A100	Advanced Motion Controls	NWEI Speedgoat	Motor current sense from motor drive
Port Water Alarm			NWEI Speedgoat	Water intrusion alarm
Stbd Water Alarm			NWEI Speedgoat	Water intrusion alarm

Measurement	Sensor PN	Sensor Mfr	DAS	Notes
Wave elevation		Edinburgh Designs	Test facility DAS	Resistance based wave probes
Wavemaker Enable	NA		NWEI Speedgoat and Test Facility DAS	The signal that enables the wavemaker. This signal was recorded across both DAS for time syncing of data files.
Surge pos. hull	Test facility Qualisys motion tracking system		Test facility DAS	
Sway pos. hull				
Heave pos. hull				
Roll pos. hull				
Pitch pos. hull				
Yaw pos. hull				
Surge pos. float				
Sway pos. float				
Heave pos. float				
Roll pos. float				
Pitch pos. float				
Yaw pos. float				

Table 6-2. Recorded hydraulic simulation signals from hardware in the loop tests.

Measurement	Notes
Hydraulic Pressure	Pressure drop across motor
Hydraulic Motor Speed	
Hydraulic Motor Displacement	
Cylinder pressure	Absolute pressure in hydraulic cylinders
Hydraulic flow	Volumetric flow from cylinders
Hydraulic motor power	Power absorbed by hydraulic motor

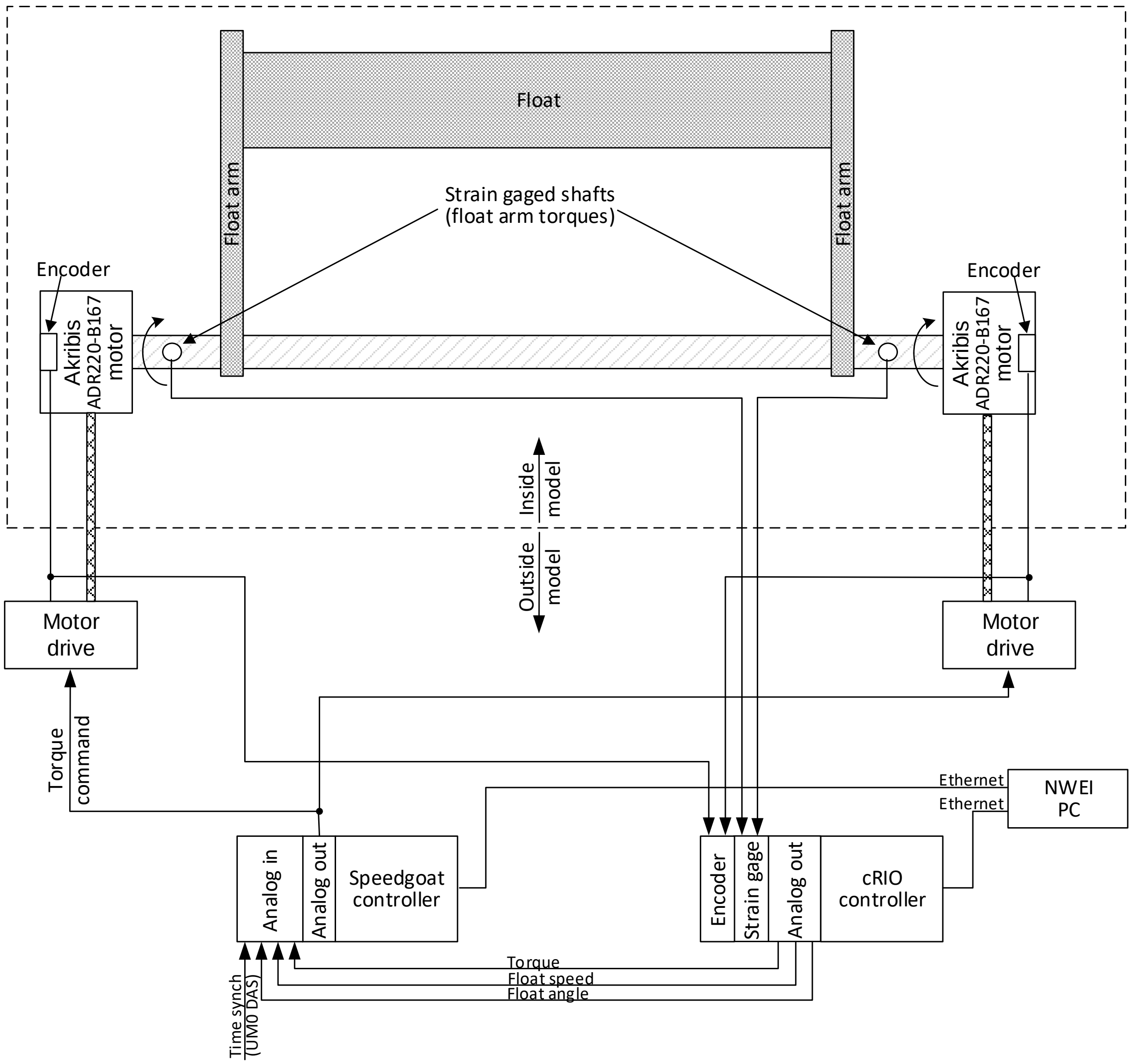


Figure 6-5 Data acquisition and tank model control for NWEI tank test

6.4. Tank model float arm torque control

Torque will be applied to the tank model float by two direct-drive permanent magnet generators that will be driven by two regenerative pulse width modulated (PWM) motor drives (see Figure 6-5). The two motor drives will be configured to control generator torques per an analog torque command from the Speedgoat controller. Equal torques will be commanded in the two PTO generators. The Speedgoat controller will be capable of providing torque commands in two alternate control modes: 1) constant damping control where torque is equal to the float speed multiplied by a damping constant, and 2) simulated hydraulic control using a hardware-in-the-loop simulation of a passively controlled hydraulic system.

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.

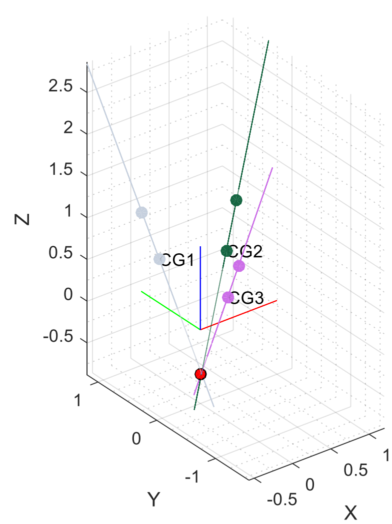


Figure 7-1: Lines are projected with respect to the part to find the center of gravity.

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

$$T = 2\pi\sqrt{\frac{l}{g} + \frac{I_A}{mgl}}$$ *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.

$$I_A = mgl\left(\frac{T}{2\pi}\right)^2 - ml^2$$ *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 target wave spectra described in Sections 7.5, 7.6, and 7.7, with random phases of each sinusoid used to reconstruct the wave field. Calibrations will be done with the repeat periods of the wave elevation time series listed in Table 7-1. 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 established during these calibrations will be used to run each wave case during NWEI model testing per the procedures described in Sections 7.5, 7.6, and 7.7.

Table 7-1 Repeat periods of wave elevation time series

Wave cases	Reference for spectra	Repeat period
Broadband	Figure 7-2	15 min
Irregular	Table 7-3	15 min
Extreme event	Table 7-4	1000 waves

7.5. Broadband wave test

Testing will be performed with the single broadband wave spectrum shown in Figure 7-2. Testing will be repeated with the tank model PTO control configured with each of the three damping settings listed in Table 7-2 (no testing of hardware-in-the-loop hydraulic control will be performed in broadband waves). The following test sequence will be used for these wave runs

1. Set model damping target setting #1 (this will be done via Speedgoat controller).
2. Start data acquisition systems. Record start time, wave spectra, and damping setting.
3. Start wave generation; wait until tank settles to desired condition (< 1 min).

4. Operate for 30 minutes (two repeat periods with identical wave elevation time series).
5. Stop data acquisition.
6. Repeat steps 1-5 for the remaining target damping settings.

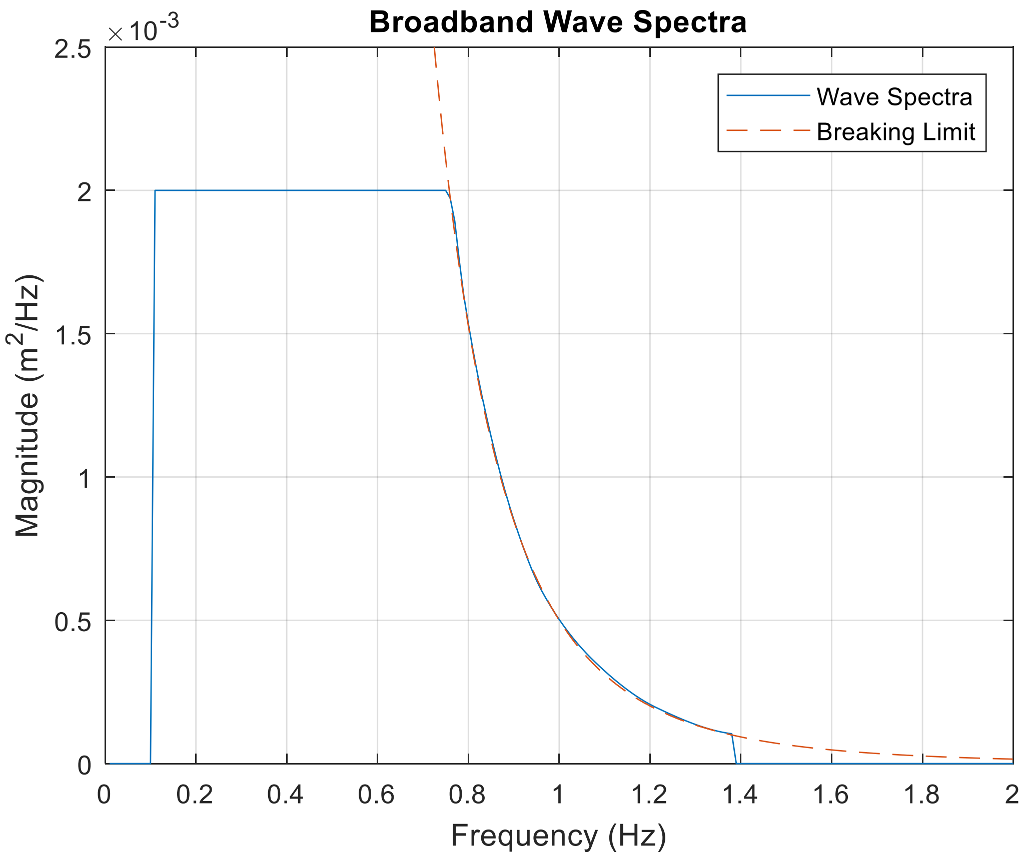


Figure 7-2 Target wave spectrum at tank scale for broadband irregular wave run

Table 7-2 Target damping values for broadband wave tests.

Damping case	Damping value (Nms/rad)
1	200
2	400
3	550
4	700
5	0

7.6. Irregular wave tests

See Table 7-3 for a list of irregular wave cases that will be run. The Azura model will be tested with both ideal damping and simulated hydraulic PTO control during irregular wave tests. A total of six test runs will be performed for each irregular wave case, three with ideal damping and three with simulated hydraulic control. The damping settings used for each test are determined from WEC-Sim simulations predicting the optimal setting for each wave case. Seven of the wave cases will use Bretschneider spectra. Note that $T_p = 1.169 * T_e$ is assumed for Bretschneider wave spectra based on theoretical definition. The final wave case will be empirically derived from typical data recorded at the Kaneohe site with bidirectional seas, which often occur at that site due to a combination of long period swell and shorter period trade wind waves.

Table 7-3 Bulk Wave statistics for Irregular wave runs

Case	Significant Wave Height (m)		Energy Period (s)		Notes
1	1.25	0.083	7.5	1.94	Bretschneider (unidirectional)
2	1.75	0.117	6.5	1.68	Bretschneider (unidirectional)
3	1.75	0.117	9.5	2.45	Bretschneider (unidirectional)
4	2.25	0.150	7.5	1.94	Bretschneider (unidirectional)
5	2.25	0.150	11.5	2.97	Bretschneider (unidirectional)
6	3.25	0.217	8.5	2.19	Bretschneider (unidirectional)
7	2.25	0.150	7.5	1.94	Bretschneider (Spread, cos2S, S = 10)
8	1.75	0.117	9.5	2.45	Specified – Bi-directional from Kaneohe – See Figure 7-4

* Note, values in shaded cells are full scale values, unshaded at tank scale.

The significant wave heights and energy periods for the six unidirectional irregular wave cases listed in Table 7-3 were selected from the WETS 60 m berth (Kaneohe, HI) occurrence matrix provided in the Scandia report *Characterization of US Wave Energy Converter (WEC) Test Sites: A Catalog of Met-Ocean Data*. Performance of the full-scale Azura is being assessed using data from that wave site. Figure 7-3 shows how these six wave cases are distributed within the WETS 60 m occurrence matrix.

Significant Wave Height (m) \ Energy Period (s)	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5
5.75														
5.25		Extreme Events												
4.75		Operational Cases				0.02								
4.25					0.03	0.05	0.02	0.01	0.03	0.01	0.01			
3.75					0.2	0.12	0.05	0.05	0.03	0.02	0.02			
3.25				0.17	0.62	0.26	0.18	0.12	0.1	0.04	0.03	0.01		
2.75			0.03	1.64	1.4	0.65	0.51	0.39	0.26	0.12	0.07	0.02		
2.25			1.5	4.4	2.17	1.46	1.06	0.72	0.46	0.22	0.1	0.04		
1.75		0.52	10.72	8.3	4.78	3.27	2.26	1.52	0.65	0.25	0.11	0.04		
1.25		4.12	13.97	8.24	5.69	4.08	2.55	1.26	0.45	0.17	0.05			
0.75		0.74	1.89	1.86	1.55	0.77	0.39	0.18	0.05	0.01				
0.25														
Peak Period (s)	5.26	6.43	7.60	8.77	9.94	11.11	12.27	13.44	14.61	15.78	16.95	18.12	19.29	20.46

Figure 7-3 WETS 60 m berth (Kaneohe, HI) occurrence matrix with irregular and extreme wave cases highlighted

Wave case 8 is selected to represent a case that sometimes occurs at Kaneohe, where a long period swell and a wind sea both exist, creating a bimodal wave spectra. At Kaneohe, when this occurs the two modes of the spectra typically come from different directions. The specified spectra consists of two standard definitions combined, a Brestschneider spectra with H_{m0} = 0.077 m, Tp = 1.68 s, and a JONSWAP spectra with H_{m0} = 0.089 m, Tp = 3.62 s. The sea state was selected to match an observed sea state at Kaneohe. The angle between the two spectra is 60˚. A plot of the combined spectra, along with each component spectra, is shown in Figure 7-4.

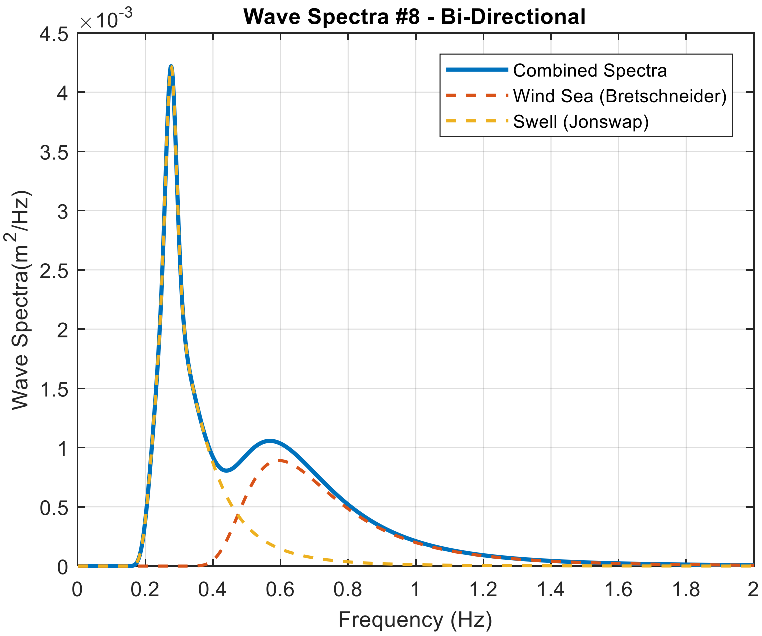


Figure 7-4. Wave case #8, the bimodal, bidirectional sea state.

The following test sequence will be used for the irregular wave runs:

1. Set model damping target setting #1 (this will be done via Speedgoat controller).
2. Start data acquisition systems. Record start time, wave spectra, and damping setting.
3. Start wave generation; wait until tank settles to desired condition (< 1 min).
4. Operate for 15 minutes (a single repeat period of the wave elevation time series).
5. Stop data acquisition.
6. Repeat steps 1-5 for the five remaining wave cases.
7. Repeat steps 1-6 until the damping value resulting in maximum output power is found.
8. Repeat steps 1-6 until the hydraulic PTO setting resulting in maximum output power is found.

7.7. Extreme wave tests

The extreme wave tests described in this section are optional tests that will be decided on as budgets are established.

See Table 7-4 for a list of extreme irregular wave cases that will be run. The Azura model will be tested with two damping values for each extreme irregular wave case (no testing of hardware-in-the-loop hydraulic control will be performed in extreme waves). The damping values for these tests will be determined from the results of irregular wave tests (per Section 7.6) for similar energy periods. For each damping value, extreme wave cases with 1000 waves will be run to simulate a full storm duration. These extreme wave conditions were selected from the WETS 60 m occurrence matrix per Figure 7-3.

Table 7-4 Bulk wave statistics for extreme event testing

Case	Significant Wave Height (m)		Energy Period (s)		Notes
1	4.2	0.28	7.5	1.9	Jonswap (Spread, cos2S, S = 7)
2	5.8	0.39	9.5	2.5	Jonswap (Spread, cos2S, S = 7)

* Note, values in shaded cells are full scale values, unshaded at tank scale

The following test sequence will be used for the extreme wave runs:

1. Set model damping target setting #1 (this will be done via Speedgoat controller).
2. Start data acquisition systems. Record start time, wave spectra, and damping setting.
3. Start wave generation; wait until tank settles to desired condition (< 1 min).
4. Operate for the full 1000 wave elevation time series (roughly 20-60 minutes depending on energy period).
5. Stop data acquisition.
6. Repeat steps 1-5 for the remaining target damping settings.
7. Repeat steps 1-6 for the two remaining wave cases.

APPENDIX A

WAVE TANK MODEL SPECIFICATION

Azura Full-Scale Design

2017

Wave Tank Model Specification

Northwest Energy Innovations

10/24/2017

TABLE OF CONTENTS

1. Scope

This specification describes requirements for a wave tank test model of the Northwest Energy Innovation (NWEI) Azura wave energy converter. This model will be used for wave tank testing at University of Maine Advanced Structures and Composites Wave Basin.

2. Design and Manufacturing Responsibilities

The selected supplier will be responsible for both the detailed design and build of the wave tank model. NWEI will be responsible for providing the following:

1. A solid works CAD model that includes the outer surfaces of the float and hull.
2. Desired mass properties of the float and hull.
3. Specification, procurement, and system testing of the specific power takeoff (PTO) components listed in Section 4.5, prior to installation by the supplier.
4. Procurement of instrumentation listed in Section 4.6

3. Review of Design

The detailed wave tank design shall be approved by NWEI before the model manufacturer begins the procurement and manufacturing process. The manufacturer shall supply a complete set of drawings, parts lists, and associated documents to NWEI for review purposes.

4. Specifications

4.1. Hull and float shape

See Figure 4-1 for a 3D rendering of the NWEI tank model, and see Figure 4-2 and Figure 4-3 for diagrams showing basic dimensions. NWEI will provide the selected supplier with CAD files in STEP file format defining the outer surfaces of the hull, float, spars, and heave plate as depicted in Figure 4-1. The pivot point of the PTO is located 0.333 m below the still water line.

Some dimensions can be modified slightly to ease construction. Thin parts of the float, the shoaling lip and the side shields, can be modified. The top support shape does not need to match the CAD model. The float arm dimensions do not need to match the CAD file, they should be designed to meet other requirements listed in the specification. Changes required to the machinery compartment to ensure the PTO system fits inside are permissible. The tube diameters of the spar have been designed to be imperial stock material sizes. Other deviations may be allowed with approval by NWEI.

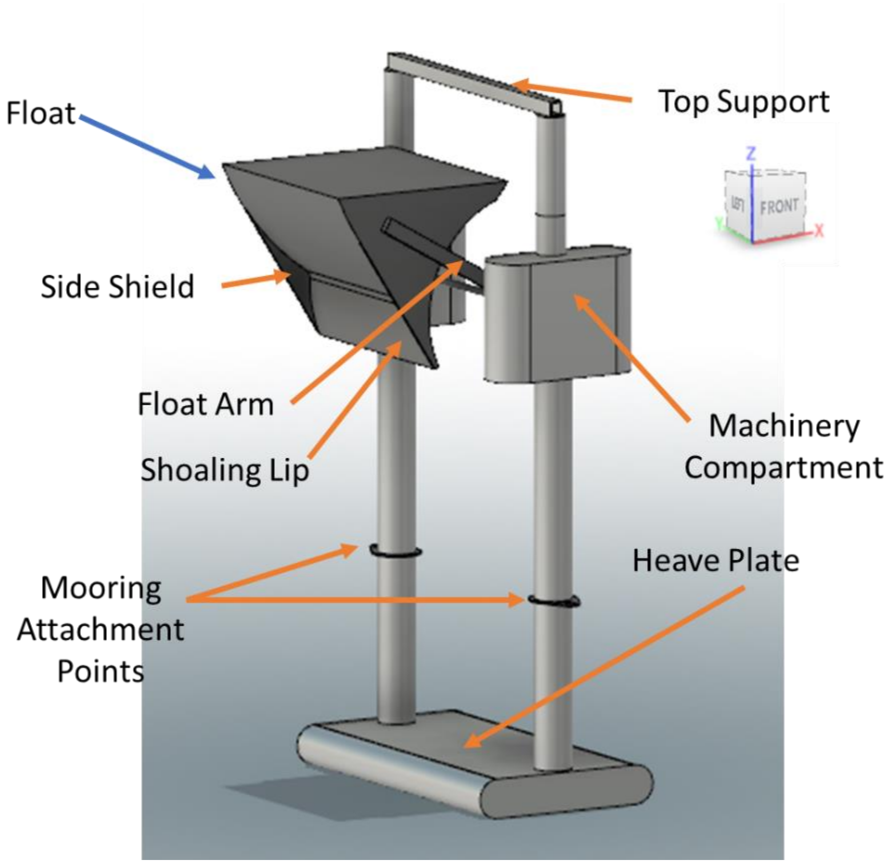


Figure 4-1 Rendering of NWEI tank model

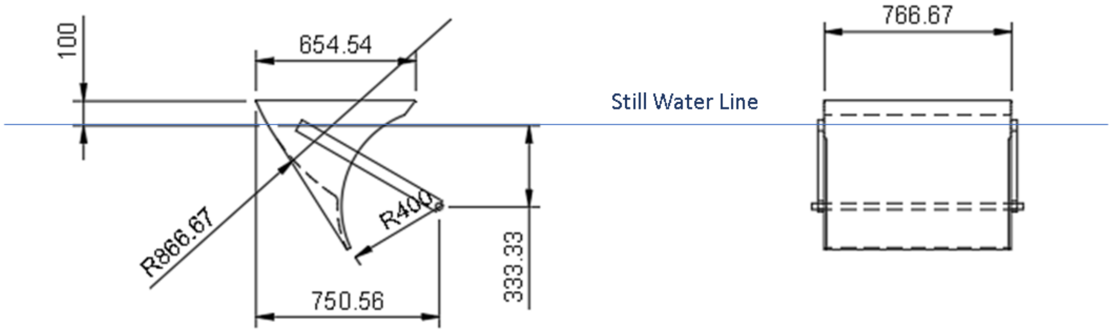


Figure 4-2 Basic dimensions of NWEI wave tank model. All dimensions in millimeters.

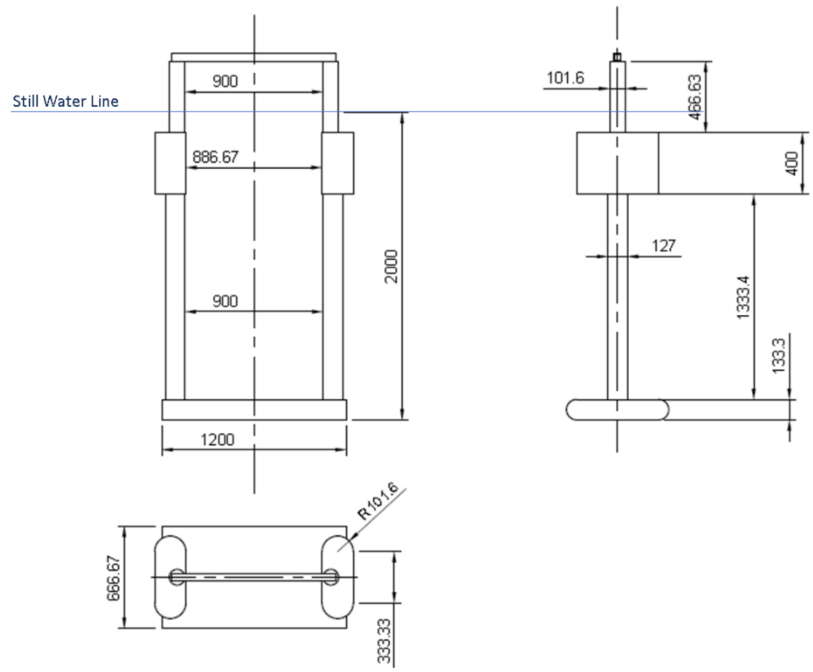


Figure 4-3 Basic dimensions of NWEI wave tank model. All Dimensions in millimeters.

4.2. Hull and float mass properties

The masses, centers of gravity, and moment of inertia around the y-axis for the spar assembly and the float alone shall be within the limits listed in Table 4-1. The three axes are defined in Figure 4-1. The water line and tilt of the completed model shall be verified in still water, and approved by NWEI. The mass moments of inertia will be measured as part of testing. An estimate of the model moments of inertia should be provided prior to testing. The order of priority of these requirements in decreasing priority are, water line, center of gravity, moment of inertia. The tolerances listed in the table reflect this priority order. Note that NWEI has done some preliminary mass estimations to determine their feasibility. Ballast water can be used to achieve the target mass properties.

Table 4-1 Required mass properties. CG Values with respect to Global Coordinate System per CAD files

Mass property	Spar Assembly	Float & arms
Mass	218 kg ± 3 kg[1]	68.6 kg ± 3 kg
CG (x-axis)	0 ± 2 cm[3]	-43.8 cm ± 3 cm[2]
CG (y-axis)	0 ± 2 cm[3]	0 ± 2 cm[3]
CG (z-axis)	-134.7 cm ± 7 cm	-11.5 cm ± 5 cm
I_{yy} about CG	125 ± 35 kg*m^2	No Requirement

1. *Tolerance derived from maximum still water line error of 2 cm.*
2. *CG of float should be directly above center of buoyancy.*
3. *will be checked by ensuring model floats within 3° of horizontal*

4.3. Float arm

The NWEI CAD file provided to selected supplier will include the float arm shape depicted in Figure 4-1. The float arm design can be modified depending on the material used. Deflections of the float arms shall be low enough during model testing so that float arm cannot contact the hull. Note that PTO torque is applied equally to the two float axles. The maximum expected operating PTO torque is 250 N-m.

The float arm should be designed stiff enough so that the resonant frequency of the float arm/float combination is the maximum response of the generator torque control loop. We estimate this frequency to be 50 Hz. Note that this frequency is also higher than the maximum cogging torque frequency that will exist in the permanent magnet generators (approximately 8 Hz at 10 rpm generator speed). NWEI will work collaboratively with the supplier to ensure this requirement is met.

4.4. Mooring

The supplier will be responsible for providing the mooring attachment points shown in Figure 4-1. The mooring points must be designed to slide and be clamped to any position along the two spars. The mooring points need to secure small mooring lines such as 1/8" spectra. The remainder of the mooring system beyond the attachment points will be NWEI's responsibility.

4.5. PTO

The tank model will use the PTO design shown in Figure 4-4. This system uses two brushless generators and a four-quadrant motor drive to provide a controlled torque. Equal torque commands will always be provided to the two generators during model operation. NWEI will be responsible for purchasing the components listed in Table 4-2, bench testing the PTO system using these components prior to installation in the tank model, and providing these components to the tank model supplier. The supplier will be responsible for installing these components in the model including designing all component mounts and procuring any additional components not listed in Table 4-2. After completion of the tank model the complete, installed PTO system will be tested by the supplier at their facilities with the assistance of NWEI.

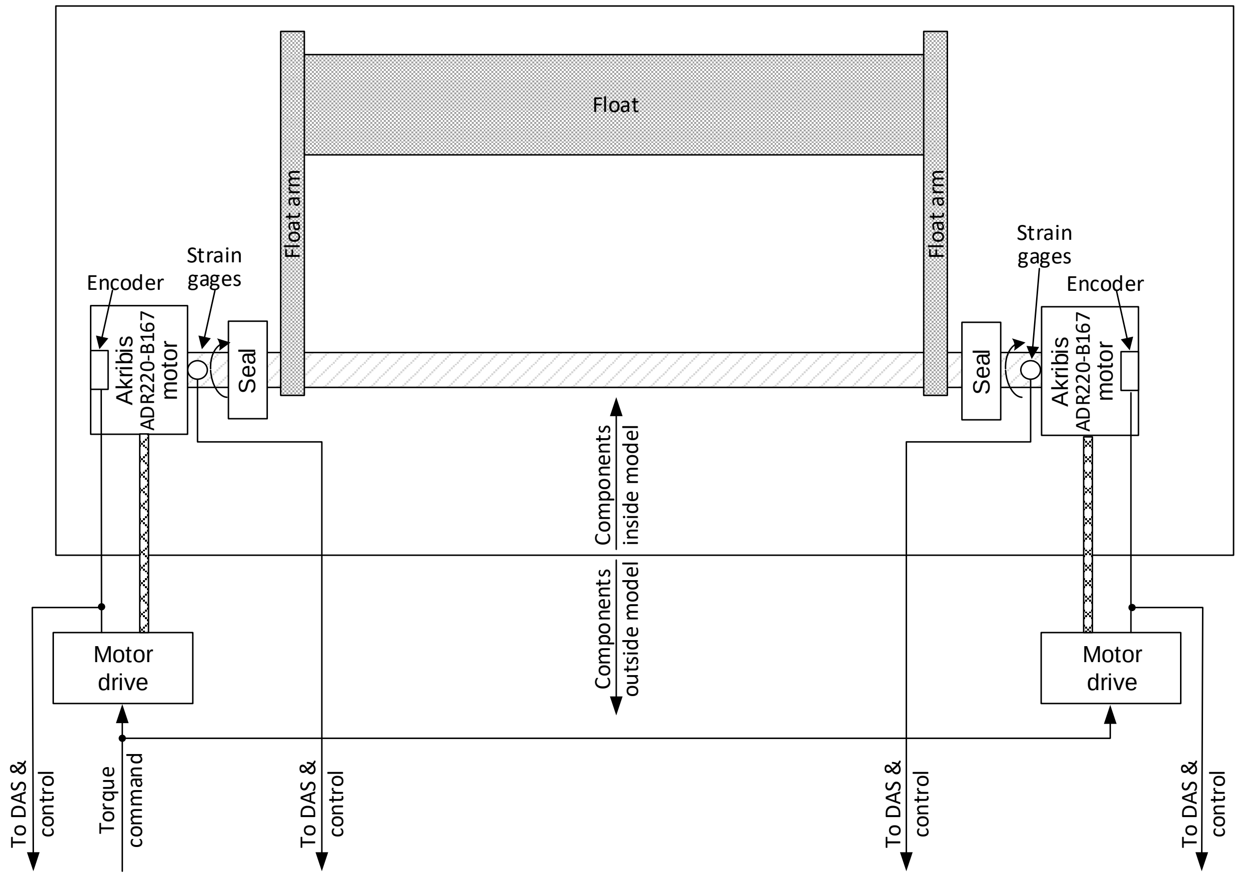


Figure 4-4 Diagram of PTO

Table 4-2 NWEI supplied PTO components

Component	Manufacturer	Part number	Notes
Motor	Akribis	ADR220-B167	Includes encoder, mass 15.6 kg each
Motor drive	TBD	TBD	External to Model

See Figure 4-5 showing the scale of the PTO components listed in Table 4-2 relative to the size of the hull. The hull shall be built with a waterproof access for each motor/generator. Mounting hardware for the motor is not shown in the model. An exploded assembly view of the preliminary PTO design is shown in Figure 4-6.

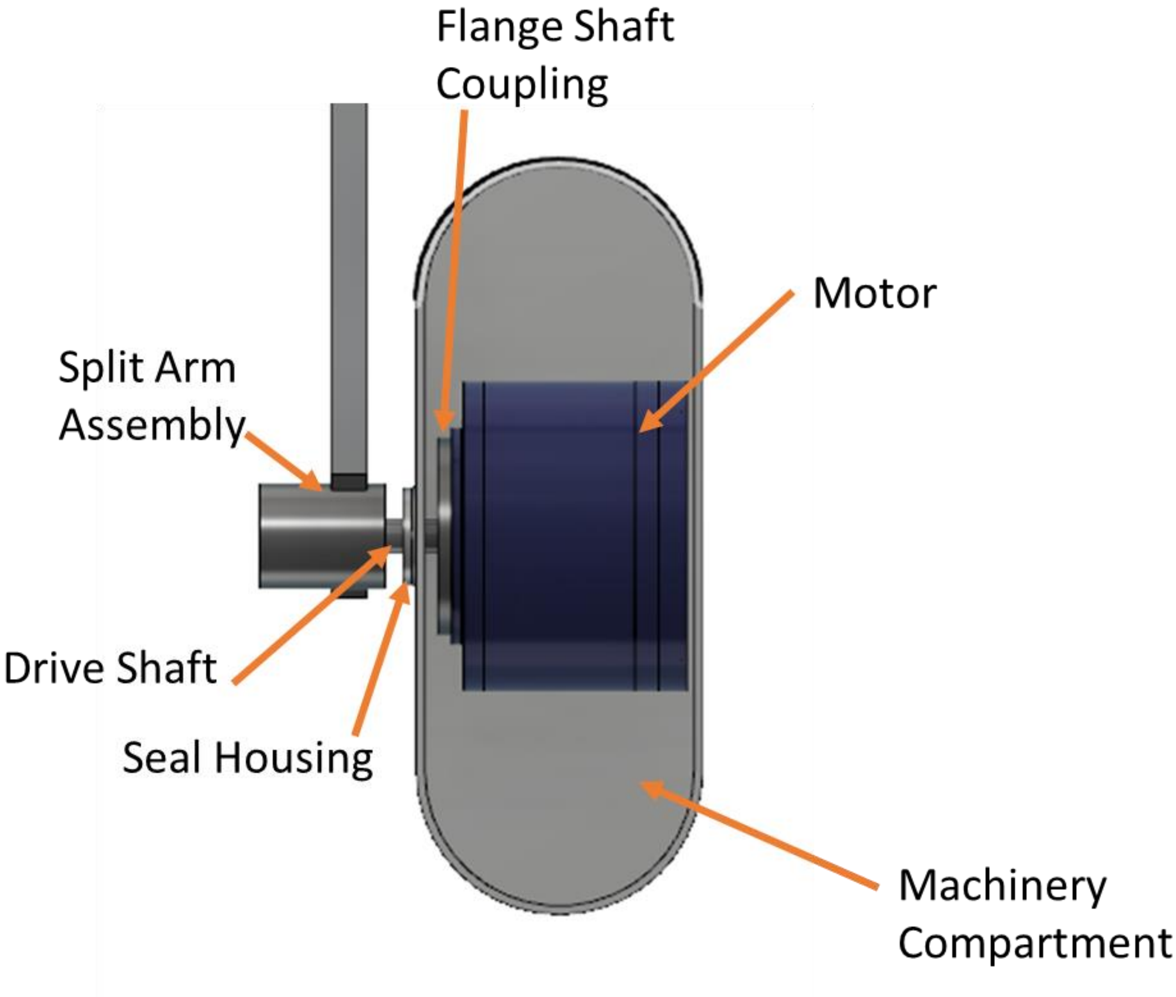


Figure 4-5 Scale of PTO components relative to hull. View is from bottom looking up, with machinery compartment bottom cut away.

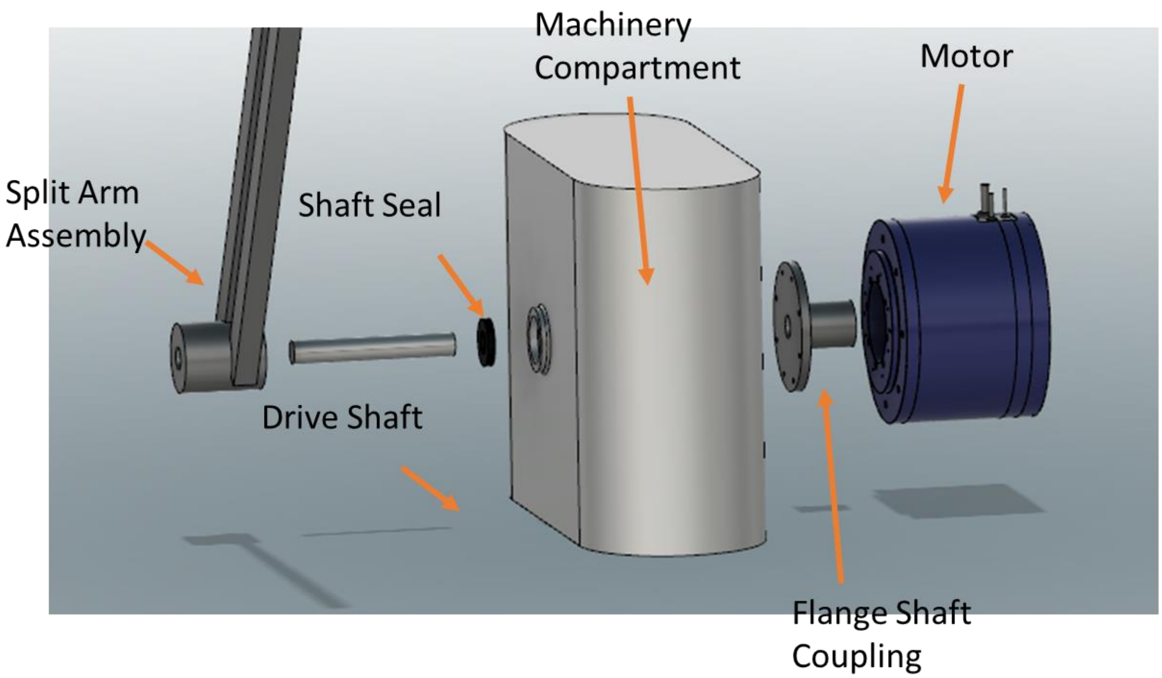


Figure 4-6 Exploded view of the preliminary PTO design.

4.6. Onboard instrumentation

See Table 4-3 for a list of the instrumentation that will be installed on board the tank model. NWEI will be responsible for specifying and procuring the components listed in Table 4-3. Mounting of these components in the tank model will be the responsibility of the supplier. The encoder and torque sensor is part of the PTO system described in Section 4.5.

The torque applied to the float by the generator will be measured by a strain gauge on the drive shaft. Installation and testing of the strain gauges will be the responsibility of the supplier. One spare drive shaft with a strain gauge installed should be supplied in case of failure during testing.

Table 4-3 Instrumentation on board tank model

Measurement	Part number	Notes
Float angle	Encoder	See Section 4.5 (PTO)
Float velocity	Encoder	See Section 4.5 (PTO)
Float shaft torque	Strain gauge on drive shaft	See Section 4.5 (PTO)
Bilge water level switch		See Table 4-4

4.7. Float axle and PTO compartment seals

The float axles will be below waterline, so seals will be necessary to keep all the onboard instrumentation and two PTO generators dry. The selection of the float axle seal will be the responsibility of NWEI. Incorporating the float axle seal into the hull design will be the responsibility of the supplier.

The PTO compartments will also require access hatches below waterline that provide access to the motors. The design of these hatches and their seals will be the responsibility of the supplier.

4.8. Bilge and bilge pump

The PTO compartments should include bilge areas at the bottom for the installation of one of the two alternate bilge pumps listed in Table 4-4, or equivalent. The bilge water sensor listed in Table 4-4 will be used to switch the pump on and either send a signal to DAS or light a bilge level indicator at the top of the model.

Table 4-4 Bilge pump and water sensor

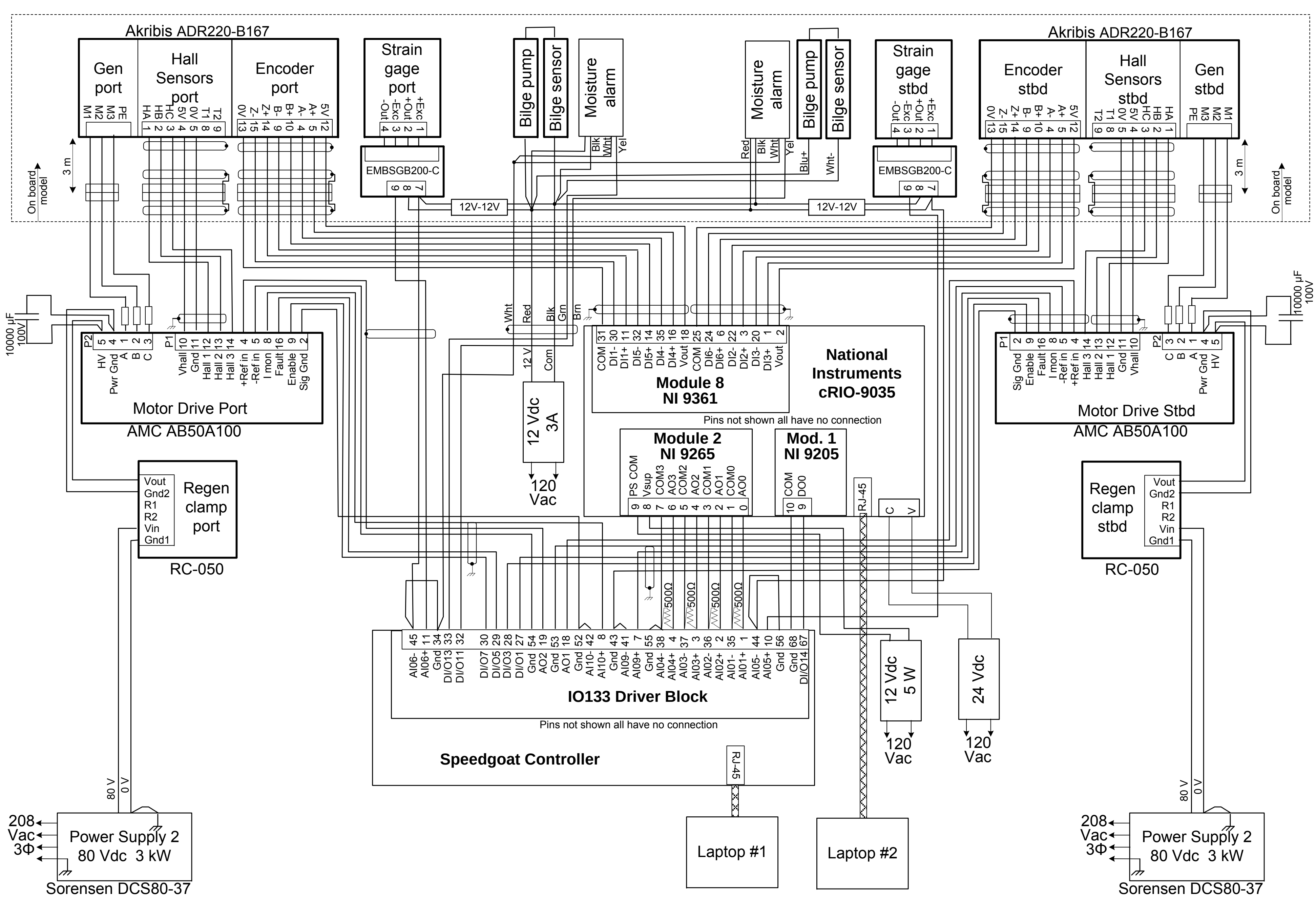
Component	Manufacturer	Part number	Notes
Bilge pump (alternate 1)	Hanperal	B01987QDKQ (ASIN)	https://www.amazon.com/Hanperal-Pumping-Submersible-Garden-Fountain/dp/B01987QDKQ
Bilge pump (alternate 2)	Cisno	CS-2469	https://www.amazon.com/Ultra-Quiet-Brushless-Motor-Submersible/dp/B01G1EGC9Q
Bilge water sensor	Ram	RAM 45	Use water sensor only (pump has insufficient head) https://www.amazon.com/Bilge-Pump-Saver-6-12V-RAM45/dp/B0006O7FNA

4.9. Lift Points

Lift points shall be provided at the top of the hull for use when hoisting the tank model out of the water. If any additional lift points are needed to experimentally measure the center of gravity, and pitch moment of inertia, of the float and the hull independently, those shall be provided.

APPENDIX B

WAVE TANK MODEL WIRING DIAGRAM



Drawn	Terry Lettenmaier	AZURA WAVE ENERGY	Project	Title	Sht
Date	Nov 17, 2017		NWEI Full Scale Developement	Wiring Diagram Wave Tank Model	1 OF 1

APPENDIX B
AZURA MODEL REPORT

CONFIDENTIAL

Design, Construction, and Measurement Report for the NWEI 1:15 Scale Model Wave Energy Converter

Prepared for:
Northwest Energy Innovations

University of Maine's Advanced Structures and Composites Center

Prepared by:

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Reviewed by:

Mr. Matthew Cameron, MS
Research Engineer,
Offshore Model Testing
and Structural Design

Author	Checked	Date	Revision	Notes
MJF	MC	1/3/2018	0	Original Issue
MJF	MC	1/25/2018	1	Release to client

ACCREDITED

An ISO 17025 accredited testing laboratory, accredited by the International Accreditation Service.

Contents

1.1 OVERVIEW

Northwest Energy Innovations (NWEI) contracted with the University of Maine (UMaine) Advanced Structures and Composites Center (Center) to design and build a 1:15-scale model of the Azura Wave energy conversion device for wave tank testing. Model specifications and design parameters were provided in the NWEI specification titled “Wave Tank Model Specification”, included in Appendix A. This report details the engineering design work performed by UMaine and documents the final as-built model parameters measured in the Center’s Alfond Wind/Wave Ocean Engineering Laboratory (W2).

1.2 MODEL PARAMETERS

Geometry

The model consists of two main sections, shown in Figure 1 below: the hull and the float.

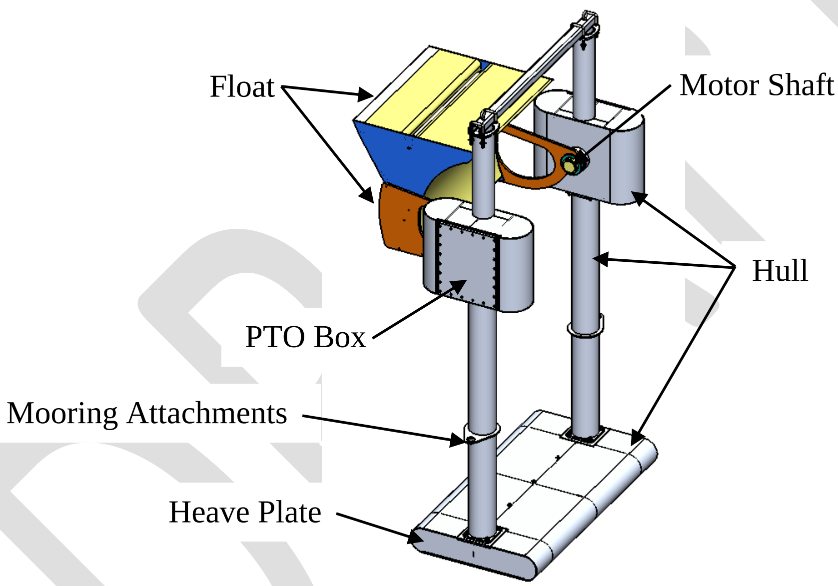


Figure 1. Rendering of NWEI tank model

For discussion purposes, the “float” consists of the items in the model that are colored yellow, blue, and orange in the figure, which represent the pieces of the model connected to the motor drive shaft that rotate relative to the hull. The “hull” corresponds to the remaining components that are colored grey in the figure. The hull is constructed from aluminum and stainless steel while the float is a composite material made of structural foam and fiberglass. In addition to the parameter specification document, NWEI provided UMaine with a computer-aided design (CAD) model of the hull and float outer geometry. Along with the specification documents, this CAD model was used as a guideline in determining the space envelope of the scale model. Key specified dimensions for the model were specified in metric (mm) and are shown in Figure 2 below.

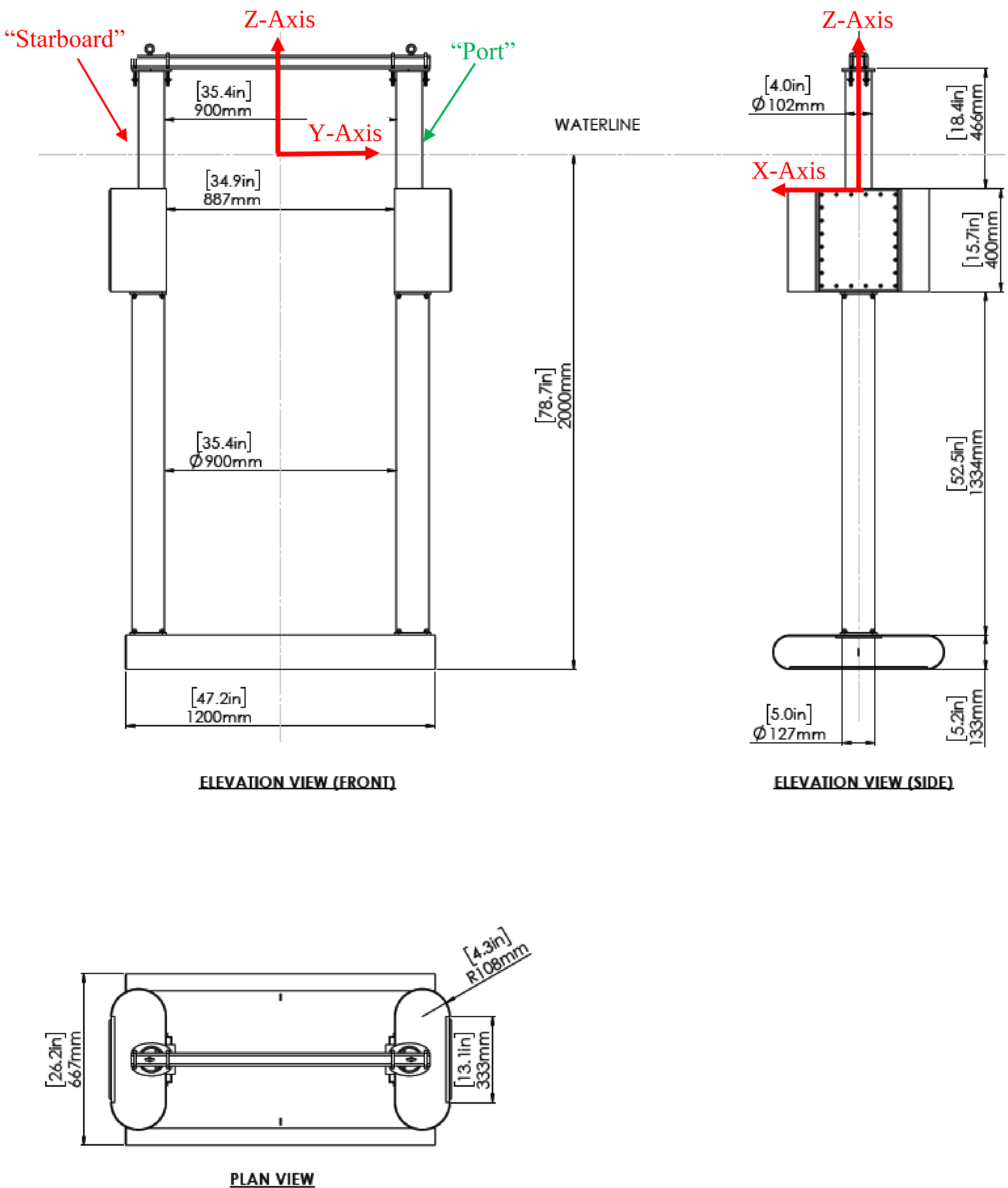


Figure 2. Key dimensions of the NWEI wave tank model hull (nominal dimensions specified in metric, "mm")

Mass Properties

The model mass and related derived quantities are based off the displacement of the hull and float respectively, which is determined by the geometry of the submerged parts, and the target waterline specification. Due to design changes in the PTO (power take-off) box for clearance reasons and torque measurement instrumentation, the PTO box was made larger and the overall displacement of the model increased slightly from the original specifications. In order to maintain the requested waterline specification, the masses of the hull and float were adjusted accordingly and are reported in Section 0 of this document. For the derived quantities of the center of gravity (CG), NWEI specified these parameters relative to the center of buoyancy (CB) of the float and hull respectively. These values are shown in Table 1.

Table 1. Mass properties of the NWEI wave tank model

Property	Float	Hull
Mass	Displacement at operating draft (59.5 kg nominal)	Displacement at operating draft (218 kg nominal)
CG (X-axis)	Float CB_x ± 3 cm	Hull CB_x ± 2 cm
CG (Y-axis)	Float CB_y ± 2 cm	Hull CB_y ± 2 cm
CG (Z-axis)	Float (CB_z – 1.5 cm) ± 5 cm	Hull (CB_z – 13 cm) ± 7 cm
Iyy (about CG)	No Requirement	125 ± 35 kg-m^2

The CG and CB of the hull and float are shown in Figure 3 below.

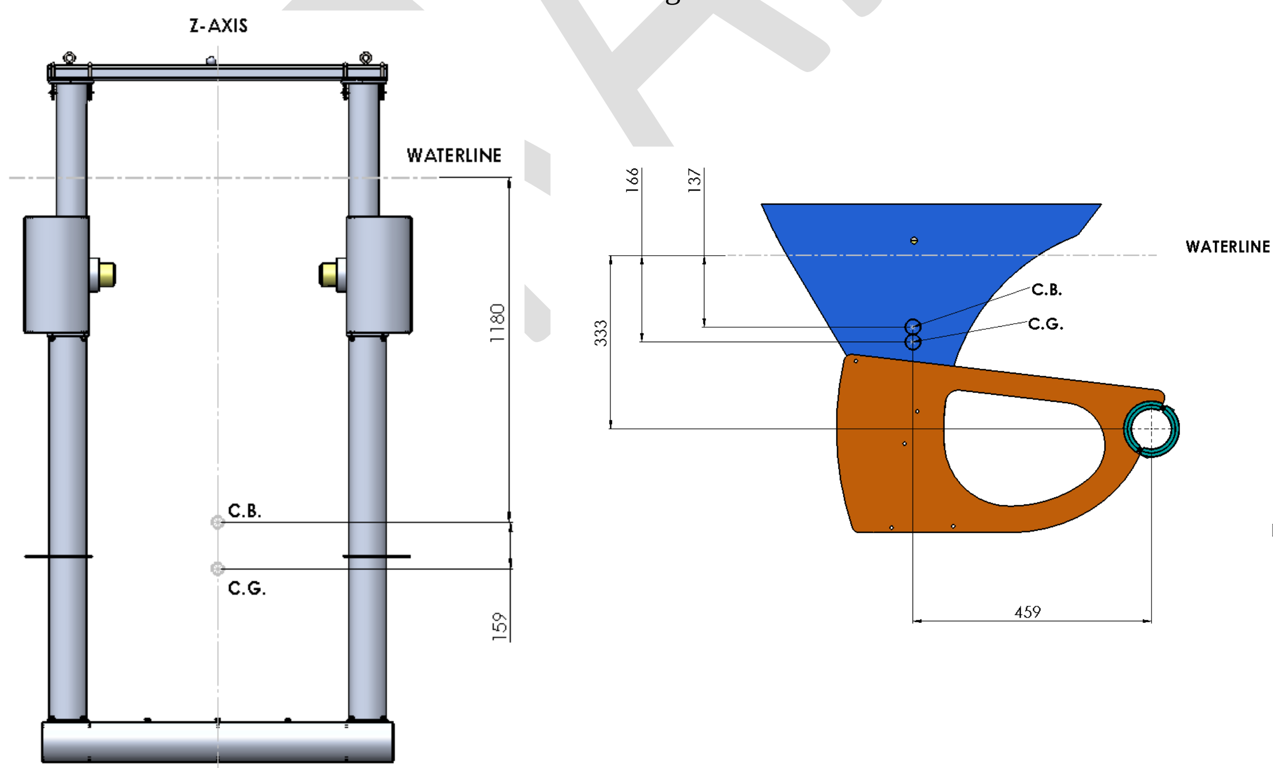


Figure 3. CG and CB locations for NWEI wave tank model: Hull (left) and Float (right)

Instrumentation

The model is instrumented to measure torque on each drive shaft. These sensors were designed and fabricated by UMaine to accurately measure torsion in each of the drive shafts. NWEI specified a total torque rating of 250 N-m with the torque on each drive shaft electronically limited by the PTO system to <150 N-m. Additionally, NWEI requested that the fundamental natural frequency of vibration be a minimum of 35 Hz for the float, incorporating all items downstream from the motor flange.

NWEI originally proposed a torque cell measurement technique using axial load cells, shown in Figure 4. In this design, the torque measurement was calculated by multiplying the axial load by the known distance from the pivot point on the shaft. However, based on the frequency requirement of the system, it was determined to be prohibitively difficult to obtain sufficient stiffness from this arrangement.

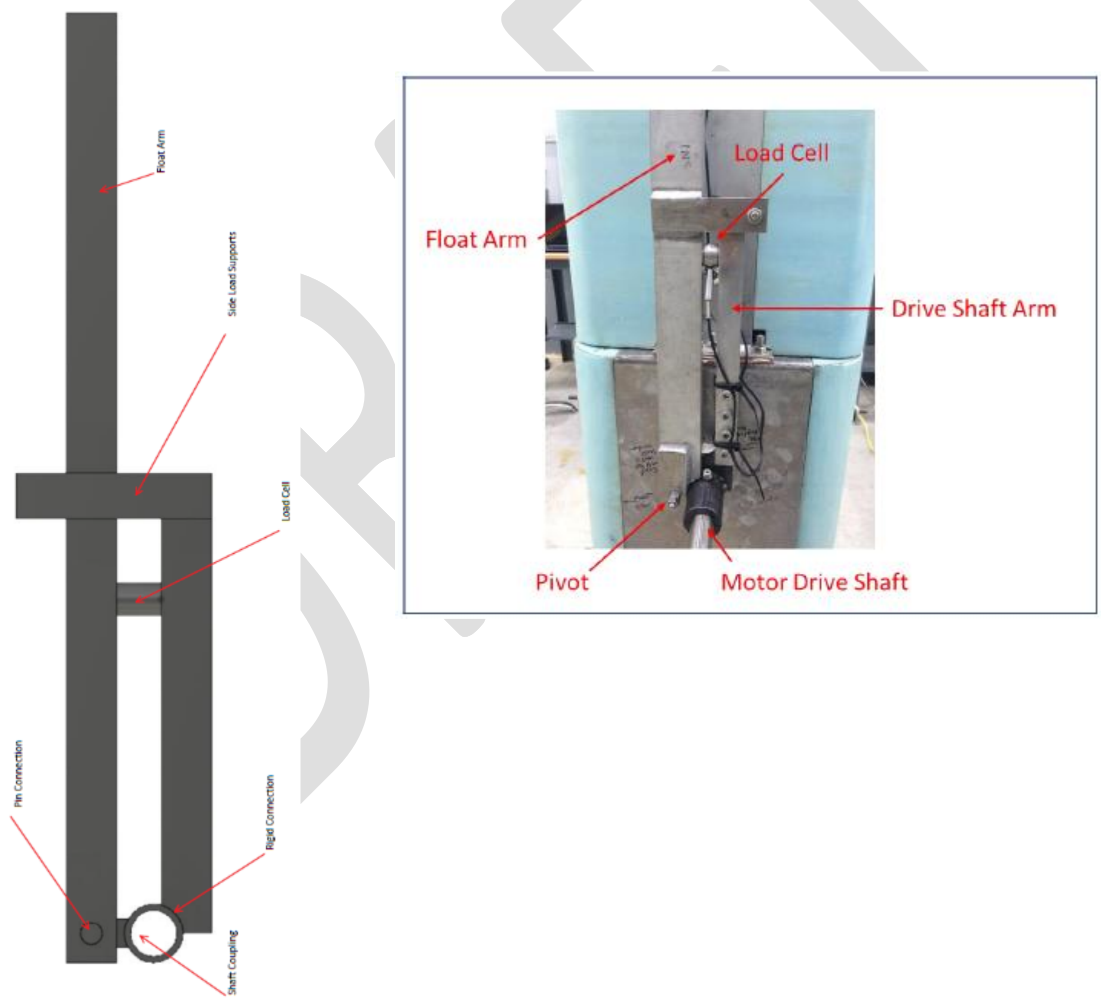


Figure 4. Original PTO torque measurement

To address these concerns, the torque measurement instrumentation was redesigned using two full Wheatstone strain gauge arrays on each drive shaft to measure torque via torsional strain in the shaft. For stiffness, each shaft is made out of a 3” diameter, 2” inner diameter, 304 stainless steel tube and the float arm attaches using a split shaft collar. The full Wheatstone arrangement compensates for temperature, axial, and bending load effects to give an isolated torque measurement. Figure 5 shows the drive shaft with the two full Wheatstone bridges. Initial sizing calculations for the strain are shown in Appendix A.

The strain arrays were connected to a strain gauge amplifier from Tacuna Systems (Model EMBSGB2000) in order to bring the strain voltage into a range that could be more easily measured by the shoreside data acquisition system (DAS). To quantify the performance of the strain gauges, known torques were applied to the drive shaft covering the desired operating range and the DAS measured output from the gauges. From this data we obtained the torque characterization curves presented in Appendix B. The final model used Array A and B connected in parallel to obtain the cleanest signals.

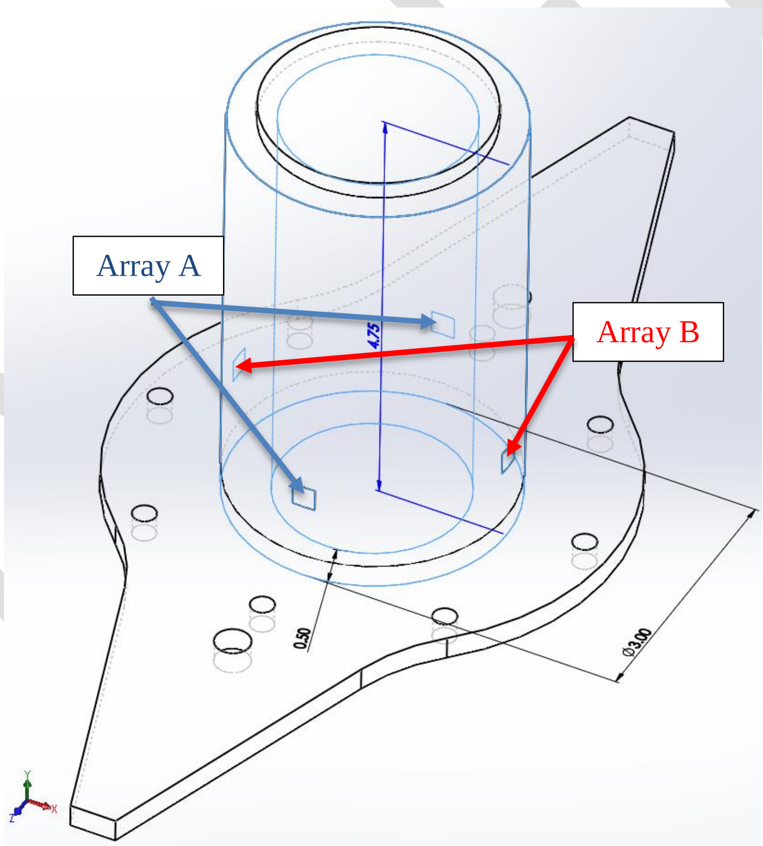
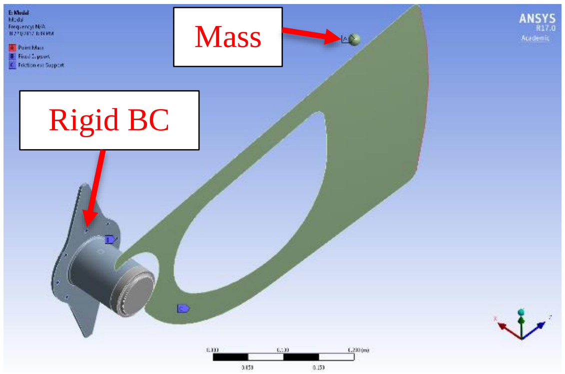


Figure 5. PTO drive shaft with two independent, full Wheatstone strain gage arrays. Units are inches



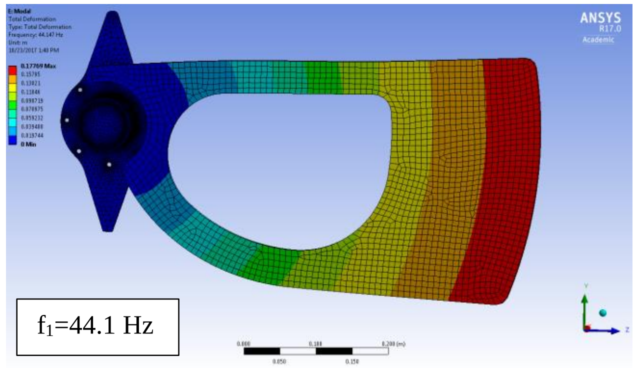


Figure 6. (Left) Geometry and boundary conditions. (Right) Results for the first mode of vibration

The natural frequency of the float assembly was estimated from a finite element model of a single arm using half of the float mass and half of the estimated added mass. The added mass was estimated using an ANSYS AQWA model of the float based on CAD provided by NWEI. Half of the float mass is 31kg and half of the added mass of the float in heave is 17.5kg. These were both represented by a single point mass of 48.5 kg located 48cm from the point of rotation, labeled in the figure above. The arm, shaft collar, drive shaft, and flange were modeled using 3D solid elements with a steel material definition. Rigid boundary conditions were enforced on the flange bolts representing the motor connection and a rotary joint was created on the drive shaft to ensure the correct rotary motion of the float arm assembly. Results were calculated using the modal analysis tool in ANSYS R17.0 and the first natural frequency is shown on the right in Figure 6 and corresponds to the desired degree of freedom. The predicted natural frequency of the drive linkage was 44.1 Hz. Acceptable performance with respect to the device natural frequency was verified by NWEI during model shakedown using a methodology they developed that imposed high frequency torques on the system and looked for resonant behavior in the response. This testing was performed with the model in the water and was completed prior to using the model in the first test campaign.

1.3 AS-BUILT SUMMARY

The as-built model properties are summarized in this section. These properties were derived from system identification tests and measurements performed in the UMaine W2 test facility. The methods used to measure the mass, center of gravity, and moment of inertia are outlined in the test plan for the model. Measurements of the center of buoyancy were taken from the 3D SolidWorks model, which is included along with this report. The model contains the representative geometry of all wetted surfaces and was exported in a format that is readable by NWEI. All specifications were met. Photographs from the model construction and shakedown testing are shown in Appendix D.

Hull Properties

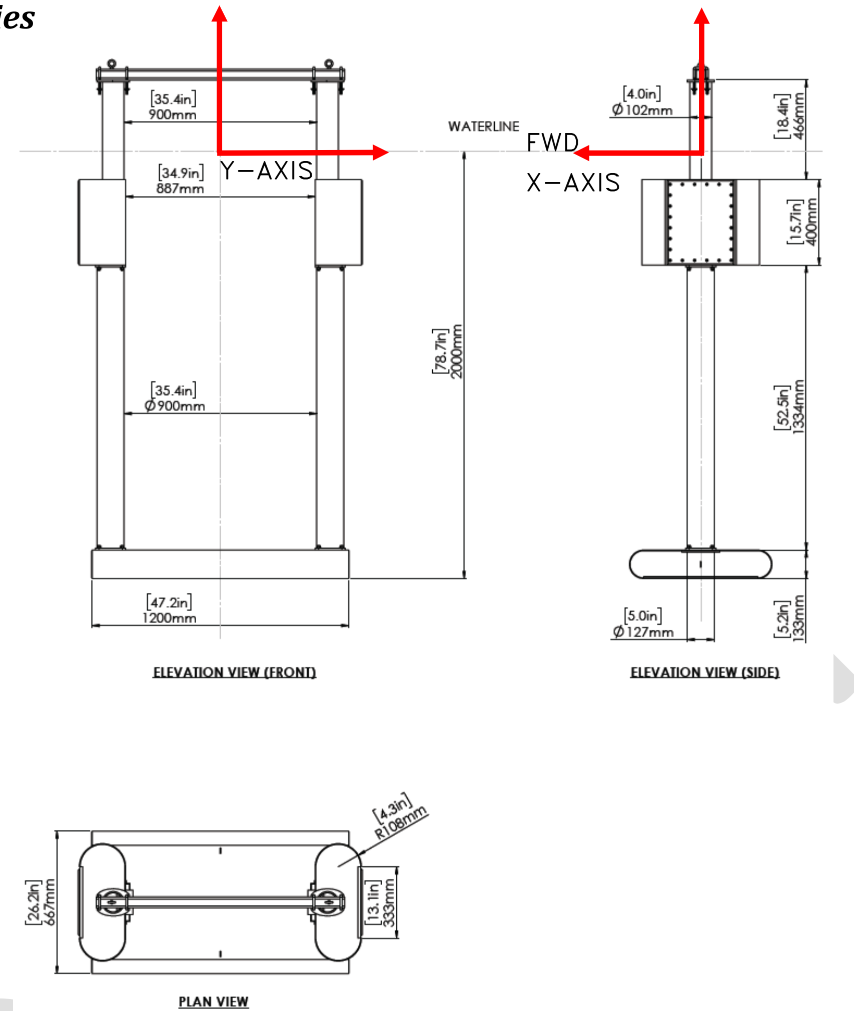


Figure 7. Hull geometry and coordinate system

Table 2. Hull as-built properties

	Specified	**Calculated**	**As-Built**
Mass wet (kg)	218	214 + trim	227
CG wet (x-axis) (m)*	0 ± 0.02	0	0.008
CG wet (y-axis) (m)*	0 ± 0.02	0	0.007
CG wet (z-axis) (m)*	-1.31 ± 0.07	-1.34	-1.271
Iyy wet about CG (kg-m^2)*	125 ± 35	141.0	158.4
Mass dry (kg)	-	-	136.2
CG dry (x-axis) (m)	-	-	0.008
CG dry (y-axis) (m)	-	-	0.07
CG dry (z-axis) (m)	-	-	-0.833

*Note: "wet" refers to the heave tank being filled with water, coordinate system defined in Figure 7

Float Properties

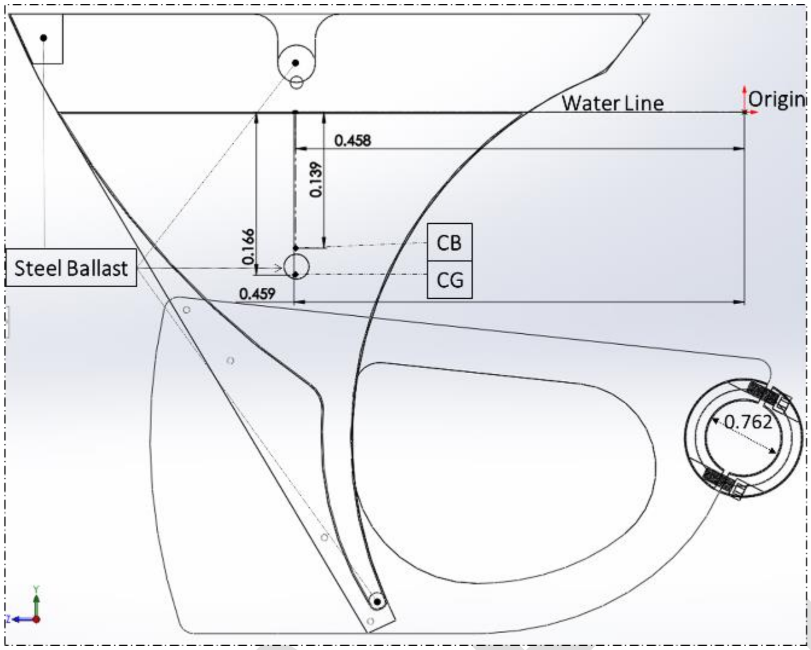


Figure 8. Float geometry and coordinate system

Table 3. Float as-built properties

	Specified	**Calculated**	**As-Built**
Mass (kg)	Displacement	59.5	58.4
CG (x-axis) (m)	0.46 ± 0.03	0.46	0.48
CG (y-axis) (m)	0.00 ± 0.02	0.00	0.00
CG (z-axis) (m)	0.17 ± 0.05	-0.17	-0.16
Iyy about CG (kg-m^2)	-	5.3	4.6

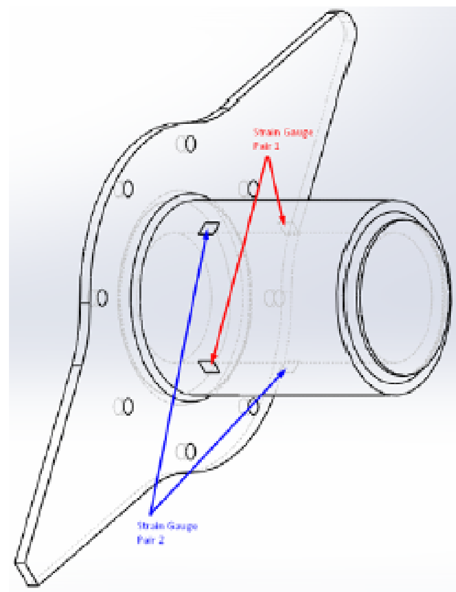
Note: All measurements are taken with the float at its final trim weight. The Iyy of the float is notional and not prescribed by NWEI.

APPENDIX A. PTO STRAIN GUAGE SIZING CALCULATIONS

PTO Initial Sizing Calculations

Azura WEC Device
Torque Strain Gauge Calculation

Prepared by: Matthew Fowler, 2017.11.06
Checked by: Matthew Cameron, 2017.11.08



Dimensions

$OD := 3\ in$

$ID := 2\ in$ $\qquad t := \frac{(OD - ID)}{2} = 0.5\ in$

$J := \pi \cdot \frac{\left(OD^4 - ID^4\right)}{32} = 6.381\ in^4$ $\qquad$ Polar Moment of Inertia

Properties

$G := 86.0\ GPa$ $\qquad$ Shear Modulus (asm.matweb.com)

Loads

$M := 150\ N \cdot m$ $\qquad$ Applied Moment

$\tau := \frac{M \cdot \left(\frac{OD}{2}\right)}{J} = 2.152\ MPa$ $\qquad$ Torsional Stress

Strain Results

$\gamma := \frac{\tau}{G} = 2.502 \cdot 10^{-5}$ $\qquad$ Torsional Strain

$\varepsilon := \frac{\gamma}{2} = 1.251 \cdot 10^{-5}$ $\qquad \frac{\varepsilon}{10^{-6}} = 12.509$ $\qquad$ microstrain @ 45°

$Output := \varepsilon \cdot 10\ V = 125.095\ \mu V$ $\qquad$ Based on estimate of 10 microvolt per microstrain

APPENDIX B. STRAIN GAUGE CHARACTERIZATION

Background:

This characterization of the torque sensors manufactured for the NWEI wave basin model characterizes the performance of each gauge in its as-built configuration. As described earlier, each gauge consists of an array of four strain gauges arranged in two Wheatstone pairs. The two Wheatstone pairs are wired together in parallel to improve the robustness of the signal. An initial characterization was done prior to the December 2017 test campaign by hanging known masses from the drive arms and measuring the response. After the initial campaign, we checked performed another characterization using a calibrated torque cell (certificate in final section). One concern with the initial characterization is that it appeared the sensors were sensitive to the float arm bolt torque and this was investigated during the second characterization by comparing with the calibrated load cell. The results of this characterization are explained in this report.

Setup

In order to use the calibrated torque load cell, the model needed to be relocated to another section of the lab. Therefore, the model was partially disassembled and the PTO boxes were fastened to the test stand, see Figure 10. This arrangement allowed for the PTO boxes to be rigidly fixed and torque applied to each drive system and torque cell independently. The calibrated torque transducer was mounted collinear to the motor, as shown in Figure 9, and measured the torque applied to each torque sensor. The connection between the transducer and the motor was done with expandable plug inside motor's hollow rotor.

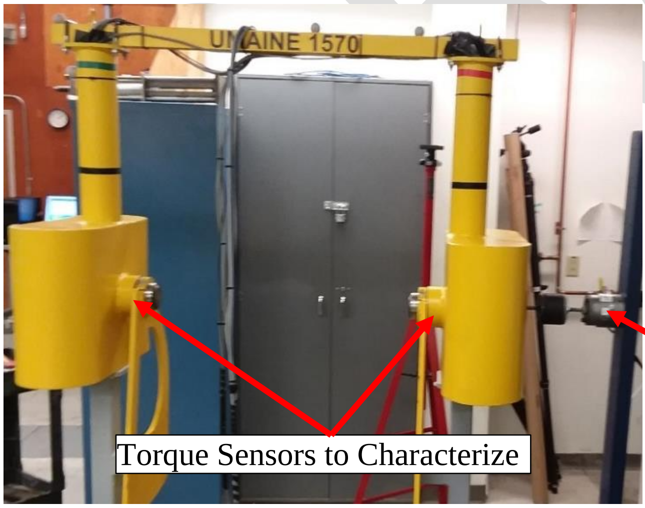


Figure 10. NWEI model PTO boxes on test stand

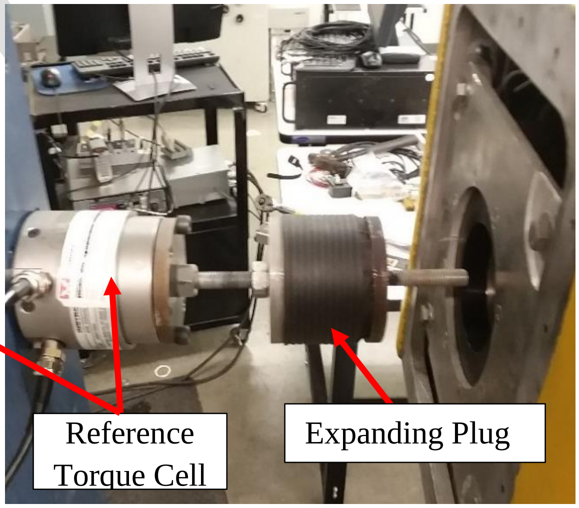


Figure 9. Calibrated reference torque cell

In this configuration, the entire mass of the arm is supported from a strap above the fixture, see Figure 11. By varying the tension in the strap, as well as adding mass to the arm when appropriate, we were able to apply positive and negative torques ranging approximately +/- 90 N-m which is within the calibrated range of +/- 100 N-m for the reference torque load cell. The strain gauge torque sensors were configured in the same manner used during the model test, including the wiring harness and strain gauge amplifiers used for testing. This allowed us to measure the as-built conditions and obtain a reliable characterization. The voltage from the PTO shaft strain bridge was read from the amplifier analog output pins and the output from the reference torque load cell was read from its own analog output channels. They were both recorded and saved to a file using LABVIEW and a PXI-6225 analog input module. A total of three runs of +/- 90 N-m were done for each torque sensor and between each run the set up was disassembled and reassembled to measure the system sensitivity. The arms were realigned with the shaft using indexing marks and rotation of the motor shaft was aligned by eye, which was the same method used during testing. The bolts on the arm were torqued to 23 ft-lbs using a torque wrench.

Figure 11. Method of applying torque

The time history results were analyzed and characterization parameters were determined through Excel's linear trendline function. The slope of the linear trendline is used to convert Voltage (V) output to Torque (N-m) readings and values for each sensor are summarized in Table 4. Full time histories are presented in Table 5 and Table 6. The calibration record for the reference load cell is included in the Reference Torque Cell Calibration Certificate section.

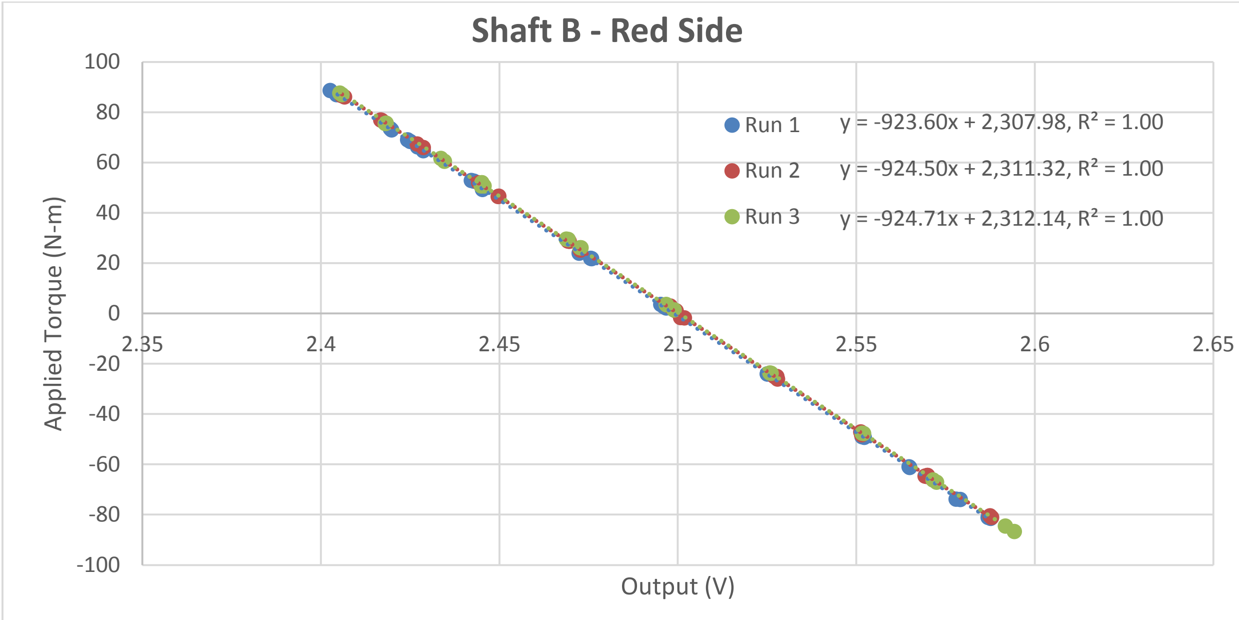


Figure 12. Shaft B – Red Side Characterization

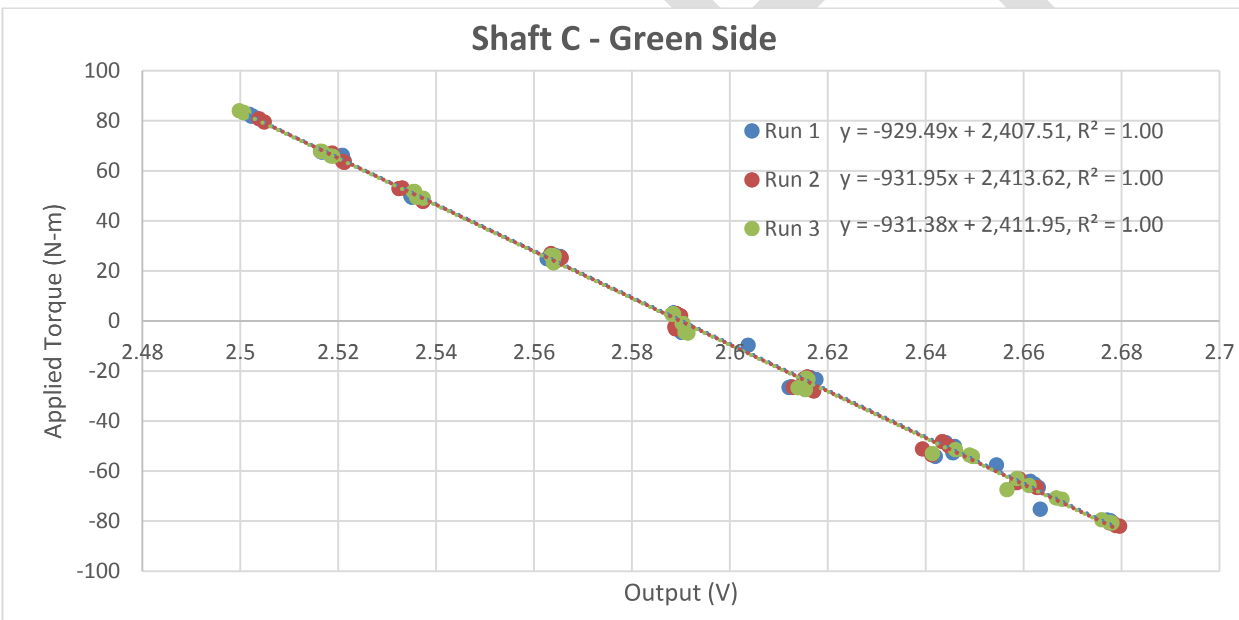


Figure 13. Shaft C – Green Side Characterization

Table 4. Characterization parameters

	Slope 1 (N-m/V)	Slope 2 (N-m/V)	Slope 3 (N-m/V)	Std Dev (N-m/V)	Mean (N-m/V)	Uncertainty (N-m/V)	COV
Shaft B – Red Side	-923.60	-924.50	-924.71	0.481	-924.27	1.036	-0.052%
Shaft C – Green Side	-929.49	-931.95	-931.38	1.051	-930.94	2.262	-0.113%

Table 5. Shaft B – Red Side Characterization

Run 1		Run 2		Run 3	
Applied Torque (N-m)	Voltage (V)	Applied Torque (N-m)	Voltage (V)	Applied Torque (N-m)	Voltage (V)
3.59	2.4952	1.03	2.4995	1.39	2.4989
2.23	2.4967	1.03	2.4995	1.43	2.4989
23.97	2.4724	25.19	2.4727	26.12	2.4726
24.08	2.4724	25.22	2.4726	26.11	2.4729
49.43	2.4453	46.54	2.4497	50.70	2.4449
49.34	2.4453	46.64	2.4498	50.65	2.4457
66.23	2.4271	67.37	2.4269	60.49	2.4346
64.69	2.4287	65.93	2.4287	61.67	2.4336
73.41	2.4194	86.07	2.4066	87.64	2.4053
72.90	2.4198	86.52	2.4058	87.00	2.4059
86.96	2.4044	76.65	2.4171	75.46	2.4180
88.58	2.4026	76.87	2.4167	75.67	2.4183
68.98	2.4243	51.86	2.4444	51.93	2.4451
68.38	2.4250	51.91	2.4442	51.94	2.4451
52.87	2.4422	28.66	2.4695	29.57	2.4688
52.64	2.4428	28.84	2.4692	29.44	2.4693
21.78	2.4759	2.92	2.4979	3.51	2.4967
21.95	2.4756	2.85	2.4978	3.49	2.4968
2.64	2.4961	-24.88	2.5269	-23.85	2.5261
2.76	2.4961	-25.01	2.5277	-23.71	2.5258
-24.05	2.5251	-47.30	2.5514	-47.77	2.5521
-24.05	2.5251	-47.16	2.5512	-47.60	2.5516
-49.24	2.5522	-64.43	2.5700	-67.03	2.5725
-49.03	2.5516	-64.38	2.5698	-66.20	2.5715
-61.20	2.5649	-80.46	2.5874	-86.66	2.5943
-60.99	2.5648	-81.09	2.5879	-84.52	2.5918
-73.80	2.5779	-64.68	2.5692		
-73.97	2.5791	-64.76	2.5697		
-81.14	2.5869	-48.29	2.5515		
-81.48	2.5876	-48.12	2.5515		
		-25.24	2.5272		
		-26.07	2.5279		
		-1.65	2.5007		
		-1.80	2.5018		

Table 6. Shaft C – Green Side Characterization

Run 1		Run 2		Run 3	
Applied Torque (N-m)	Voltage (V)	Applied Torque (N-m)	Voltage (V)	Applied Torque (N-m)	Voltage (V)
2.69	2.5888	2.48	2.5891	-1.02	2.5905
2.80	2.5883	2.38	2.5894	-1.01	2.5903
24.87	2.5628	24.18	2.5643	23.33	2.5640
24.82	2.5627	24.16	2.5646	23.23	2.5640
49.98	2.5348	47.83	2.5373	49.44	2.5360
49.40	2.5350	47.91	2.5372	49.03	2.5374
67.75	2.5164	63.78	2.5209	67.87	2.5164
67.48	2.5166	63.47	2.5212	67.80	2.5167
81.79	2.5023	80.80	2.5039	83.24	2.5007
82.59	2.5018	79.50	2.5048	83.33	2.5007
63.94	2.5213	67.07	2.5187	84.03	2.4998
66.17	2.5208	67.01	2.5187	65.87	2.5189
66.02	2.5207	52.91	2.5324	66.00	2.5185
50.07	2.5355	53.15	2.5331	51.79	2.5354
50.11	2.5359	26.91	2.5635	51.80	2.5356
25.83	2.5653	25.33	2.5656	26.03	2.5641
26.05	2.5646	2.15	2.5899	26.17	2.5635
3.09	2.5887	2.99	2.5890	2.78	2.5882
3.26	2.5885	-23.12	2.6152	2.88	2.5885
-23.40	2.6176	-22.32	2.6158	-23.29	2.6159
-22.66	2.6164	-49.87	2.6447	-22.87	2.6156
-48.63	2.6441	-48.20	2.6434	-54.10	2.6496
-50.18	2.6459	-63.19	2.6592	-51.36	2.6461
-65.17	2.6622	-66.49	2.6627	-62.87	2.6586
-64.04	2.6614	-80.84	2.6783	-65.73	2.6611
-79.61	2.6771	-80.68	2.6776	-80.73	2.6781
-80.00	2.6778	-81.78	2.6789	-80.50	2.6775
-79.85	2.6777	-82.01	2.6796	-79.48	2.6760
-75.15	2.6634	-64.64	2.6586	-70.78	2.6667
-52.64	2.6456	-64.62	2.6587	-71.23	2.6679
-57.55	2.6545	-53.39	2.6412	-53.56	2.6490
-66.54	2.6630	-51.10	2.6394	-52.95	2.6414
-54.08	2.6420	-28.03	2.6172	-27.50	2.6154
-26.26	2.6125	-26.44	2.6129	-26.64	2.6139
-9.62	2.6037	-2.35	2.5888	-4.76	2.5914
-4.50	2.5901	-3.18	2.5889	-4.60	2.5908

Reference Torque Cell Calibration Certificate

REPORT OF CALIBRATION

ISSUED BY: INSTRON CALIBRATION LABORATORY

DATE OF ISSUE: 22-Jun-17

REPORT NUMBER: **83061217095535**

Instron
825 University Avenue
Norwood, MA 02062-2643
Telephone: (800) 473-7838
Fax: (781) 575-5750
Email: service_requests@instron.com

APPROVED SIGNATORY

Type of Calibration: **Torsion**

Relevant Standard: **Torsion**

Date of Calibration: **12-Jun-17**

Customer Requested Due Date: **30-Jun-18**

Customer

Name:	University of Maine System
Address:	35 Flagstaff Rd. Advanced Structures & Composites Ctr Orono, Me 04469 ken.williams@unit.maine.edu
P.O./Contract No.:	
Contact:	Ken Williams

Machine

Manufacturer:	Instron
Serial Number:	8874/Q3191- AS 512
System ID:	8874/Q3191- AS 512
Range Type:	Single

Transducer

Manufacturer:	Instron
Transducer ID:	2527-201/48190/AS 518
Capacity:	885 lbf-in
Type:	Clockwise/Counterclockwise

Classification

Indicator 1. - Digital Readout - PASSED

Adjustments

The testing machine was verified in the 'as found' condition with no adjustments carried out.

Summary of Results

Temperature at start of verification: 68.5 °F.

Indicator 1. - Digital Readout (lbf-in)

Range Full Scale (%)	Tested Force Range (lbf-in)	Mode	Max Error (%)	Max Repeat Error (%)	Zero Return	Resolution (lbf-in)	Lower Limit (lbf-in)
100	8.50164 to 874.8952	Clockwise	-0.41	0.42	Pass	0.001	0.2
	9.61296 to 870.0534	Counterclockwise	0.42	0.54	Pass	0.001	0.2

Temperature at end of verification: 69.6 °F.

REPORT OF CALIBRATION

ISSUED BY: INSTRON CALIBRATION LABORATORY

REPORT NUMBER:
83061217095535

Data Point Summary - Indicator 1. - Digital Readout (lbf-in)

CLOCKWISE

% of Range	Run 1 Error (%)	Run 2 Error (%)	Run 3 Error (%)	Repeat Error (%)	Relative Uncertainty* (%)	Uncertainty of Measurement* (± lbf-in)
100% Range (Full Scale: 874.8952 lbf-in)						
1	0.06	-0.02	0.36	0.08	0.27	0.023
2	-0.06	0.36	0.38	0.42	0.32	0.055
4	-0.04	0.21	0.14	0.25	0.21	0.073
7	-0.27	-0.40	-0.34	0.13	0.16	0.100
10	-0.25	-0.20	-0.14	0.05	0.15	0.14
20	-0.04	-0.41	-0.40	0.37	0.28	0.50
40	-0.18	-0.21	-0.18	0.03	0.14	0.51
70	-0.08	-0.07	-0.09	0.01	0.14	0.88
100	0.11	-0.05	-0.01	0.16	0.17	1.5

Data Point Summary - Indicator 1. - Digital Readout (lbf-in)

COUNTERCLOCKWISE

% of Range	Run 1 Error (%)	Run 2 Error (%)	Run 3 Error (%)	Repeat Error (%)	Relative Uncertainty* (%)	Uncertainty of Measurement* (± lbf-in)
100% Range (Full Scale: 870.0534 lbf-in)						
1	0.09	-0.13	-0.38	0.22	0.31	0.030
2	-0.01	-0.34	-0.31	0.33	0.25	0.049
4	0.31	-0.23	0.06	0.54	0.34	0.13
7	-0.03	0.41	0.10	0.44	0.30	0.18
10	0.18	0.07	0.02	0.11	0.17	0.15
20	0.07	0.18	0.07	0.11	0.16	0.28
40	0.14	0.25	0.25	0.11	0.16	0.56
70	-0.24	0.15	0.12	0.39	0.29	1.8
100	0.42	0.34	0.41	0.08	0.15	1.3

** The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.*

Data - Indicator 1. - Digital Readout (lbf-in)

CLOCKWISE

	Run 1		**Run 2**		**Run 3**	
% of Range	Indicated (lbf-in)	Applied (lbf-in)	Indicated (lbf-in)	Applied (lbf-in)	Indicated (lbf-in)	Applied (lbf-in)
100% Range (Full Scale: 874.8952 lbf-in)						
0 Return	0.026		0.016		0.008	
1	8.65	8.64444	8.50	8.50164	8.76	8.72844
2	17.83	17.83992	17.06	16.9995	17.01	16.9449
4	36.15	36.16536	35.81	35.73612	35.01	34.96248
7	62.771	62.9391	61.94	62.1909	61.99	62.2038
10	89.17	89.397	88.59	88.7692	88.57	88.6918
20	177.63	177.7018	176.94	177.676	177.007	177.719

Instron CalproCR Version 3.34

REPORT OF CALIBRATION

ISSUED BY: INSTRON CALIBRATION LABORATORY

REPORT NUMBER:
83061217095535

Data - Indicator 1. - Digital Readout (lbf-in)

CLOCKWISE

% of Range	Run 1 Indicated (lbf-in)	Run 1 Applied (lbf-in)	Run 2 Indicated (lbf-in)	Run 2 Applied (lbf-in)	Run 3 Indicated (lbf-in)	Run 3 Applied (lbf-in)
100% Range (Full Scale: 874.8952 lbf-in)						
40	353.97	354.6124	355.11	355.8508	354.099	354.7199
70	619.50	620.0084	618.76	619.2086	622	622.5755
100	868.8	867.8088	874.5	874.8952	877.59	877.6902

Data - Indicator 1. - Digital Readout (lbf-in)

COUNTERCLOCKWISE

% of Range	Run 1 Indicated (lbf-in)	Run 1 Applied (lbf-in)	Run 2 Indicated (lbf-in)	Run 2 Applied (lbf-in)	Run 3 Indicated (lbf-in)	Run 3 Applied (lbf-in)
100% Range (Full Scale: 870.0534 lbf-in)						
0 Return	0.009		0.052		0.029	
1	9.65	9.6411	9.60	9.61296	9.58	9.61674
2	19.41	19.41156	19	19.06464	19.06	19.12008
4	38.34	38.22252	38.29	38.38002	38.41	38.38548
7	61.16	61.1804	61.17	60.9181	60.91	60.8493
10	87.56	87.4061	87.44	87.376	87.41	87.3889
20	175.61	175.4916	175.83	175.5088	175.64	175.5088
40	351.61	351.1337	352.03	351.138	352.01	351.1466
70	614.38	615.8632	616.73	615.8116	616.59	615.8331
100	865.20	861.548	873.03	870.0534	877.56	873.9363

The Return to Zero tolerance is ± the indicator resolution, 0.1 % of the maximum force verified in the range, or 1% of the lowest force verified in the range, whichever is greater.

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ISSUED BY: INSTRON CALIBRATION LABORATORY

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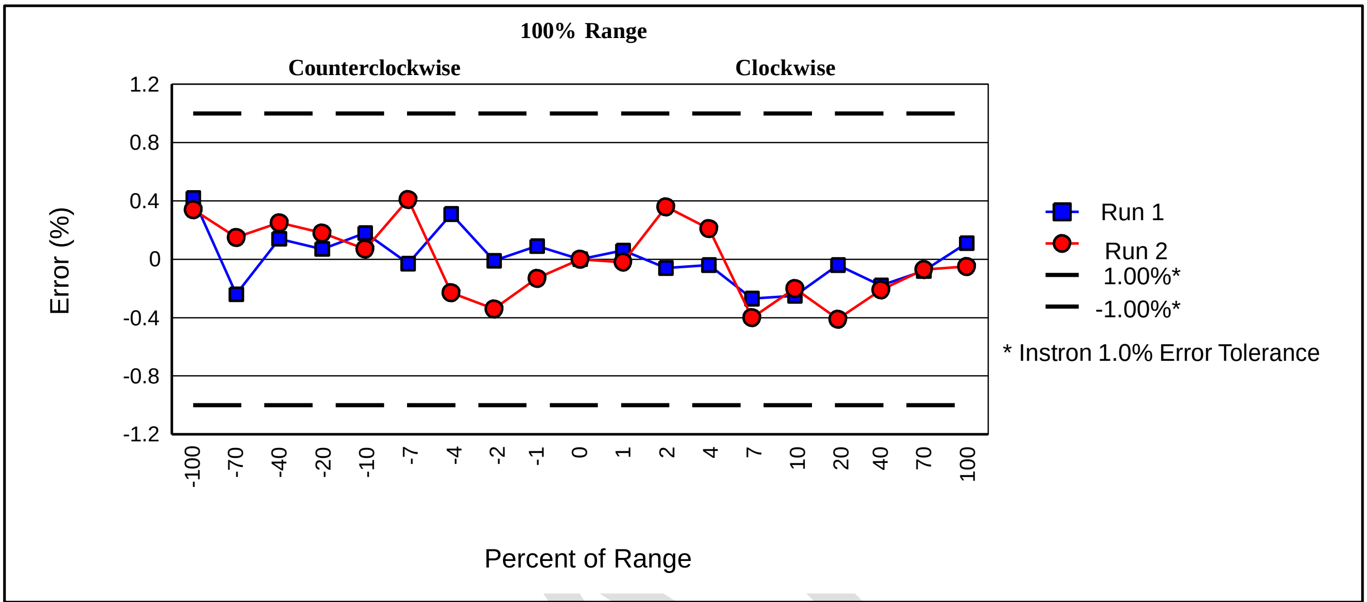
Graphical Data - Indicator 1. - Digital Readout (lbf-in)



Verification Equipment

Make/Model	Serial Number	Description	Calibration Agency	Capacity	Cal Date	Cal Due
Extech 445580	1078704	temp. indicator	Masy	NA	06-Jan-16	06-Jan-18
Interface 9840	93035	force indicator	Instron	NA	05-Jan-16	05-Jan-18
Lebow 1517429	1517429	load cell	Interface	1000 lbf-in	22-Jun-16	22-Jun-17
Lebow 1517440	1517440	load cell	INTERFACE	110 lbf-in	30-Aug-16	30-Aug-17

The value of acceleration due to gravity used to calculate the force exerted by the mass was 9.8062 m/s².

Verification Equipment Usage

Range Full Scale (%)	Standard Serial Number	Mode	Percent(s) of Range	Lower Limit for Standard Class A / A1 (lbf-in)
100	1517429	Clockwise	7/10/20/40/70/100	40 / 40
100	1517440	Clockwise	1/2/4	2 / 4
100	1517429	Counterclockwise	7/10/20/40/70/100	40 / 40
100	1517440	Counterclockwise	1/2/4	2 / 3

Instron standards are traceable to the SI (The International System of Units) through standards maintained by the National Institute of Standards and Technology (NIST) or other internationally recognized National Metrology Institutes (NMIs). The standard Class A lower limit is used for systems with an accuracy of +/- 1.0% and the Class A1 lower limit is used for systems with an accuracy of +/- 0.5%.

Comments

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Verified by: Pete Petersson
Senior Field Service Engineer

APPENDIX C. WAVE TANK MODEL SPECIFICATION

APPENDIX D. PHOTOGRAPHS

Figure 14. Model test fitting

Figure 15. Float and arms on test stand

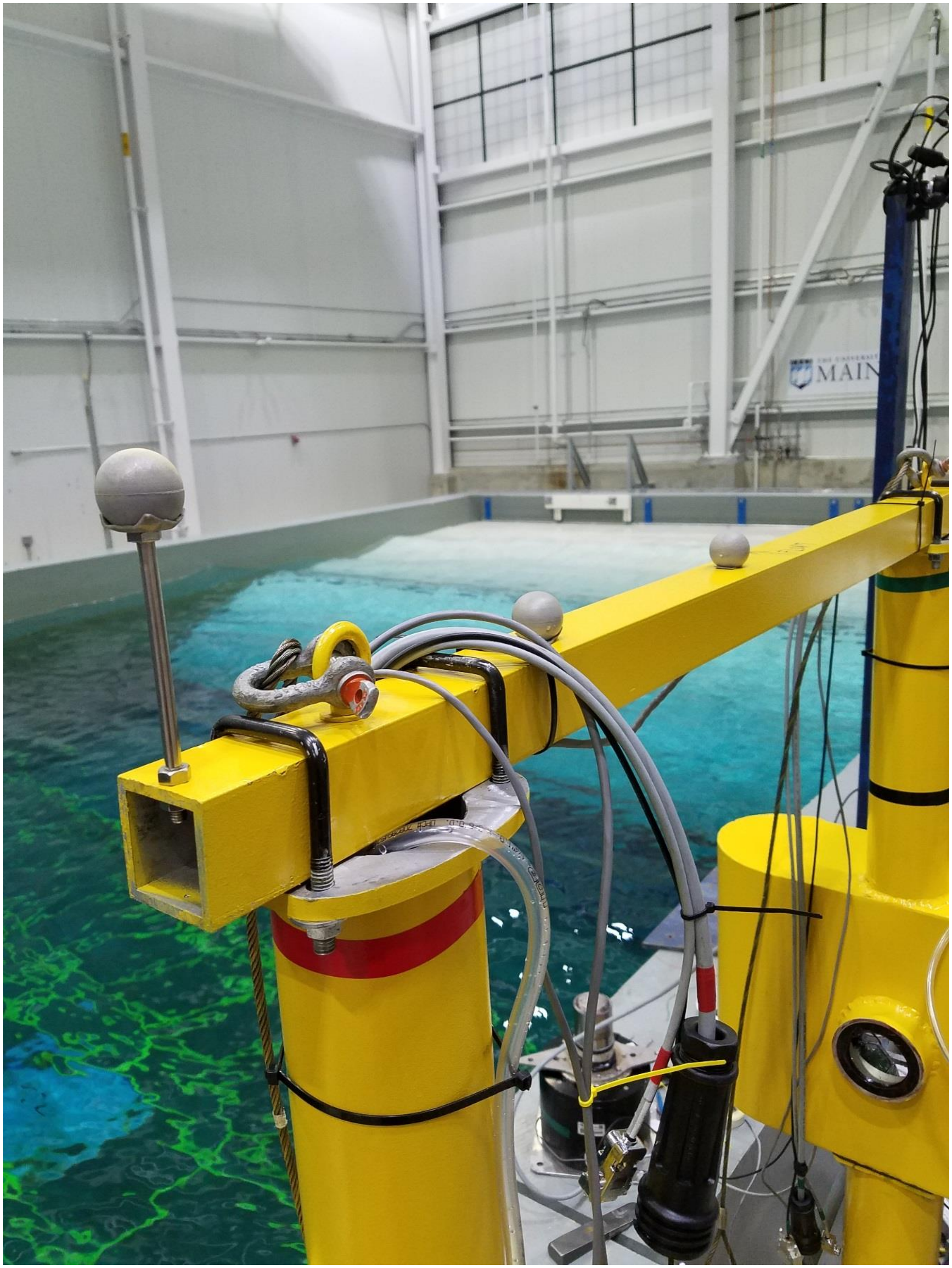

Figure 16. Detail of Qualisys motion tracking markers and cable routing

Figure 17. Fully assembled model being lowered into water

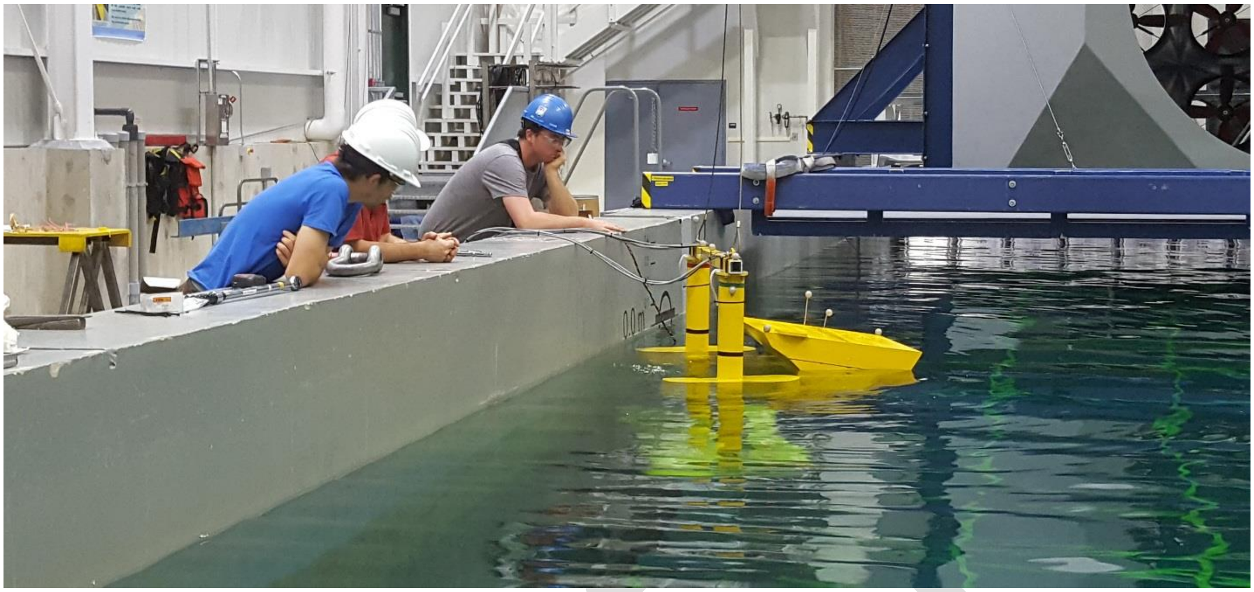

Figure 18. Model in water and adjusting trim

Figure 19. Fully assembled model