Post Access Report

Halona WEC

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TEAMER

Testing & Expertise for Marine Energy

1 EXECUTIVE SUMMARY

Halona functions as an omnidirectional spar buoy oscillating water column (OWC) wave energy converter (WEC). The buoy consists of a cylindrical spar, a heave plate at the base, and four axisymmetric waveguides. The overall design features are intended to improve buoy stability for autonomous underwater vehicle (AUV) docking.

Objective: To understand the power performance and motion response of Halona for the purpose of improving the state of WEC based AUV docking. Halona has yet to be optimized for power extraction. As Halona is designed for AUV docking, dynamic positioning and motion control will be needed, which require an in-depth understanding of motion response in multidirectional irregular waves.

Methods: A 1/10th scale Halona was tested in unidirectional regular waves with a range of power take off (PTO) damping values represented by different diameter orifice plate dampers. Halona was tested at the O.H. Hinsdale Wave Research Laboratory Directional Wave Basin in a scaled version of the design field conditions. The eventual field deployment will occur at Kilo Nalu on the south shore of Oahu, which is a strongly bimodal wave condition, with distinct wind and swell conditions and minimal seasonal variability. Halona was also tested in directional waves to understand directional motion dependence. The directional dependence was determined for each orifice.

Results: The resonant frequency of Halona was determined for both a free floating and fixed configuration. It was determined that the directional dependence of the incident wave is insignificant. The impact of the PTO damping on WEC motion and power performance was determined for the target operational wave conditions..

2 INTRODUCTION TO THE PROJECT

Halona functions as an omnidirectional spar buoy oscillating water column (OWC) wave energy converter (WEC). The buoy consists of a cylindrical spar, a heave plate at the base, and four axisymmetric waveguides. The overall design features are intended to improve buoy stability for autonomous underwater vehicle (AUV) docking. The central cylindrical spar houses the compression chamber of the OWC. A conceptual drawing can be seen in Figure 1.1.1.

Based on previous work on a fixed structure, the ratio of the diameter of the chamber, the length of the wave guides, and the design wavelength can be optimized to amplify the displacement of the internal water surface. The resonant frequency is centered on 6 second period waves, with the ability to capture energy between 5 and 10 second waves. The amplified displacement is used to compress air into a pneumatic power take-off, which has yet to be established.

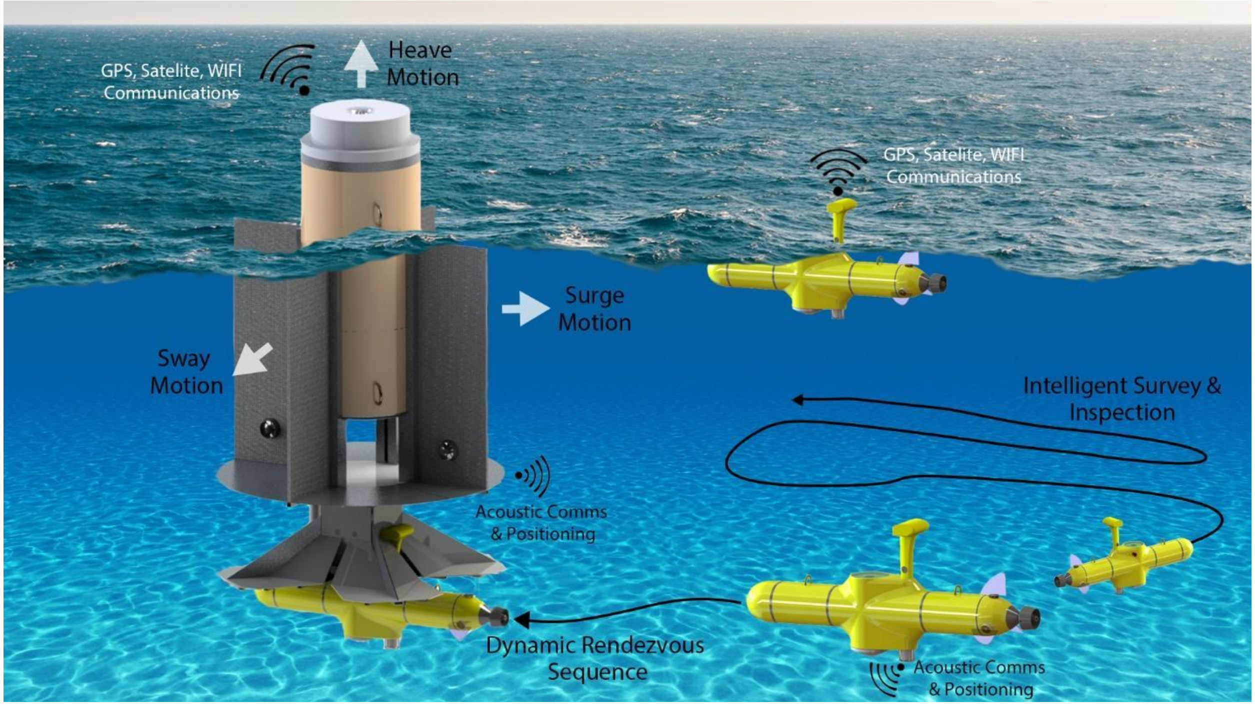


Figure 1.1.1 Conceptual Drawing of Halona

Objective: To understand the power performance and motion response of Halona for the purpose of improving the state of WEC based AUV docking. Halona has yet to be optimized for power extraction. As Halona is designed for AUV docking, dynamic positioning and motion control will be needed, which require an in-depth understanding of motion response in multidirectional irregular waves.

Methods Overview:

A 1/10th scale Halona was tested in unidirectional regular waves with a range of power take off (PTO) damping values represented by different diameter orifice plate dampers. Halona was tested at the O.H. Hinsdale Wave Research Laboratory Directional Wave Basin in a scaled version of the design field conditions. The eventual field deployment will occur at Kilo Nalu on the south shore of Oahu, which is a strongly bimodal wave condition, with distinct wind and swell conditions and minimal seasonal variability.

Differential pressure sensors were used to quantify the flow across an orifice plate, and thus represent overall PTO damping. We used a range of orifice diameters to vary PTO damping, which will be used to validate an OpenFOAM model and optimize power extraction.

Halona was also tested in directional waves to understand directional motion dependence. The directional dependence was determined for each orifice. The motion response and PTO damping observed will be used to validate an OpenFOAM model. This model will be used to establish the values of viscous damping to be used in linear hydrodynamic models, such as ProteusDS.

A fixed test article was deployed simultaneously to enable faster characterization of the orifice damping. The experimental results will be recreated in OpenFOAM to allow for a faster timeline on developing a parametric model of the orifice in the floating test article.

3 Roles and Responsibilities of Project Participants

3.1 Applicant Responsibilities and Tasks Performed

Applicant was responsible for the design, numerical modeling, and construction of the 1:10 scale prototype of Halona. The prototype was primarily fabricated at the University of Hawaii, and assembled at Oregon. Minor fabrication was required in Oregon. The applicant was responsible for providing funds for manufacturing. The applicant also provided the springs incorporated into the mooring lines required for the floating test article.

Applicant was responsible for defining the wave conditions to be tested, assisting OSU staff in preparing the model for testing, and defining the measurements needed to be taken. The applicant was present for testing.

3.2 Network Facility Responsibilities and Tasks Performed

The Network Facility was responsible for the overall implementation of testing. This included the following:

1. Preparation of the wave basin
2. Instrumentation set-up (wave gauges, pressure gauges, motion capture system, load cells)
3. Instrumentation hook-up, survey and calibration. DAQ deployment.
4. Set-up of the swing for dry-tests
5. Instrumentation for the dry-tests
6. Fill the basin
7. Work with the applicant on the design and instrumentation plan of the test article
8. Work with the applicant on the test plan
9. Set-up of the characterization (System-ID) of the test article (static load and free decay tests)
10. Deployment of the test articles
11. Run the prescribed wave conditions
12. Record and measured data

13. At the end of the experiments, perform the data post-processing to transform raw data into engineering units
14. Upload and backup the measured data
15. Model recovery and basin clean-up

Also included is the setup of the data acquisition system used to record the instruments. The facility was responsible for the operation of the wavemaker and recording all experiments on the data acquisition system. The facility also provided the applicant with a copy of the recorded data in raw form, as well as in engineering units. Further post-processing is the responsibility of the applicant.

4 PROJECT OBJECTIVES

The technical assistance objectives were to understand the power performance and motion response of Halona. Halona has yet to be optimized for power extraction, and thus it was desired to test a 1:10 scale Halona in unidirectional waves with a range of power take off (PTO) damping values. Differential pressure sensors were used to quantify the flow across an orifice plate, which can be used to calculate overall PTO damping and power extraction. We used a range of orifice diameters to vary PTO damping. This will be used as a baseline to validate an OpenFOAM model to optimize power extraction.

As Halona is designed for AUV docking, dynamic positioning and motion control will be needed. Thus, Halona was tested in directional waves to understand directional motion dependence and understand the directional dependence on power extraction. The motion response and PTO damping observed will be used to validate an OpenFOAM model. This model will be used to establish the values of viscous damping to be used in linear hydrodynamic models, such as ProteusDS or AQWA.

The support requested included operation of the directional wave basin, installing sensors and mooring Halona in the basin. The hull of the prototype was partially 3D printed, with additional solid flotation affixed to the hull using adhesive. Lead weights were used to make adjustments to mass. Acrylic orifice plates were used to emulate the effects of the PTO.

This testing was fundamental to progressing in developing WEC-based AUV docking. Such docking is a two part problem: understanding WEC motion, and navigating the AUV based on the WEC motion. This testing robustly quantified WEC motion and thus enables future research to investigate the AUV navigation side of WEC-based AUV docking.

The key parameters that were measured included OWC chamber pressure and motion response. Indirect measurements of power take-off damping can be found through the use of these key parameters. The power take-off damping and motion response will be used to optimize power extraction in the platform, which can map to quantifiable metrics such as LCOE and performance improvements. Although an exact LCOE cannot be determined at this stage, the data produced will allow us to quantify a range for the LCOE.

5 Test Facility, Equipment, Software, and Technical Expertise

Test Facility

The Directional Wave Basin was used to test the Halona in a variety of wave conditions.
The wavemaker for the Directional Wave Basin (DWB) is 48.8 m long and 26.5 m wide, with 2.1 m high walls and a maximum still water depth of 1.5 m. It is constructed as a reinforced concrete reservoir, with a 15 cm wall and floor thickness. A vehicle access ramp, 3 m wide, allows equipment and materials to be transported conveniently into and out of the basin. A bridge crane with a capacity of 7.5 tons spans the length and width of the DWB to position the models and to facilitate instrumentation. Unistrut inserts were placed in rows at 2.1 m spacing to affix specimens, and instrumentation throughout the basin.

The wavemaker for the Directional Wave Basin (DWB) is a 30-channel piston-type belt-driven servo-motor system. It consists of a segmented vertical wall, referred to as the wavemaker piston. Each segment of the wall has a drive point on either side; there are 29 segments in total being driven by 30 drive points. Each drive point is moved by a 21.3kW servomotor and toothed belt that moves the piston back and forth on a bearing rail connected to supporting steel that is bolted into the basin floor and side walls. Each drive point can move at up to 2 m/s and has a 2.1 m total stroke, which is defined as the distance between its most offshore and most onshore positions. The maximum difference between adjacent drive points is 0.25 m. The maximum still water depth of the DWB for running short waves (wind waves) is 5 ft (1.5 m), and the maximum still water depth for running tsunamis (solitary waves) is 1 m. The wavemaker is capable of generating repeatable regular, irregular, tsunami, and user-defined waves, and has an active reflected wave cancellation system. The basin was filled to a water depth of 1.36 m.

Wave Gauges

All wave gauges used at the wave basin are custom gauges. Two types of gauges were used: acoustic and resistive wave gauges. All wave gauges are calibrated when changing the tank water level (filling and draining). Fill and drain calibration methods are the same. While the water level is slowly changing, the HWRL DAQ observes all analog inputs over a sample period, typically sampling at 100Hz for a 1-minute duration. Sampling of analog inputs is typically done every 5 minutes for an entire fill or drain, which can take up to 9 hours. The mean voltage of every input channel is estimated for each sample period. Mean voltage estimates are then put into a wave gauge calibration spreadsheet that calculates a linear least-squares fit between the observed wave gauge voltages and the calibrated water depth observations from a traceably-calibrated pressure sensor, referred to as *level* in the HWRL DAQ.

In addition, some wave gauges (referred to as self-calibrating wave gauges) can be calibrated without changing the water level. The self-calibrating wave gauges are equipped with a lead screw of known pitch, a stepper motor, and a rotary encoder. Each set of self-calibrating wave gauge wires are driven up and down by the stepper motor, and the accompanying encoder position is observed. Combining the observed position of the encoder with the known pitch of the lead screw provides an observation of vertical motion of the wave gauge. The observed voltages are linearly least squares fitted to the observed vertical motion, generating a calibration slope. Self-calibrating wave gauges are typically calibrated at the beginning and end of every day.

Pressure Sensors

Setra Very Low Differential Pressure Sensors were used to measure the pressure inside the OWC chamber, with a pressure range of +/- 2488 Pascals (10” WC). See Appendix A for data sheets on the pressure sensors.

PhaseSpace Motion Capture System:

We used the 8 camera PhaseSpace Impulse system package to measure the motion response.

The PhaseSpace Impulse system captures complex motion in real time using advanced hardware and software technology. Motion capture is accomplished by placing the PhaseSpace cameras around a capture volume and moving objects with LEDs attached to them. The cameras detect the positions of the LEDs and transmit this information to a central computer that processes the data and calculates actual positions. These positions are then available for further processing by client systems in a client server environment.

PhaseSpace cameras and active LED markers were placed strategically on the ring collar float of the floating test article in the wave tank in order to track and quantify the response of floating structures to wave action with high resolution (~2 mm) and high speed (up to 500 Hz).

Load Cells for Mooring
Four load cells were attached to each mooring line. Load cells were used to validate the calculated spring force from the mooring. The load cells were WMC-500 sensors with a 2200 N capacity. See Appendix A for more information on the load cells.

Data Acquisition and Analysis

The test facility used NI LabView for data acquisition software and MATLAB for data processing to engineering units. The applicant used MATLAB to process the collected data into normalized response amplitude operators. AQWA, ProteusDS, and OpenFOAM will be used simulate the results from the wave basin experiments. Within OpenFOAM, the package waves2FOAM will be employed to recreate a numerical wave tank representing the observed portion of the wave basin. The API function within ProteusDS will be used to handle the effects of PTO damping. See Appendix B for more information on data acquisition.

Critical Personnel
Bret Bosma was the point of contact and Project Manager at Hinsdale. He overviewed the day to day activities of the project, and ensure the timely execution and progress of the project.
Tim Maddux was responsible for the day-to-day operations of the HWRL. He also serves as Safety Officer and supported the different activities along the project.
Pedro Lomonaco was the HWRL Director, with full oversight of the project, providing administrative, scientific and technical advice.
Permanent and temporary staff at HWRL were trained to perform major tasks in support of the project, including construction, planning, deploying instruments, operating the wavemaker, recording data, recovery, and demolition.

6 Test or Analysis Article Description

Intended Purpose of Halona

Halona is designed as an autonomous underwater vehicle docking station for marine resident ocean observations. Halona utilizes its large subsurface profile to act as a drogue drifter to cover vast distances to enable high temporal and spatial resolution data collection. The platform will use the Regional Ocean Modeling System to develop a navigation system to control drifting. The platform will use background flow patterns to propel itself, while expending energy to orient itself and navigate across the flow. This principle has been previously studied by Dr. Zhouyuan Song at the University of Hawaii.

The anticipated market for Halona is the offshore observing market. This market includes metocean data users and offshore oil & gas service providers. End users have been identified through over 20 interviews with industry professionals and university scientists.

Metocean data users, which include university and governmental scientists, are currently limited by the availability of both high temporal and spatial resolution data. The primary limitations are the availability of adequate power at sea and the cost of ship-based operations to conduct AUV missions.

Offshore oil and gas service providers provide inspection, repair, and maintenance (IRM) services to oil and gas producers to fulfill regulatory requirements. Active and existing offshore infrastructure requires routine inspection. Current inspections are conducted with ship-based ROV/AUV inspections, which cost on the order of $100,000 per day.

Halona will function as a marine resident ocean observation platform that will enable high temporal and spatial resolution data collection by maintaining marine resident AUV capabilities, while also supporting met sensors. Halona will have two applications: a moored and drifting case. The moored case will be first validated, and once the motion response of the platform is understood, a drifting case will be developed.

This testing is fundamental to progressing in developing WEC-based AUV docking. Such docking is a two part problem: understanding WEC motion, and navigating the AUV based on the WEC motion. This testing will robustly quantify WEC motion and thus enable future research to investigate the AUV navigation side of WEC-based AUV docking.

Test Article Description

We tested 2 test articles simultaneously in the wave basin at a water depth 1.36 meter. One test article is a free-floating model, with light lateral springs to resist the mean drifting force. The other test article is a fixed acrylic tube of the same diameter as the floating test article and is affixed to the bottom of the basin via a frame built by the OSU team.

The hull of the floating test article can be seen below. The prototype has a central hollow cylinder with a diameter of 22.5 cm and 6 mm thickness of SLA Resin. The central cylinder is affixed 16 cm above the 84 cm diameter plate of thickness 1.3 cm of PVC. Along the exterior of the central cylinder are 4 waveguides, spaced radially every 90 degrees. Each waveguide is a 60 cm tall and 30 cm wide carbon fiber sandwich panel that is 6 mm thick. The hull is comprised of 3D printed sections, acrylic orifice plates, and lead weights attached via 0.5” hex bolts. The solid floatation ring collar is that is 6 inches thick and 20 inches outer diameter. The dry weight of the buoy is 25.9 kg, with 90% of the weight centered at the base plate.

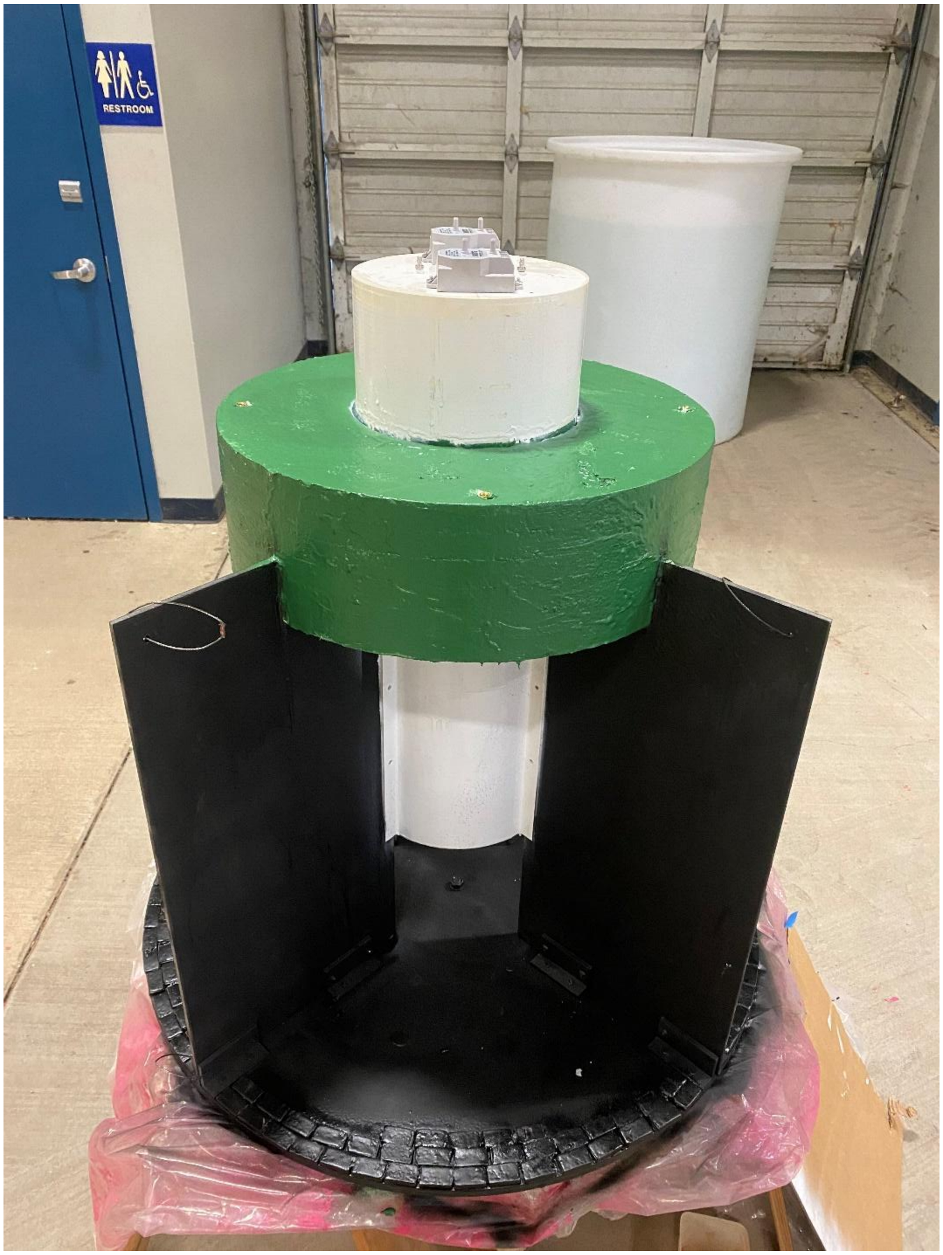


Figure 5.1.1 Image of Floating Test Article at O.H. Hinsdale Wave Research Lab. Bricks along the heave plate edge are trim weights. Differential Pressure Sensors affixed to the top of the model.

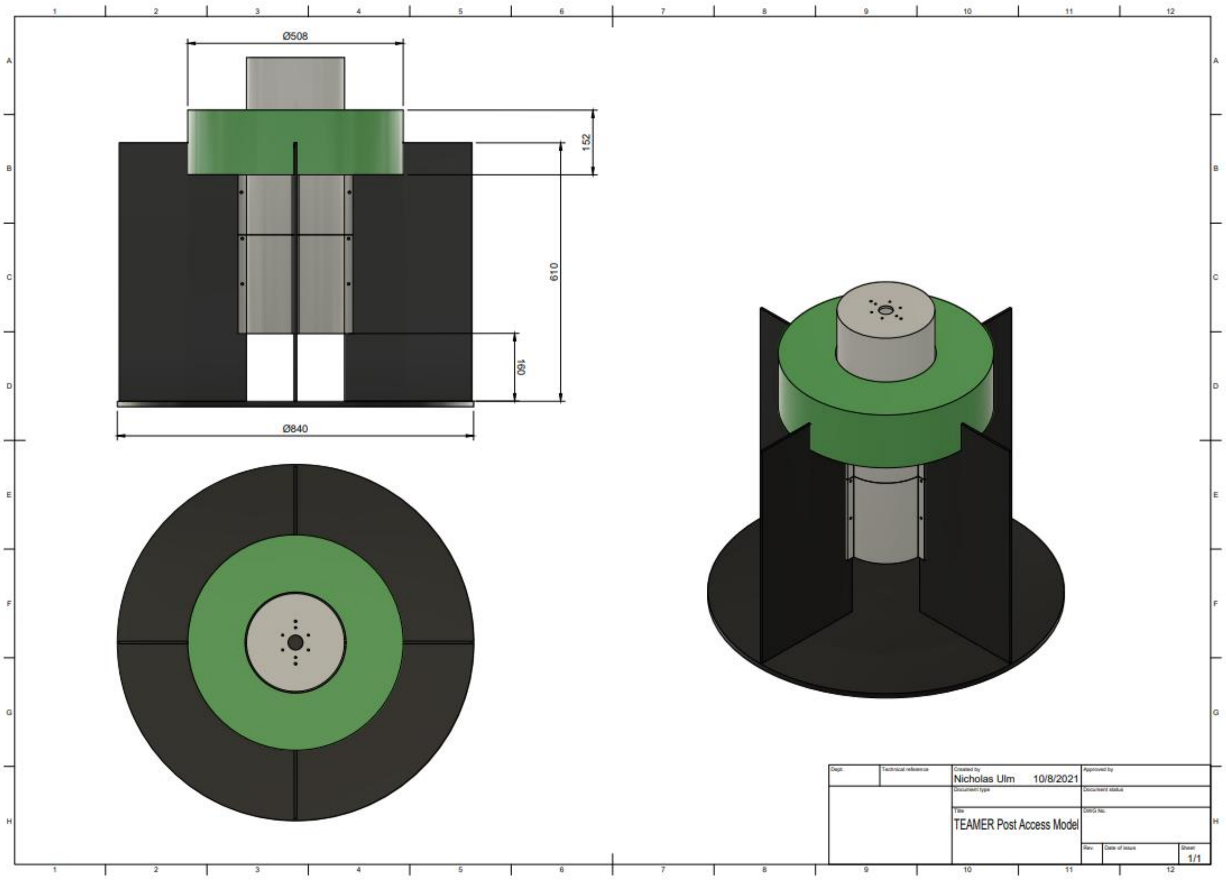


Figure 5.1.2 Drawing of Floating Test Article. Dimensions in mm

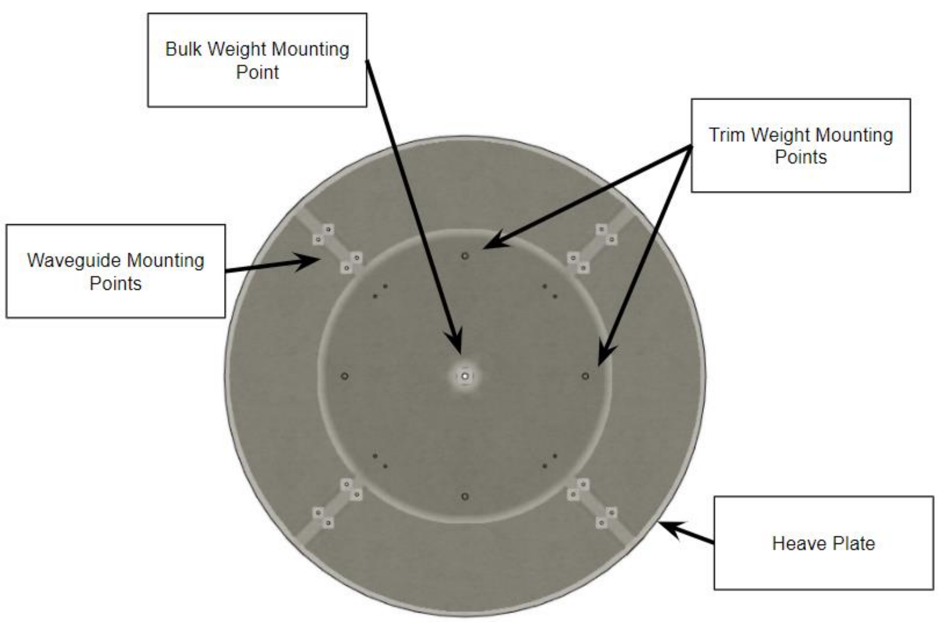


Figure 5.1.3 Floating Test Article Heave Plate Mounting Points

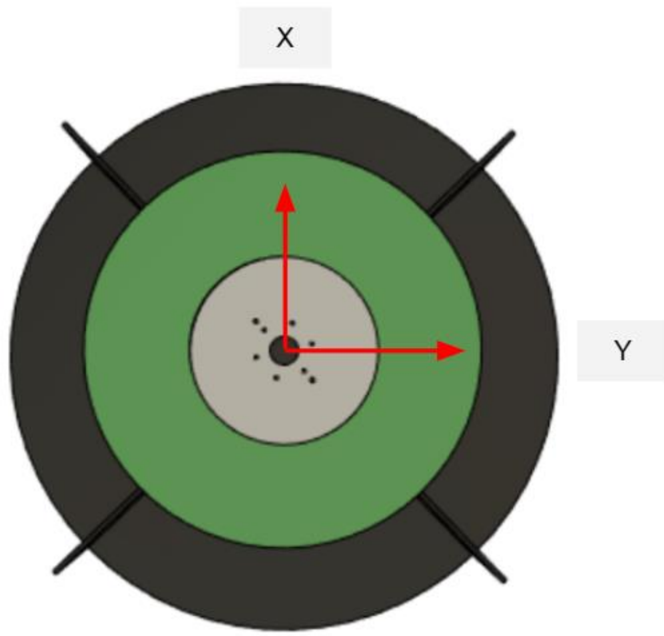


Figure 5.1.4 Floating Test Article Coordinate Axis (Top View)

Weight Distribution:

The weight distribution for the floating test article was as follows:

Component	Weight (kg)	Center of Gravity (from keel)
Compression Chamber	1.89	0.528 m
Floatation	1.1	0.622 m
Heave Plate + Ballast	21.708	-0.0212 m
Wave Guides	0.202	0.317 m
Sensors	1.00	0.805 m
TOTAL	25.9	0.0807 m
Radius of Gyration (X and Y)	0.298 m	

Table 5.1.1 Weight Distribution in floating test article

Table 5.1.1 depicts the physical properties of the floating test article. Radius of gyration in X and Y is symmetric due to the axisymmetric design of the floating test article. Radius of gyration in Z can be neglected, as the model does not have a yaw response in the wave field. Radius of gyration was measured via the compound pendulum methodology, where the model was suspended along each axis as a pendulum and the period of oscillation was measured using a distance measurement tool. See the Appendix D for details on how the radius of gyration was measured.

7 Work Plan

7.1 Experimental Setup, Data Acquisition System, and Instrumentation

We tested 2 test articles simultaneously in the wave basin at water depth 1.36 meter. One test article was floating, with light lateral springs to resist the mean drifting force. The other test article was a fixed acrylic tube of the same diameter as the floating test article and was affixed to the bottom of the basin via a frame built by the OSU team.

In both the floating and fixed test articles, a series of orifice plates were tested. The central cylinder was sealed at the top with an acrylic orifice plate. We tested 5 different acrylic plates, with different opening ratios. The opening ratios, represented as α, were as follows: [0.005 0.007 0.01 0.015 0.02]. The opening ratio is the opening area of the orifice over the area of the inner diameter of the OWC chamber, represented as the percentage of area, as seen below:

$$\alpha = \frac{A_{orifice}}{A_{OWC}}$$

<u>Fixed Test Article</u>

The purpose of having a fixed test article is to enable us to observe and model the pressure drop across the orifice plate. This allows us to accomplish two goals: verify the orifice quadratic loss coefficient and to function as a validation case for future numerical modeling. The quadratic loss coefficient defines the relationship between pressure and velocity, such that power capture can be estimated through a single measurement. The fixed model data will function as a computationally less complex validation case, where we can validate our PTO parameterization method. This allows us to quickly assess the overall PTO damping occurring in the floating test article without directly modeling the orifice plate, which can take up to two weeks to directly model. By including a fixed test article, modeling of the floating article can be parameterized and brought down to roughly 2 days.

The fixed test article consists of a 22.5 cm acrylic tube, attached to a ntended frame that was affixed to the bottom of the wave basin. The acrylic tube was equipped with 2 differential pressure sensors, mounted in two different locations on the model radially to allow for the observation of possible compressibility issues. For a test article of this size, it has been established that compressibility should not create a significant impact on spatial pressure variation. Each Pressure tap was placed on either side of the orifice.

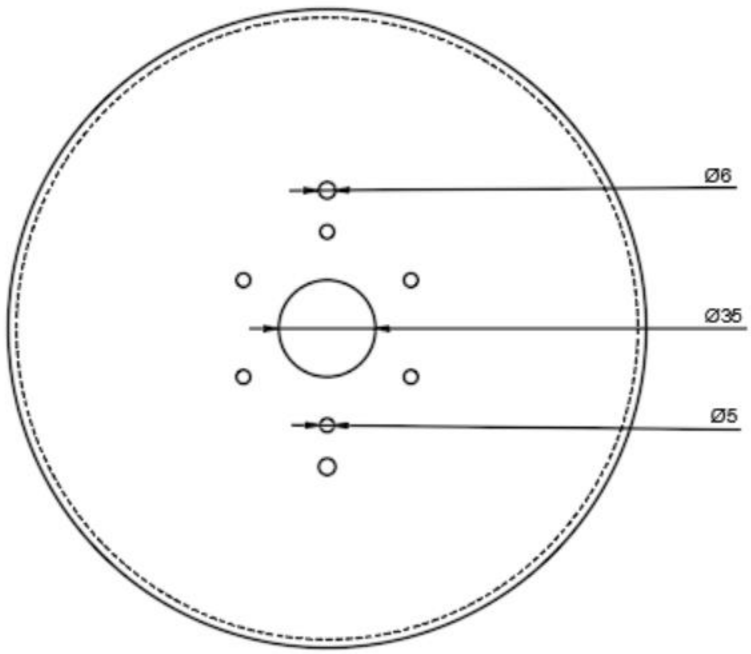


Figure 6.1.2. Top View of Test Articles

Floating Test Article

The prototype has a central hollow cylinder with a diameter of 22.5 cm and 6 mm thickness of SLA Resin. The central cylinder is affixed 16 cm above the 84 cm diameter plate of thickness 1.3 cm of PVC. Along the exterior of the central cylinder are 4 waveguides, spaced radially every 90 degrees. Each waveguide is a 60 cm tall and 30 cm wide carbon fiber sandwich panel that is 6 mm thick. The hull is comprised of 3D printed sections, acrylic orifice plates, and lead weights attached via 0.5" hex bolts. The solid floatation ring collar is that is 6 inches thick and 20 inches outer diameter. The dry weight of the buoy is 25.9 kg, with 90% of the weight centered at the base plate.

Figure 6.1.3. Wave Basin Shore Side View. (Left) Floating Test Article. (Right) Fixed Test Article.

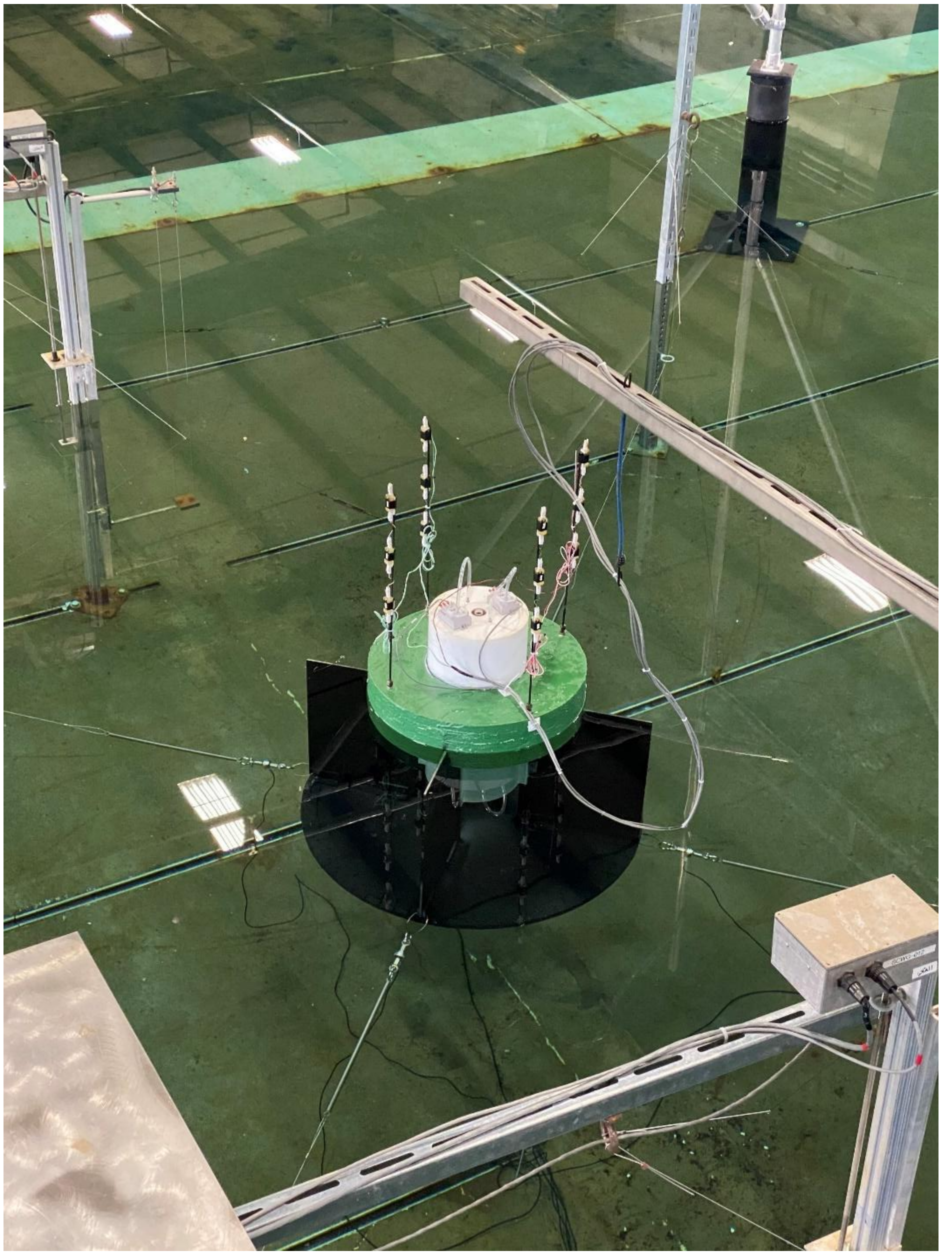


Figure 6.1.5. Isometric View of Floating Test Article

Figure 6.1.6. Drained Tank Set Up

The floating test article was tethered to be at equilibrium in the middle of the PhaseSpace Motion Capture system's observable area, with eight motion capture cameras. The PhaseSpace Motion Capture system meets the requirements to recreate the motion of the floating test article to submillimeter accuracy. The motion capture system has a selected sampling frequency of 100 Hz, which is more than sufficient to recreate the motion of the device.

Four resistive wave gauges surrounded the test article along one side, as it is an axisymmetric model. Each wave gauge was mounted to a structure affixed to channels spaced 4 ft on center. The fore and aft wave gauges were 6 ft from the center of the test article. To observe and quantify the coefficient of reflection an array of nine wave gauges were deployed in the area between the wavemaker and the floating test article. Nine wave gauges were used to conduct wave separation for the various wavelengths tested. The array was oriented in a rosette to enable wave separation in both unidirectional waves and oblique waves.

The floating test article was moored with four weak linear springs (0.015 lb/mm spring rate) to resist the mean drifting force exerted on the floating model. The spring moorings were affixed at the base of each of the wave guides, centered 3 cm above the keel. The four springs were attached to steel cabling which was tether to ntended members fixed to the bottom of the wave flume.

Signal cabling was suspended from above the water surface, down to the test articles. The cables were supported by a ntended beam protruding from the bridge above the wave basin. The signal cables used were 2 Belden 8723 cables for the differential pressure sensors and 1 Belden 5502G1 cable to provide power to the PhaseSpace Motion Capture lights. See Appendix A for a detailed list of sensors used, sensor type, and accuracy. The HWRL data acquisition system (DAQ) will be used for testing. See Appendix B for detailed information on the data acquisition system, data rate, and rate of measurement.

D.4 Test and Analysis Matrix and Schedule

7.2 Test and Analysis Matrix and Schedule

α = 0.5%						
	Wave Height (cm)					
T(s)	5	6.5	8	9.5	11	14
1			1			
1.25			1			
1.5			1			
1.75			1			
2	1	1	3	1	1	1
2.25			1			
2.5			1			
3			1			
4			1			
5			1			
6	1		1			

α = 0.7%						
	Wave Height (cm)					
T(s)	5	6.5	8	9.5	11	14
1			1			1
1.25			1			
1.5			1			
1.75			1			
2	1	1	3	1	1	1
2.25			1			
2.5			1			
3			1			
4			1			
5			1			
6	1		1			
α = 1.0%						
	Wave Height (cm)					
T(s)	5	6.5	8	9.5	11	14
1			1			
1.25			1			
1.5			1			
1.75			1			
2	1	1	3	1	1	1
2.25			1			
2.5			1			
3			1			
4			1			
5			1			
6	1		1			
α = 1.5%						
	Wave Height (cm)					

T(s)	5	6.5	8	9.5	11	14
1			1			
1.25			1			
1.5			1			
1.75			5			
2	1	1	1	1	1	1
2.25			1			
2.5			1			
3			1			
4			1			
5			1			
6	1		1			
α = 2.0%						
	Wave Height (cm)					
T(s)	5	6.5	8	9.5	11	14
1			1			
1.25			1			
1.5			1			
1.75			1			
2	1	1	5	1	1	1
2.25			1			
2.5			1			
3			1			
4			1			

Table 6.3.1. Test matrix of wave conditions per Opening Ratio (α). Values correspond to the number of test runs per wave height and period for the zero-degree incident wave.

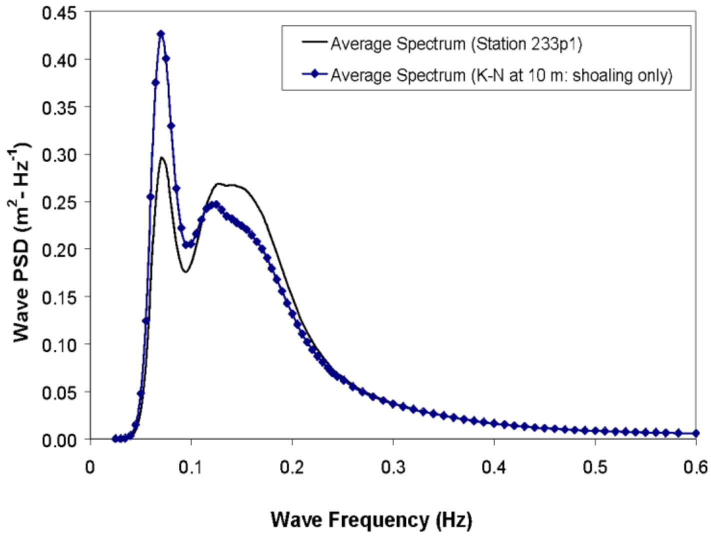


Figure 6.3.2 Kilo Nalu Spectrum

Table 6.3.1 depicts the number of test runs for each regular wave condition tested per orifice. The incident angle for each of these tests was zero degrees. The rows indicate the regular wave period tested for each section, while the columns represent the wave height in cm.

Repeatability tests were conducted for each orifice in 2 second waves with 8 cm wave height, except for the α = 1.5%. Repeatability tests for the α = 1.5% were conducted in 1.75 second waves with 8 cm wave height. The repeatability tests allow us to determine the uncertainty of each orifice.

Two additional test runs were conducted per orifice with different incident wave angles of 15 and 25 degrees. These tests are not denoted in the test matrix. The wave conditions for the directional waves were 2 second period and 8 cm wave height.

Figure 6.3.2 depicts the Kilo Nalu spectrum tested. Each orifice was tested in the KNO spectrum at 0 degree, 15 degree, and 25 degree incident waves, with the exception of 1.5% opening and 2% opening. The 1.5% opening ratio was tested in the KNO spectrum for the zero degree incident angle. We did not test the 2% opening in the KNO spectrum. In total, we conducted 115 tests in the wave basin.

Prior to basin testing, system identification occurred to determine the radius of gyration, center of gravity, center of buoyancy, dry weight, resonant period, and added mass. The system identification was conducted in two stages: dry and wet. The dry system identification involved directly weighing the test article, conducting hanging center of gravity tests, and compound pendulum tests. The center of gravity was determined by hanging the model from multiple points and sighting the intersection of the vertical axis for each orientation. The radius of gyration was determined by conducting compound pendulum tests, where the period of oscillation was measured to calculate the radius of gyration. Wet system identification involved floating decay tests. Two types of decay tests occurred: Heave and Pitch. In the heave decay test, the model was lifted vertically 6 cm from the still water line via a steel cable. A sacrificial steel cable was cut and the resulting decayed motion was captured with the PhaseSpace system. In the pitch decay test, the model was lifted 6 cm from the top corner of a wave guide. Again a sacrificial steel cable was cut and the resulting motion was capture with the PhaseSpace system. Each test was conducted multiple times to determine the uncertainty of the measurement.

Wave Testing occurred over the course of 8 days. See the schedule below. Due to delays in shipping with COVID, assembly of the model was extended as parts were delayed in transit.

	Start Date	End Date
Assembly		
Assemble Floating Test Article	3/1/21	3/9/21
Assemble Fixed Test Article	3/15/21	3/17/21
Basin Set Up	3/15/21	3/17/21
Dry Testing		
Weigh Model	3/10/21	3/10/21
Center of Gravity Test	3/11/21	3/11/21
Compound Pendulum	3/11/21	3/12/21
Wet Testing		
Overnight Float	3/10/21	3/11/21
Heave Decay	3/18/21	3/18/21
Pitch Decay	3/18/21	3/18/21
0.7 OR Regular Waves	3/19/21	3/22/21
0.7 OR KNO Waves	3/22/21	3/22/21
0.5 OR Regular Waves	3/23/21	3/24/21
0.5 OR KNO Waves	3/23/21	3/24/21
1.0 OR Regular Waves	3/24/21	3/25/21
1.0 OR KNO Waves	3/25/21	3/25/21
1.5 OR Regular Waves	3/26/21	3/29/21
1.5 OR KNO Waves	3/29/21	3/29/21
2.0 OR Regular Waves	3/29/21	3/30/21
Repeatability Tests	3/30/21	3/30/21
Wet Testing		
Decommissioning	3/15/21	3/17/21

7.3 Safety

The applicant and OSU facility staff followed all relevant safety procedures and protocols outlined in Appendix C, as defined by the OH Hinsdale Safety Plan 2020. This document describes the comprehensive and proactive safety plan in use at the O.H. Hinsdale Wave Research Laboratory (HWRL) at Oregon State University (OSU). The plan is built upon the principles of involvement, identification, rules, and training. The plan applies to anyone and everyone conducting work at the facility, including but not limited to faculty, instructors, post-docs, researchers, staff, and students, whether University employees or visitors.

The facility adheres to the University safety policy as described below. The policy requires everyone to follow safe working practices and procedures. It applies to all Oregon State University employees, students, and any other individuals conducting business on OSU property. The policy states the following:

> *Effective management of health and safety at Oregon State University is fundamental to delivering excellence in research and teaching. Health and safety should be a concern to everyone since our mutual efforts and vigilance are necessary to eliminate incidents that result in personal injury and loss of property. The majority of injuries and property loss are costly and preventable. Through the dedicated efforts of everyone involved, we can maintain a safe and healthy environment while accomplishing the mission of the University. 2 Oregon State*

University will make reasonable efforts to provide a safe and healthful working environment for all employees, students and others who may utilize the University's facilities and grounds. All University departments/units will develop and implement safety policies and procedures that promote an injury free environment. Anyone engaged in University related activities must exercise personal responsibility and care to prevent injury and illness to themselves and others who may be affected by their acts or omissions. No person shall intentionally interfere with or misuse anything provided by the University in the interests of health and safety. Individuals are required to have the proper training for the safe operation and use of university facilities, equipment and supplies as well as animal handling. Faculty and staff administrators will be held accountable for fulfilling their safety responsibilities. Flagrant disregard of the University safety policies and procedures may result in disciplinary action. Priority should be given to safe working conditions and job safety practices in the planning, budgeting, direction and implementation of University activities. The OSU Health and Safety Policy should be read in conjunction with SAF 103: OSU Safety Program and other safety policies contained in the OSU Safety (SAF) Policy and Procedure Manual.

All visitors, researchers and clients performing an activity within HWRL underwent a specific and documented Safety Training, reviewing general safety procedures, rules and hazards. Temporary visitors used yellow safety vests for best identification and awareness, and wore use safety shoes at all times while working on the laboratory floor.

Safety Briefings were performed at the beginning of the project and every time a safety hazard or activity was identified. HWRL staff and visitors were required to attend each and every briefing.

7.4 Contingency Plans

In the event of complications with testing, a set of contingency plans had been developed. The possible complicating scenarios were identified:

1. Failure of prototype
2. Failure of sensors
3. COVID-19 complications

Failure of Prototype

Although it was unlikely to occur, complications in handling the prototype could have resulted in damage to or destruction of the floating test article. To prevent a delay in testing, a second floating test article was constructed as a backup.

Failure of Sensors

Although it was unlikely to occur, complications during handling or installing the sensors could have resulted in damage to a sensor. For this reason, with the exception of the load cells, we did not utilize the full amount of sensors in the facilities possession to enable backup sensors. Unfortunately, backup load cells could not be acquired. Some load cells failed during testing and were unable to be replaced. As the load cells were not critical to the functionality of the experiment, testing continued without issue.

COVID-19 Complications

To prevent complications that could have occurred due to contracting COVID-19 while traveling to Oregon from Hawaii, the applicant traveled early to Oregon and quarantined. Prior to arriving to the test facility, a negative COVID-19 test was confirmed. All CDC COVID-19 guidelines were adhered to the best of our ability to prevent such complications. The applicant received COVID-19 vaccination doses prior to and during testing.

HWRL enforced site-specific protocols to reduce spreading. These included continuous use of face coverings, sanitization, and social distancing. Specific entry and exit doors were identified and circulation routes within the facility were established to minimize common touching surfaces and crossing paths. Hand sanitizer and cleaning solutions were available throughout the premises.

7.5 Data Management, Processing, and Analysis

7.5.1 Data Management

Raw Data: Surface elevation at wave gauge locations, differential pressures from sensors, 6 degree of freedom motion response of test article, load cell measurements.

Processed Data: RAOs, Pressure Signal RAO, Capture Efficiency, calculated mooring loads.
Data was stored locally at OSU and on hard drive backup. Compressed and zipped onto UH Google Drive. ReadMe file for the data describing the data was included with all data files. See Appendix B for naming conventions. Processing of data was conducted at OSU in between test runs. We verified our MATLAB code upon arrival at OSU.

OSU has a server that housed the data on their end. They also had a hard drive backup. At the end of the project, they locked the directory and archived it (read only). That data was copied onto a UH hard drive. Raw data file and raw data in engineering units were transferred to MHK DR and then processed on site the following day.

Raw data path:

1) Recorded locally on each individual DAQ hardware component (PXI system). All filenames include a timestamp off a PTP (IEEE-1588) synchronized clock, so there's no possibility of accidental overwrites. After each trial is completed, every data file is pushed on to step (2).

2) Recorded locally on the DAQprocessor (Mac mini). This is continuously backed up to an external drive (macOS Time Machine). It's not running any services other than accepting inbound connections from the PXI systems to dump data. When each file arrives, it is evaluated and then placed on depot (step (3)) in the correct project, experiment, and trial. Data is put in the DAQprocessor trash after each project is completed, and then erased a month later. The backups persist for years.

3) Stored on the depot file server. This is also where the path for everything BUT raw data (intermediate data, code, photos, videos) forks in. Depot has an hourly snapshot backup system, so if something is deleted by accident it can be recovered immediately. More here:

https://it.engineering.oregonstate.edu/restore-using-snapshots

4) Archived on attic. This is not backed up by snapshots. Instead it's backed up by multiple hard drives, spread in different locations around the lab and around Corvallis at a radius on the scale of miles.

7.5.2 Data Processing

Our redundant sensors helped with quality control and quality assurance. Data was processed using MATLAB code at OSU in between tests to enable quality assurance in the event of signal errors. Repeatability tests were conducted to allow us to quantify the uncertainty in measurements. Calibration data was provided for each sensor to address uncertainties and quantify. Repeating a standard calibration test in specific wave conditions enabled us to quantify additional uncertainties.

7.5.3 Data Analysis

Plots to be presented include: Normalized RAO, Normalized Chamber Pressure, and Normalized Capture Efficiency.

RAO Curves

The RAO curves visually present the response of the platform per meter wave amplitude relative to the normalized wavelength. The normalized wavelength is represented by the actual wavelength (L) normalized by the diameter of the chamber (D), which functions as a proxy for wave period Translational RAOs are represented by (m/m). The rotational RAOs are represented by (degree/m). RAO is calculated by the motion response divided by the wave amplitude. The motion response is characterized by 10 sample waves, where the 10 sample waves are chosen for each wave period when the wave field has stabilized, and the influence of reflected waves is not present in the data. The MATLAB *lowpass* function and the 2^{nd} Order nonlinear curve fitting was applied to the motion response. The fitted data is compared to the unfiltered data to confirm that the phase, amplitude, and frequency of the data is unchanged. The amplitude of motion response is found using the *findpeaks* function in MATLAB and is averaged across all peaks.

Chamber Pressure

The normalized chamber pressure enables researchers to recreate the experiment numerically and conduct further analysis. The Chamber pressure visually represents the peak pressure drop across the orifice for each normalized wavelength. The normalized wavelength is represented by the actual wavelength (L) normalized by the diameter of the chamber (D), which functions as a proxy for wave period. The chamber pressure is filtered using the MATLAB *lowpass* function, and a 2^{nd} Order nonlinear curve fitting is applied. The fitted data is compared to the unfiltered data to confirm that the phase, amplitude, and frequency of the data is unchanged. The peak pressure drop is found using the *findpeaks* function in MATLAB and is averaged across all peaks. Pressure is presented as a coefficient of pressure, Cp.

$$Cp = \frac{\Delta \mathrm{p}}{\rho \mathrm{gH}}$$

Where Δp is the total range of pressure, ρ is the density of freshwater, g is gravitational acceleration, and H is the regular wave height.

Capture Efficiency

The capture efficiency curves identify the appropriate sizing of an eventual power take off, as well as creating a means of calculating the energy extraction potential. To obtain capture efficiency, the power extracted is calculated and compared to the incident wave power per meter wave crest and multiplied by the diameter of the OWC chamber. Power extracted is calculated using the time series data of pressure drop, as defined in Xu et. al 2019. The following equation was used to calculate extract power:

$$P_{owc} = \frac{A_o\sqrt{2}}{T\sqrt{C_f \rho_a}} \int_{t0}^{t0+T} |p(t)|^{\frac{3}{2}}\, dt$$

where A_o is the OWC chamber area, T is the wave period, C_f is the measured quadratic loss coefficient, ρ_a is the density of air, and $p(t)$ is the pressure drop across the orifice. To ensure compressibility is not an issue, the phase of the two pressure readings are compared. Using the quadratic loss coefficient calculated for each orifice, the pressure drop can be used to directly calculate extracted power for the fixed and floating test articles. The incident wave energy per unit wave crest is calculated by the following equations:

$$E_{incident} = \frac{\rho g H^2}{8},$$

where E is the incident wave energy per meter wave crest. ρ is the density of freshwater, g is the acceleration due to gravity, and H is the wave height. For each test run, the actual wave height measured is used to calculate the incident wave energy. To determine the actual wave height, the surface elevation is filtered using the MATLAB *lowpass* function, and a 2nd Order nonlinear curve fitting is applied. The fitted data is compared to the unfiltered data to confirm that the phase, amplitude, and frequency of the data is unchanged. Surface elevation from two wave gauges are used to verify the present wave frequencies. The Goda & Suzuki two-point wave separation method is applied and wave gauges are selected to comply with the required spacing. The peak surface elevation for the intended wave frequency is found using the *findpeaks* function in MATLAB and is averaged across all peaks.

$$C_g = \frac{L\left(1+\frac{2kh}{\sinh(2kh)}\right)}{2T},$$

where C_g is the group velocity, L is the wavelength, k is the wave number, T is the wave period, and h is the water depth.

$$P_{incident} = E_{incident} C_g D$$

where E is the incident wave energy and B is the diameter of the OWC chamber.

$$\epsilon = \frac{P_{owc}}{P_{incident}}$$

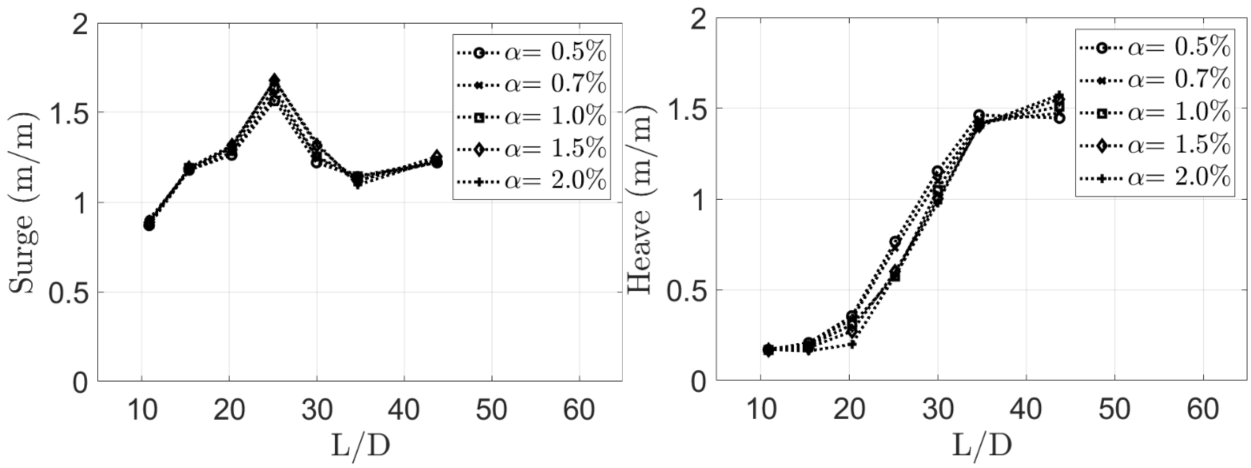
where ϵ is the capture efficiency.

Removed Data Sets

Data from 1 second, 5 second, and 6 second waves were removed due to the presence of strong partial standing waves. For 5 and 6 second waves, it was determined that the coefficient of reflection was too large and the wavelength too long to obtain a stable sample wave regime. In the case of 1 second waves, it was determined that cross basin resonance was present, such that capture efficiency could not be resolved. Additionally, the 1 second 14 cm wave conditions were removed, as overtopping wetted pressure sensors and compromised the data. Data from mooring tension is not included, as load cells failed during testing.

8 Project Outcomes

8.1 Results



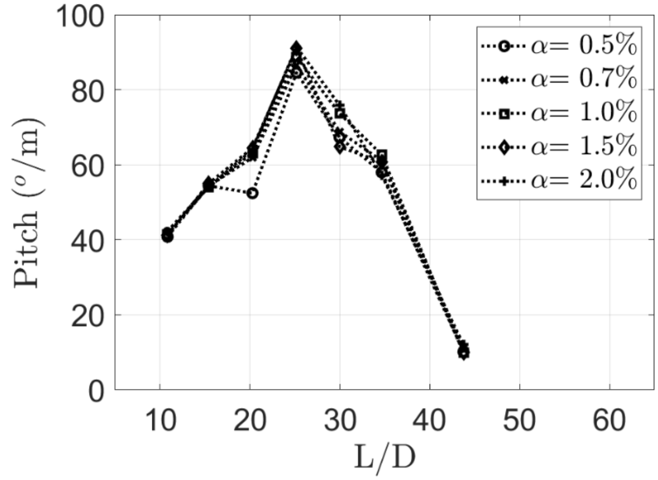


Figure 7.1.1 Response Amplitude Operators for (Top Left) Surge, (Top Right) Heave, and (Bottom) Pitch. D represents the diameter of the OWC chamber, while L is the wavelength.

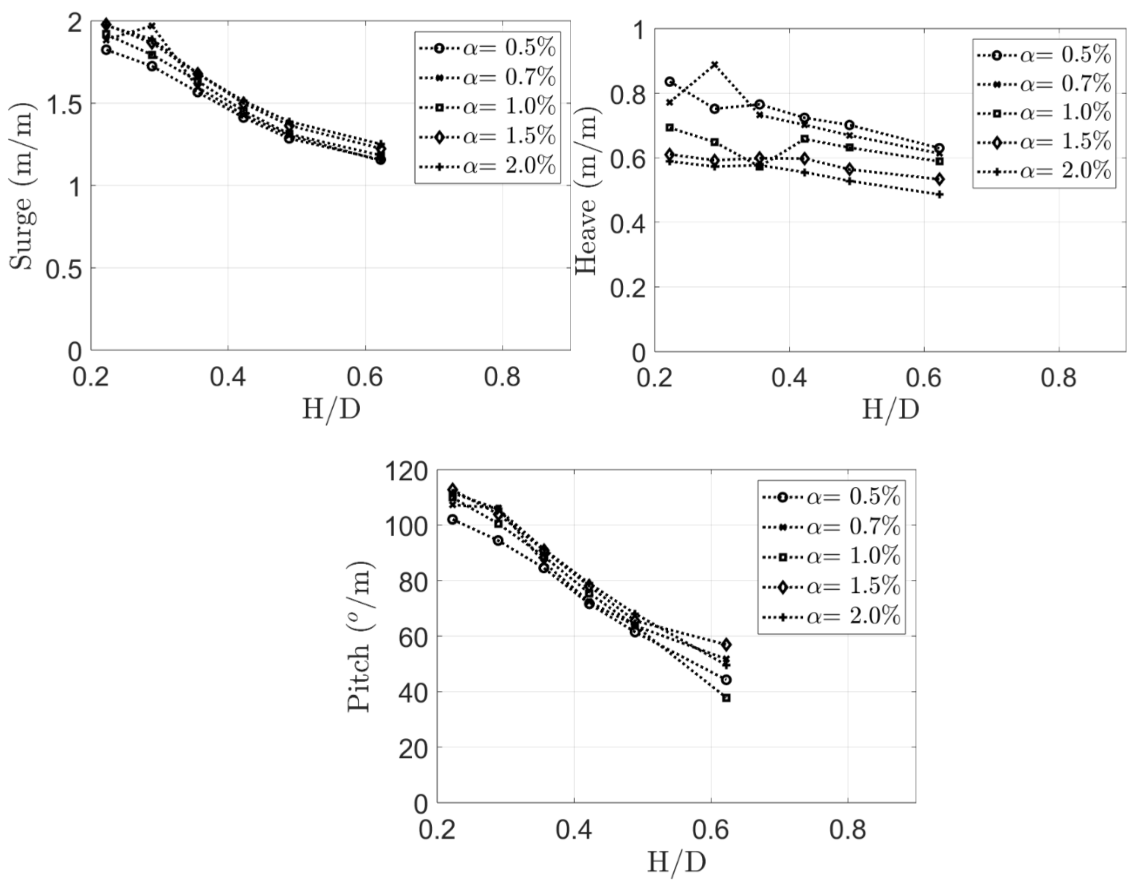


Figure 7.1.2 Amplitude dependent motion response for (Top Left) Surge, (Top Right) Heave, and (Bottom) Pitch. D represents the diameter of the OWC chamber, while L is the wavelength.

It was observed that for zero-degree incident waves, the floating test article demonstrates 2 DOF response in translation. We can conclude from the results that the test article has a negligible sway response. Note that L/D = 30 on the x-axis represents the damped resonant frequency of the floating test article in heave, as determined from the heave decay tests conducted. The heave RAO demonstrates that the floating test article performs as expected. Heave motion is minimal for smaller wave periods, while the floating test article adheres to water surface motion in longer period waves. Overall, PTO damping between the smallest and largest opening ratio orifices induces a 20% change in the heave RAO.

The surge RAO demonstrates that platform motion is not sensitive to a change in wave period, except for the resonant period of the structure. The change in PTO damping has a minimal impact on the surge RAO, except for the resonant period of the structure. Between the smallest and largest opening ratio orifices, the maximum induced change in the surge RAO is roughly 10%.

Pitch was found to be consistent across tests in amplitude. It was observed that the rotational response in roll is minimal and there does not appear to be a coupled RAO response. Given the axisymmetric geometry of the test article, it can be assumed that pitch and roll RAOs are symmetric for oblique waves. The range of PTO damping indicates a minimal impact on the rotational RAOs, with a maximum change in response of 5%.

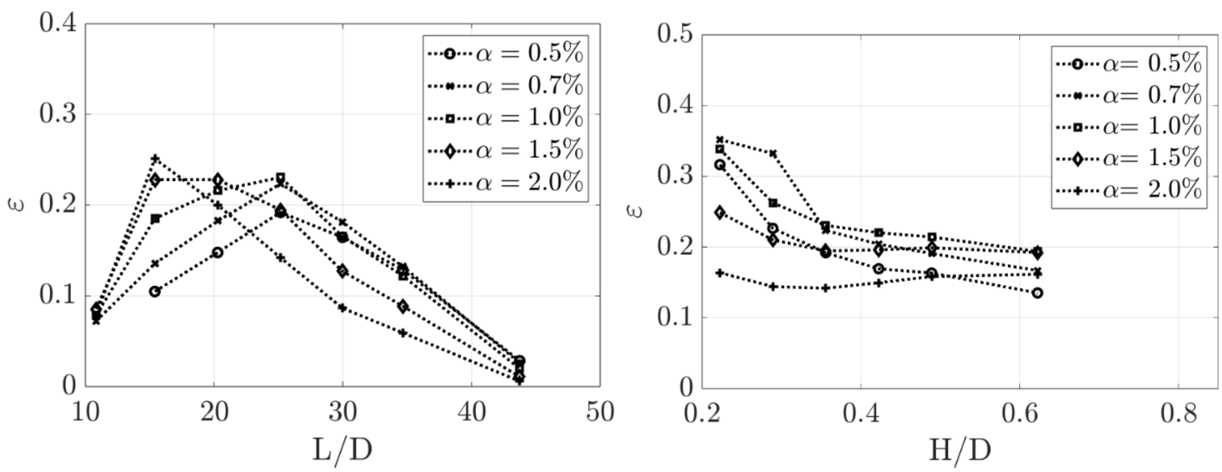


Figure 7.1.3 Normalized Floating Model Efficiency. (Left) Normalized relative to a change in wave height. (Right) Normalized relative to change in wavelength. Lines represent the percentage opening ratio.

The top plot in Figure 7.1.3 depicts the change of efficiency relative to the wave height at the resonant frequency. At smaller wave heights, the capture efficiency for larger damping orifices tends to increase, while the efficiency is unchanged the underdamped orifices. The bottom plot implies the possibility of two resonant modes of the floating test article: the damped resonant frequency of the structure, and the Helmholtz resonant frequency of the internal water surface. For larger damping orifices, the peak capture efficiency is centered on the known damped resonant frequency of the test article. As orifice damping decreases, the peak efficiency shifts to higher frequency waves. If we compare this to the peak efficiency frequency in the fixed model (Figure 7.1.4), we observe that the peaks coincide. We also observe that around the peak capture efficiency, the capture efficiency is not sensitive to a change in wave frequency.

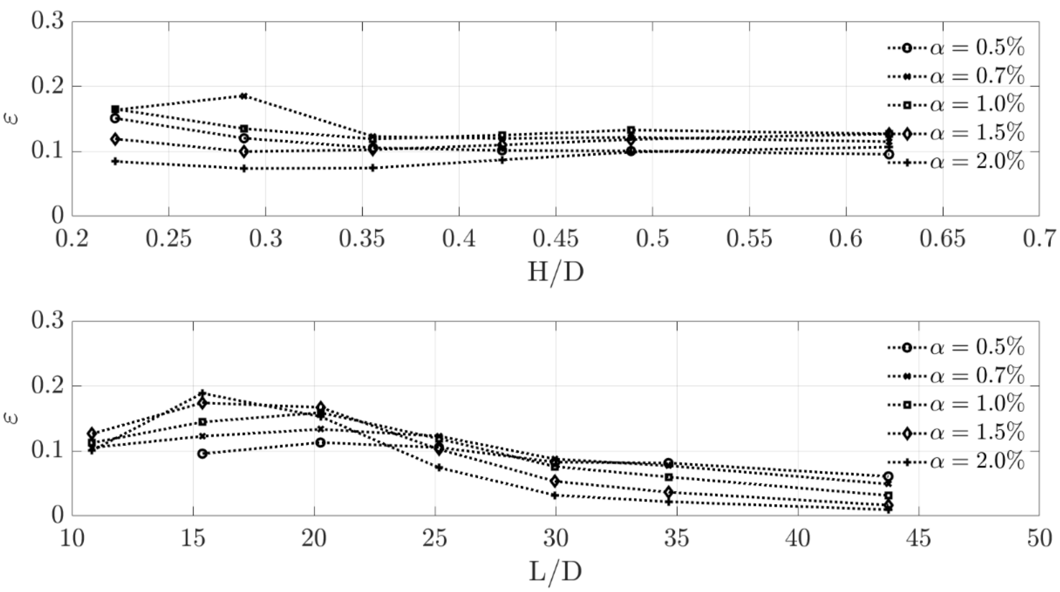


Figure 7.1.4 Normalized Fixed Model Capture Efficiency. (Top) Normalized relative to a change in wave height. (Bottom) Normalized relative to change in wavelength.

The top plot in Figure 7.1.4 depicts the change of efficiency relative to the wave height at the resonant frequency. The impact of wave height on efficiency is relatively minimal across all orifices. The bottom plot implies the possibility of a resonant mode of the fixed model centered around 0.064 on the x-axis. This coincides with the 1.5 second wave period. Further, we observe that for waves shorter than 2 seconds, the capture efficiency of the model is not sensitive to a change in wave frequency.

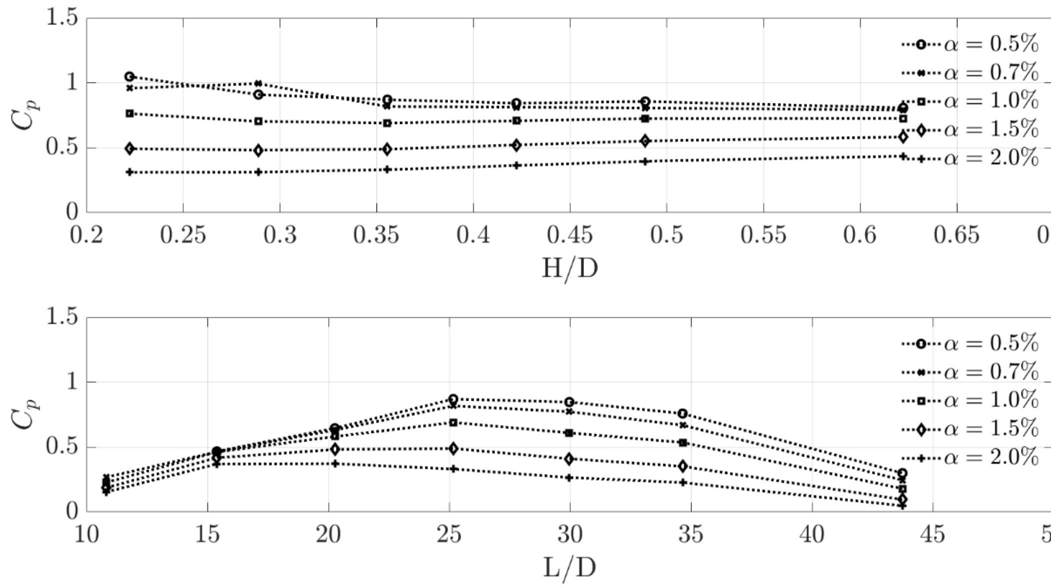


Figure 7.1.5 Normalized Floating Model Pressure Drop. (Top) Normalized relative to a change in wave height. (Bottom) Normalized relative to change in wavelength. Cp represents the differential pressure across the orifice, normalized by the hydrostatic pressure of the wave. For changes in amplitude, a wave period of 2 seconds is assumed. For changes in wavelength, a wave height of 8 cm is assumed.

The top plot in Figure 7.1.5 depicts between the pressure drop across the orifice plate and the wave height in the floating model. Additionally, the increase in pressure due to the orifice opening ratio is proportional. The bottom plot indicates the dependence of pressure on the wave frequency. Note that the relative peak pressure is observed at the resonant frequency of the floating test article for the smaller opening ratio orifice plates. There is an increase in steepness for smaller orifices around the resonant frequency. For larger opening ratio orifices, the overall pressure is decreased and is not sensitive the wave frequency.

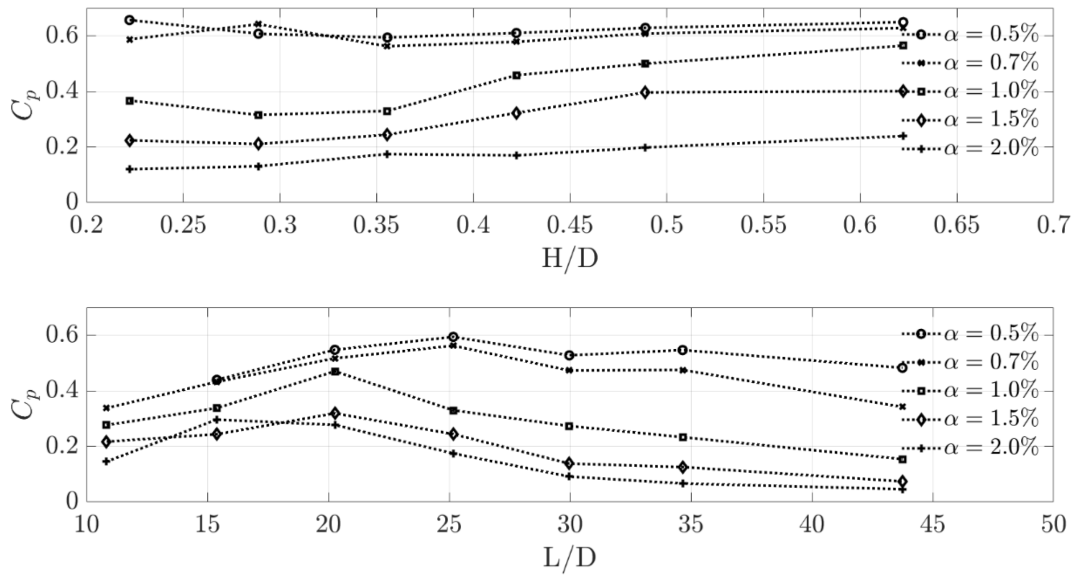


Figure 7.1.6 Normalized Fixed Model Pressure Drop. (Top) Normalized relative to a change in wave height. (Bottom) Normalized relative to change in wavelength. Cp represents the differential pressure across the orifice, normalized by the hydrostatic pressure of the wave. For changes in amplitude, a wave period of 2 seconds is assumed. For changes in wavelength, a wave height of 8 cm is assumed.

The top plot in Figure 7.1.6 depicts a quasi-linear trend between the pressure drop across the orifice plate and the wave height in the floating model. The bottom plot indicates a weak dependence of pressure on the wave frequency. As the opening ratio increases, the peak pressure drop decreases and the peak frequency increases. The shift in peak pressure frequency per orifice helps to explain the peak capture efficiency, since pressure is a cubic relationship with power extracted.

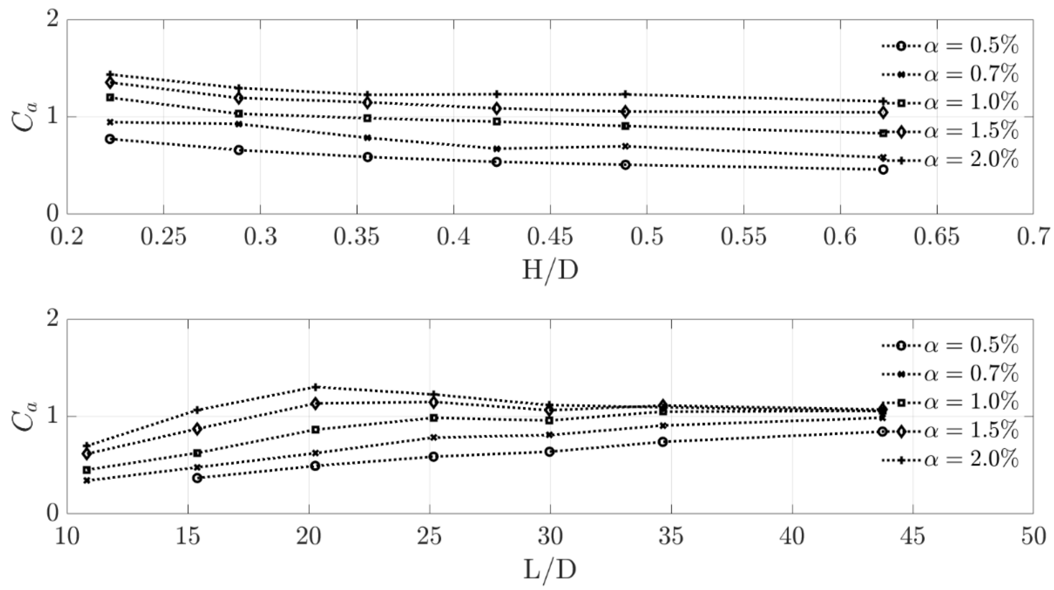


Figure 7.1.7 Normalized Fixed Model Surface Amplification. (Top) Normalized relative to a change in wave height. (Bottom) Normalized relative to change in wavelength. Ca represents the internal surface displacement range, normalized by the regular wave height. For changes in amplitude, a wave period of 2 seconds is assumed. For changes in wavelength, a wave height of 8 cm is assumed.

Although not originally included in the Test Plan, surface amplification data is presented in Figure 7.1.7 to highlight the relative internal water surface displacement inside the fixed OWC. This represents the ratio of total displacement range relative to the incoming wave height.

8.2 Lesson Learned and Test Plan Deviation

Ample planning prior to arrival led to a valid testing method, and helped to prevent critical delays from issues that arose. Given all the issues that will be listed below, the primary issue was a lack of guidance from previous developers and an understanding of the facilities capabilities. Ample time (2 weeks) was allocated prior to testing to address unforeseen issues and led to minimal complications that did not jeopardize our ability to complete all the desired tests. Lessons learned below are in regards to project planning, personal safety, efficiency in testing, and headache reducing tips. All test results required were obtained, but more efficient planning and guidance could have achieved additional test results.

1. **Project Planning**
    a. **Verify prior to arrival that the facility to has back up sensors for each sensor used.** Load Cells failed mid testing and were not replaced due to the facility not having ample replacements. Facility staff knew that load cells failed frequently but failed to notify us that this was the case and that back ups would be desirable. Given the timing and delays due to covid, replacement load cells would not have arrived in time.
    b. **Allow for longer lead times and have parts manufactured and ready to go upon arrival.** Certain parts did not arrive on time (specifically 3D prints and Pressure Tubing), which caused additional stress and delays that could have been used to get extra test runs completed. Ideally both test models should have been fully assembled prior to shipping to OSU. Both models were manufactured and evaluated at the facility instead. Had the manufacturing process been thoroughly planned, constructing the model could have failed, and compromised our ability to test at all. Even with a 4-month lead time on ordering parts, parts were not manufactured until I had arrived at OSU. I had to rely on volunteer labor to assist in manufacturing, which was a risk that turned out satisfactory.
    c. **Bring additional prototypes.** Although not all prototypes were assembled or used, duplicate prototype allowed for us to not have as much stress when things inevitably broke. Parts breaking was accounted for, and in total stock material to build four prototypes was shipped to OSU. Of the four prototypes, two were successfully constructed.
    d. **Require Coefficient of Reflection for differing wave conditions to validate which conditions we are capable of running.** We asked the facility for their basin's coefficients of reflection initially but did not press the issue, as they informed us that wave reflections would not be an issue. This was misguided information as certain wave conditions saw reflections that compromised the data. 1 second waves, as well as waves above 4 seconds did not yield

meaningful results for the purpose of our testing. In total 2 days' worth of testing data was discarded. We would not have planned to test these conditions had this been known. Thankfully we did not require those conditions to understand the performance of our model but could have led to serious issues had we needed to test in those conditions.

   e. **Additional Undergraduate / Graduate Student and Machinist involvement is necessary early on.** I had to rely on volunteers at OSU to help fabricate and assemble parts. This led to issues of parts breaking at the facility due to the fact that the volunteers were not professional fabricators. Since volunteers were not involved early on, they did not fully understand the objectives of testing. This led to time needing to be used explaining details midway through, which caused confusion and frustration on our part. Having a well written testing procedure helped to keep us on track.

2. **Testing Procedure**
   a. **Check the variance of each test configuration during the original installation.** We conducted repeatability tests at the end of testing rather than at the start. Had we inverted our testing schedule, we would have potentially saved us time, a number of wave basin entries, and the ability to test an additional 3 wave conditions. On the last day, replacing orifice plates to check variance of each test run involved me getting in and out of the wave basin a number of times, which was time consuming and cold. Had this been conducted at the start, the number of repeatability tests needed could have been established at the start, and allowed us to run fewer repeated tests.
   b. **Avoid changing the testing plan mid testing.** Changes made mid-testing led to decisions that were not well thought out and wasted time. No tests were compromised but some of the "tests of opportunity" that we conducted were not fruitful. Additional "tests of opportunity" should be planned and decided prior to arrival at the test facility if testing moves forward ahead of schedule.

3. **Safety Protocols**
   a. **Bring your own waders / wetsuit.** The test facility had waders and wetsuits, but was limited in size. The provided waders did not fit, leaked, and were not tall enough for the design water line. It was extremely cold (30 – 40 F) and led to team members having to brunt the cold water without proper insulation. The test facility provided a hot shower on site and ample warm beverages post wave basin entry, but in the event that these amenities were not available, team members could have experienced severe hypothermia. No incident occurred during testing where we felt our safety was at risk, but for those of us from Hawaii, the temperature was definitely a shock.

Test Plan Deviations

A number of deviations from the original test plan occurred due to analysis that was conducted between the time we submitted our original test plan and actual testing. The diameter of the model solid floatation increased on the assumption that the increased waterplane area would result in an improved power performance. The increase in buoyancy required the model weight to increase to maintain the same still waterline.

The fixed model geometry changed to match the geometry of the floating test model. The original fixed model was to be a cylinder and was amended to include a heave plate and wave guides. This was due to the realization that a fixed replica of the floating model could yield the same underlying goal of characterizing the orifice relationship, while enabling an improved validation case for OpenFOAM numerical modeling.

The testing matrix was changed to center our higher resolution frequency testing around the actual peak power performance. The original peak period was selected based on Froude scaling, though scale effects shifted the peak power performance to a shorter period.

The number of test conditions conducted at oblique angles was reduced due to the realization that the same results could be captured through testing irregular waves at the same angle. This allowed us to save on time while achieving the same desired results.

9 Conclusions and Recommendations

From model testing of both the fixed and floating test articles, we can conclude that a fundamental understanding of PTO sizing and baseline motion response was achieved. The above results depict a clear picture of the influence of PTO damping on the power performance and motion response of the model.

An estimated peak PTO damping was determined for each model. In the fixed model, we observe the peak capture efficiency is centered on the 1.5 second wave. From the previous literature that investigated fixed cylindrical OWCs with V-shaped wave channels, we know that the geometry can induce Helmholtz resonance inside the OWC chamber. This was confirmed in our model testing, as a clear peak pressure and capture efficiency can be observed around the expected Helmholtz frequency. We also observe that the capture efficiency and pressure drop are not sensitive to the wave frequency for waves shorter than 2 seconds.

When we compare the performance of the fixed model to that of the floating model, we can arrive at a few conclusions on the fundamental physics of the design. Our analysis of the fixed model provides evidence that the efficiency of the floating model is not solely controlled by motion response, but that heave is the dominant mode of energy extraction. We observed that for larger orifices, the peak capture efficiency coincides at the same frequency for the fixed and floating models. If we consider the heave response of the floating model at that frequency, we can conclude that the floating model functions like that of a fixed platform. This implies that the possibility of Helmholtz resonance within the water column of the floating model, which can impact the capture efficiency.

In the floating model, the peak orifice size lies between the 0.7% opening ratio and the 1% opening ratio. For this range of opening ratios, the results imply that the efficiency is not very sensitive to the wave period within +/- 0.5 seconds of the peak efficiency. This is beneficial to the design, as the model is designed as an ocean observing platform that will experience a range of irregular waves where the peak period is not perfectly aligned with the peak efficiency of the model. The peak efficiency for the floating model is centered on the damped resonant frequency. From this we can conclude that motion response can be used to control the capture efficiency of the model. We conclude that the power performance is controlled by two resonant modes: the resonant mode of the structure and the resonant mode of the internal water surface.

With this fundamental understanding of the model's power capture method, we can look to the motion response to conclude some control methods. The motion response of the model is clearly characterized with the RAOs for the range of periods tested. Understanding that the model has negligible sway response to incident zero-degree waves, we can conclude that the translational controls are limited to surge and heave. This behaves as expected, as the device is an axisymmetric about the z-axis. The heave response is clearly defined by wave frequency. Platform motion in heave follows the water surface for waves above the resonant wave period and behaves as a fixed structure for waves below the resonant period. This allows the platform to extract power from smaller period waves and perform similar to a fixed structure. At the resonant frequency, we clearly observe that the PTO damping has a mild impact on heave motion. Conversely, the surge motion response is not sensitive to the wave frequency, except for the resonant frequency of the structure. At the resonant frequency, the increase of surge response implies that surge motion has an impact on capture efficiency.

With these fundamentals understood, we can make a few recommendations for future design changes. When addressing future design changes, it is important to consider the intended application for this WEC. As it is designed to be an ocean observing platform, deployment capability is a design constraint. The current design is too heavy for practical deployment. It is recommended that an optimization study be conducted to reduce the dry mass of the model. The implication of two resonant modes allows for the possibility that further design optimization needs to consider the resonant frequency of the model, which is controlled by the total mass of the structure. It is recommended to address an increase in added mass to compensate for a reduction in dry mass.

Outside of the assumption of a free floating WEC, it is important to consider alternate deployment locations of Halona, which could include moored applications. Understanding that heave and surge control the capture efficiency of the model, the future mooring design can potentially impact the peak capture frequency. The inclusion of a mooring line can create an additional restoring force, which can shift the damped resonant frequency of the model, and thus change the power performance of the WEC. Additionally, certain mooring designs, such as catenary moorings can introduce a lateral restoring force on the model and damp the surge motion response of the platform. It is recommended to conduct a mooring design study to understand how the inclusion of mooring can impact the cost and performance of the WEC.

Results are published in *Energies* and have been submitted to *Nature: Scientific Reports.* Irregular wave tests were processed and included in the PhD dissertation of Nicholas Ulm. The publications can be found below:

Ulm, Nicholas, Zhenhua Huang, and Patrick Cross. 2023. "Experimental Study of a Fixed OWC-Type Wave Energy Converter with a Heave Plate and V-Shaped Channels for Intermediate-Water-Depth Applications." *Energies* 16 (16): 5988. https://doi.org/10.3390/en16165988.

Ulm, Nicholas. 2024. "Designing Wave-Powered Ocean Observing: Findings of an Oscillating Water Column Type Wave Energy Converter with a submerged heave plate and V-shaped Channels in Irregular Waves." Ph.D., United States – Hawaii: University of Hawaii at Manoa.

10 REFERENCES

Xu, C., Huang, Z., "Three-Dimensional CFD simulation of a circular OWC with a nonlinear power-takeoff: Model validation and discussion on resonant sloshing inside the pneumatic chamber." *Ocean Engineering*, vol 176, 2019

11 ACKNOWLEDGEMENTS

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Jonah Gadasi – Oregon State University

Courtney Beringer – Oregon State University

Daniel Hinshaw – University of Hawaii

12 APPENDIX

Appendix A.

Sensor	Measurement Type	Calibration Date	Range	Accuracy	Data Rate	Quantity	Engineering Unit
Acoustic Wave Gauge	Analog	Daily	2 meter	1 mm	100 Hz	13*	Meter
Resistive Self Calibrating Wave Gauge	Analog	Daily	1 meter	1 mm	100 Hz	13*	Meter
Setra Very Low Differential Pressure Sensor	Analog	Aug. 2016	+/- 2488 Pa	0.25% FS (Standard)	100 Hz	4	Pascal

PhaseSpace Motion Capture System	Digital	Each Test Series	--	0.1 mm	100 Hz	8	Meter
Load Cells	Analog	Aug. 2019	2200 N	0.15 %FS	100 Hz	4	Newton

Table A.1. Sensor Information. *Total Wave Gauges between acoustic and resistive, not total for each.

GENERAL SPECIFICATIONS

Performance Data

	Standard	Optional	
Accuracy RSS[1] (at constant temp)	±1.0% FS	±0.4% FS	±0.25% FS
Non-Linearity, BFSL	±0.98% FS	±0.38% FS	±0.22% FS
Hysteresis	0.10% FS	0.10% FS	0.10% FS
Non-Repeatability	0.05% FS	0.05% FS	0.05% FS
Thermal Effects[2]			
Compensated Range °F (°C)	0 to +150 (-18 to +65)		
Zero Shift %FS/100°F(50°C)	±0.033 (±0.06)		
Span Shift %FS/100°F(50°C)	±0.033 (±0.06)		
Max. Line Pressure	10 PSI		
Overpressure	Up to 10 PSI (range dependent)		
Long Term Stability	0.5% FS/YR		
Warm-Up Shift	±0.1% FS Total		

Pressure Media

Typically air or similar non-conducting gases.

Environmental Data

Temperature	
Operating °F (°C)[3]	0 to +150 (-18 to +65)
Storage °F (°C)	-40 to +185 (-40 to +85)

[1] RSS of Non-Linearity, Non-Repeatability and Hysteresis
[2] Units calibrated at nominal 70°F. Maximum thermal error computed from this datum.
[3] Operating temperature of the electronics only. Pressure media temperatures may be considerably higher or lower.
[4] Unit is factory calibrated at 0g effect of vertical position.
[5] Calibrated into 50K ohm load. Operable into 5000 ohms or greater.
[6] Zero & Span (FS) output factory set to within ±50mV (±25 mV for optional accuracies).
[7] Calibrated at factory with a 24 VDC loop supply voltage and a 250 ohm load.
[8] Zero & Span (FS) output factory set to within ±0.16 mA (±0.08 mA for optional accuracies.).
NOTE: Setra quality standards are based on ANSI-Z540-1. The calibration of this product is NIST traceable.

Physical Description

Pressure Fittings	1/4" Fitting
Case	Fire Retardent Glass Filled Polyester (UL 94-V Approved)
Weight	3 oz
Elec. Connection	Screw Terminal Strip
Position Effect[4]	
Range	Zero Offset (%FS/G)
To 0.5"W.C.	0.60
To 1.0"W.C.	0.50
To 2.5"W.C.	0.22
To 5.0"W.C.	0.14

Electrical Data (Voltage)

Circuit	3-Wire (Com, Out, Exc)
Excitation/Output[5]	9 to 30 VDC / 0 to 5 VDC[6] 9 to 30 VAC / 0 to 5 VDC 12 to 30 VAC / 0 to 10 VDC[6]
Output Impedance	<100 ohms
Bidirectional output at zero pressure	2.5 VDC (±50 mV)

Electrical Data (Current)

Circuit	2-Wire
Output[7]	4 to 20 mA[3]
External Load	0 to 800 ohms
Min. Loop Supply Voltage (VDC)	9 + 0.02 x (resistance of receiver plus line)
Max. Loop Supply Voltage (VDC)	30 + 0.004 x (resistance of receiver plus line)
Bidirectional output at zero pressure	12 mA

U.S. Patent Nos. 5442962, 6019002, 6014800 and other Patents Pending.
Specifications subject to change without notice

Figure A.1 Setra Differential Pressure Sensor Specifications Sheet.

DIMENSIONS

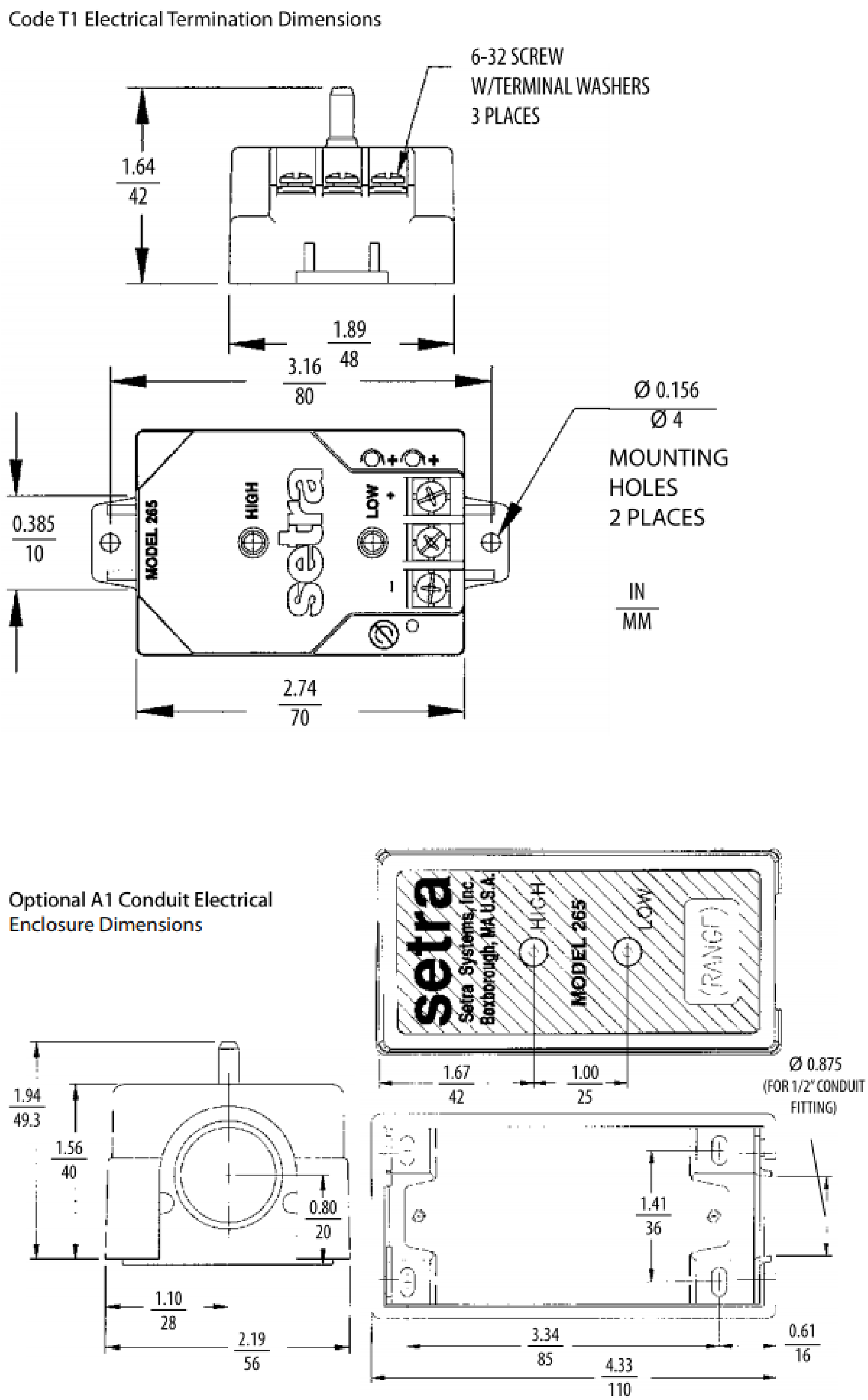

Figure A.2. Setra Very Low Differential Pressure Sensor Dimensions.

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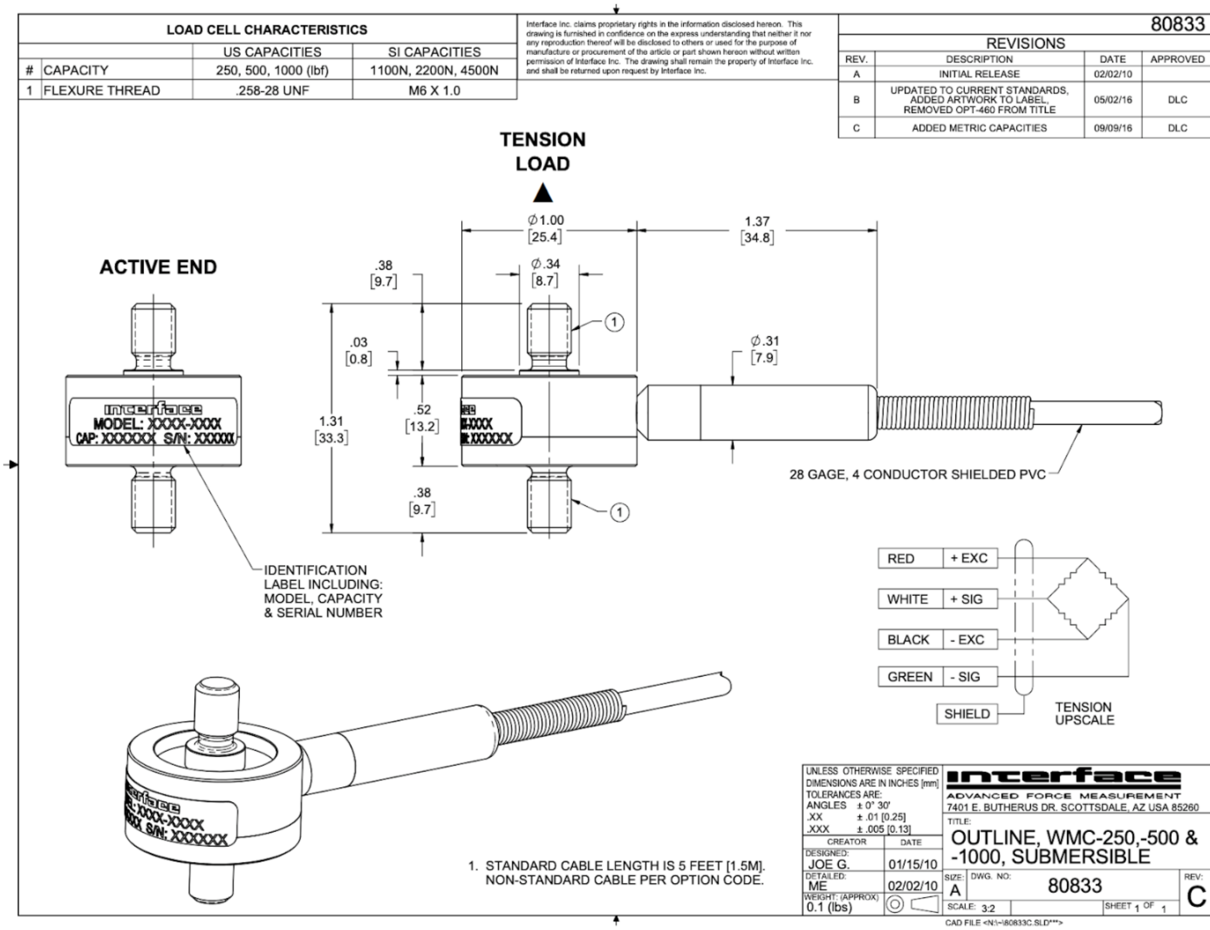

Figure A.3. WMC-500 Load Cell

Appendix B. Data handling and Measurement Standards at HWRL

D. Introduction

This is a guide to the project folder. The guide is broken into sections, starting with an overview of access to the project folder and its directory structure. Following this project folder overview, the guide describes the structure of O.H. Hinsdale Wave Research Laboratory (HWRL) data files. The next section describes the HWRL data acquisition system (DAQ), including timing and synchronization. The connection of instrumentation to the DAQ and location of instrumentation in the facility is described, as well as methods used to calibrate instruments and the tracing of these calibrations. Wave generation is described next, and finally the guide finishes with an overview of the standard post-processing steps in use at the HWRL.

D. Project Folder Access and Directory Structure

Any online access to the project folder requires an OSU College of Engineering account. Dumping the folder contents to another location, such as a shared `ftp` site or DesignSafe or a portable drive, can provide offline access. For those who have an OSU College of Engineering account, online read access is always available. Write access for active projects is always available to HWRL staff. Guest access for writing to the project folder can be granted on a case-by-case basis to those with an OSU College of Engineering account. Once the project has ceased activity, the project folder will be locked down to read only and any guest access for writing will be removed.

Accompanying this file in the project folder is a set of directories as follows: `data`, `docs`, `images`, `sw`, `video`, and `wavemaker`. Not all directories may be present; for example if no video was collected as part of the project then the empty `video` directory will eventually be removed when the project ceases activity. The project folder directories are described in the following sections.

2.1 Project Folder Directory: `data`

All observations from the project are stored in the `data` directory. Subdirectories such as `raw`, `inter`, and `final` are used to separate data processing stages. Each experiment for the project is a separate subdirectory with its own name, with trials contained in directories below those. Some experiment names such as `Calibration`, `DAQTest`, `SelfCalibration`, and `Survey`, will contain files or trials that are purely for testing or calibration or instrument location purposes.

The `raw` subdirectory includes data as recorded by the DAQ without any modification. Analog signals, such as wave gauges (*wg*) and acoustic range finders (*uswg*), are recorded in voltages. Digital signals are recorded with their own custom units; for example, Vectrino signals are recorded in channels including *velocity* (m/s), *signal level* (counts), and *correlation* (%). To maintain data integrity, raw data cannot be deleted or modified. The structure of raw data files is described in section 3 on page 4.

The `inter` subdirectory contains data that has been post-processed from its originally recorded state. The originally recorded data is always retained in the `raw` subdirectory and never modified. The `inter` subdirectory will always contain a `Calibration` subdirectory that holds all the calibration summary sheets for the project, along with any applicable wave gauge calibration sheets. This `Calibration` subdirectory should not be changed or modified; doing so will break automatic scripts used for post processing. Calibration is described in section 8 below. Post-processing is described in section 10 below.

2.2 Project Folder Directory: `docs`

All documentation and metadata from the project are stored in the `docs` directory. Various subdirectories may be used to separate different types of documentation, when appropriate. The `setup` subdirectory will always be present, with two subdirectories (`instm_locations` and `wiring_details`) always used to store spreadsheets that log instrument locations and the setup of instruments and their connectivity to the data acquisition system (DAQ). This `setup` subdirectory should not be changed or modified; doing so will break automatic scripts used for post-processing.

2.3 Project Folder Directory: `images`

All images from the project are stored in the `images` directory. Various subdirectories may be used to separate different types of images, when appropriate.

2.4 Project Folder Directory: `sw`

All source code used during the project is stored in the `sw` directory. Various subdirectories may be used to separate different types of source code, when appropriate. The `data_processing` subdirectory holds project-specific MATLAB routines for post-processing of data. The `hwrl_daq` subdirectory holds the LabVIEW source code used to run the data acquisition system (DAQ). The `wavemaker` subdirectory holds project-specific MATLAB routines for generating waves; the output from these routines is stored in the `wavemaker` project folder directory, described in section 2.6 below. Finally, a `toolbox` subdirectory may be present which holds a reference copy of the HWRL MATLAB toolboxes used for the project.

2.5 Project Folder Directory: `video`

All videos from the project are stored in the `video` directory. Various subdirectories may be used to separate different types of videos, when appropriate.

2.6 Project Folder Directory: `wavemaker`

All wavemaker input files from the project are stored in the `wavemaker` directory. Various subdirectories may be used to separate different types of wavemaker inputs, when appropriate. The `disp_bin` subdirectory holds the converted binary inputs used to run the wavemaker in displacement control mode; these are the actual files loaded by the wavemaker control computer after conversion from ASCII text. The `disp_txt` subdirectory holds ASCII text files specifying the board displacement; these are the files taken to the wavemaker control computer and subsequently converted to binary files for running waves. Finally, the `waves_txt` subdirectory holds ASCII text files specifying the free surface height at the face of the wavemaker piston(s).

In some cases, wavemaker input files will not be used, and instead built-in commands for the wavemaker control computer will be used. The distinction is typically noted in metadata headers of the data file, described in section 3 below.

MATLAB routines for wave generation are used to create all ASCII text files, whether displacement or free surface. Those routines, as well as built-in wavemaker operations, are described in section 9 below.

D. Data Files

Observations collected by the HWRL data acquisition system (DAQ) as part of the project are stored in data files. This section describes those files, for both raw data and intermediate data.

All HWRL data files are recorded in ASCII text. Headers are delimited by `%` symbols and contain metadata. Data are stored in tab-delimited columns. End-of-line characters are system-specific due to `ftp` transfers from the DAQ to the project folder. The use of ASCII text data with column tab delimiters and `%` header delimiters allows MATLAB to easily load data files using the built-in `load` function.

HWRL data file headers all follow the convention of a descriptive name using uppercase and lowercase letters with no spaces followed by a colon containing the value for that metadata field. Headers are also divided into sections for readability, with section names denoted by square brackets. Headers are preserved throughout processing steps and added to; never taken away.

All data files have the following section header, after which the data record

begins: `% [Data]`

The following two sections describe raw data and intermediate (post-processed) data file and filename conventions, including examples of headers.

3.1 Raw Data

Raw data files are those recorded by the DAQ without any modification. They are stored in the `data/raw` subdirectory, as described in section 2.1 above.

All raw data files have the following naming convention used to generate unique

filenames: `[xxxxx.xxxx]_[daqname]_[daqfiletype][port/trigger`

`id].[extension]`

Every raw data file has a prefix with a file creation timestamp. The timestamp is in Coordinated Universal Time (UTC), with units of days, where 0.0000 corresponds to midnight UTC on January 1 of 1904. Note that this is a file creation timestamp and the data acquisition start time corresponding to the timestamp of the first sample is recorded in the file when appropriate. HWRL DAQ timestamps are described in section 5 below.

The next section of the file name is a name for the DAQ computer that recorded this file. This field exists to prevent overwriting of the same data files recorded at the same time by multiple computers for an experimental trial.

The next section of the file name identifies the type of the DAQ file. Typically this is `analog` or `adv` for time series data. Other possibilities include: `mta` or `lrf` for bathymetric survey data, and `pressure` or `uswg` for calibration data for some instruments, such as pressure gauges or ultrasonic range finders.

The next section of the file name identifies the port being used, or the triggering mode in use by that system. Ports are a numerical identifier (`1`, `2`, `3`…) that immediately follow the `daqfiletype` field. Triggering mode can be: `_master` for systems that are sending out trigger pulses for synchronization purposes, or `_slave` for systems that are listening for trigger pulses for synchronization purposes, or `_off` for systems that are not being sampled synchronously.
Finally, the file extension is usually `txt` to denote an ASCII text file. Other possibilities are `log` for logs from data conversion of Vectrino binary data to ASCII, `raw.bin` for those Vectrino binary data files, and `raw.hdr.txt` for the accompanying text header for those Vectrino binary data files. You should not be concerned with anything regarding the binary data files or logs, unless you are either conducting testing of the DAQprocessor or debugging Vectrino operations.

The rest of this section describes those raw data files that are recorded in ASCII text. Raw metadata headers are formatted as described in section 3 above. Following are some examples of useful metadata that you might find in different raw data files, including section names, headers, and values. Note that the sections are deliberately separated in this example by blank lines to illustrate that the examples are only pieces of actual headers. Empty lines between sections are marked in real headers with the % delimiter.

The following headers are for an example of a raw analog data file:

```
% [O.H. Hinsdale WRL Metadata]
% FileType: DAQFile
% ProjectName: YourProjectName
% ExperimentName: OneOfYourExperimentNames

% [NEES Metadata]
% ProjectName: YourProjectName
% ExperimentName: OneOfYourExperimentNames
% TrialName: Trial91
% TrialTitle: Trial 91
% TrialDescription: Regular waves; 10 waves + 40s ramp up/down, DAQ for
4min % TrialConditions: H=0.45m, T=5s, h=2.448m,
REG_H0.45_T5_h2.448_t90_disp.bin

% [Analog Input Metadata]
% AnalogInputDeviceType: PXI-6259
% ChannelCount: 1
% DAQHardwareChannels: SC1Mod1/ai0
% MinVoltage: -5.000000 V
% MaxVoltage: 5.000000 V
% LowpassCutoffFrequency: 25.000000 Hz
% SampleRate: 50.000000 Hz

% [Timing Metadata]
% StartDateTimeUTC: Wed 2015/12/16 17:36:49.808 UTC
% StartYeardayUTC: 40892.7339098172

% [Channel Metadata]
% ChannelNames: wmstart
% ChannelUnits: Volts
```

The following headers are for an example of a Vectrino data file:

```
% [Serial Port Metadata]
% SerialPortName: ASRL7 (COM7 – PXI-8420/16)

% [Vectrino Hardware Configuration Metadata]
% HardwareSerialNumber: VNO 0099

% [Vectrino Probe Head Configuration Metadata]
% HeadSerialNumber: VCN 8173

% [Vectrino ADV Header]
% Temperature: 9.570 degC
% SpeedOfSound: 1445.500 m/s

% [Channel Metadata]
```

```
% ChannelNames: error, u, v, w1, w2, amplitude1, amplitude2, amplitude3,
amplitude4,  correlation1, correlation2, correlation3, correlation4
% ChannelUnits: n/a, m/s, m/s, m/s, m/s, counts, counts, counts, counts, %, %, %, %
```

Raw data is stored in tab-delimited columns. Each column is a channel of data, and each row is a time step. The sample rate of the data in the file is stored in the headers, and so is the start time. More details on synchronization and timing are provided in section 5 below.

3.2 Intermediate Data

Intermediate data files are data files that have been post-processed from their originally recorded (raw) states. They are stored in the `data/inter` directory, as described in section 2.1 above. Post-processing is described in section 10 below.

All intermediate data files have the following naming convention. Note that all intermediate data files are ASCII text:

```
[channelname].txt
```

The `channelname` prefix can correspond to an analog data channel name from an analog data file. If the channel name is *wmstart* from the previous examples, the resulting filename will be `wmstart.txt`. The prefix can also correspond to a Vectrino channel name (such as `u` from the previous examples) paired with the port of that Vectrino (such as `1`). In this case, the channel name prefix will be `u1` and the filename will be `u1.txt`.

Intermediate metadata headers are formatted as described in section 3 above. Following are some examples of useful metadata that you might find in different intermediate data files, including section names, headers, and values. Note that the sections are deliberately separated in this example by blank lines to illustrate that the examples are only pieces of actual headers. Empty lines between sections are marked in real headers with the `%` delimiter.

The following headers are for the example of an intermediate analog data file (`wmstart.txt`) described previously. Note that some of the headers don't have valid values, because the *wmstart* channel doesn't have a location in the HWRL coordinate system:

```
% [Calibrated Metadata]
% StillWaterDepth: 2.4479e+00
% ChannelName: wmstart
% CalibrationSlope: 1.000
% CalibrationOffset: 0.000
% CalibrationUnits: V
% X: NaN
% Y: NaN
% Z: NaN
```

The following headers are for the example of an intermediate Vectrino data channel (`u1.txt`) described previously:

```
% [Calibrated Metadata]
% StillWaterDepth: 2.4479e+00
% MeanSNR: 27.069
```

```
% MeanCorrelation: 98.203
% TemperatureOK: YES
% ChannelName: u1
% CalibrationSlope: 1
% CalibrationOffset: 0
% CalibrationUnits: m/s
% X: 45.018
% Y: 0.568
% Z: 1.562
```

Intermediate data files are recorded as single columns, so that there is one file for each channel, with its own channel name as a file name as described previously. The time coordinate for intermediate data files is stored in a separate file (time.txt) and the post-processing steps to create that file and all other intermediate files are described in section 10 below on post-processing.

D. Data Acquisition System (DAQ)

The data acquisition system (DAQ) used at the HWRL runs on National Instruments PXI architecture computers. These computers use a real-time version of the LabVIEW programming environment. Computers are upgraded approximately every three years. The LabVIEW programming environment is updated annually, typically on the spring release cycle of the campus-wide site license in place at Oregon State University. This is done so that the LabVIEW programming environment in use is the presumably more stable "Service Pack 1" programming environment instead of the first release of a new environment. Each computer is installed in a PXI chassis along with accompanying PXI and or SCXI modules.

Analog data acquisition for each DAQ is controlled by a NI PXI-6259 M-series 16-bit multifunction DAQ module. The DAQ module communicates via the PXI/SCXI backplane to SCXI-1143 Butterworth anti-aliasing filter modules in its containing PXI-1052 chassis. Each filter module is fronted with SCXI 1305 terminal blocks that take ±5V differential inputs from analog channels via 50Ω coaxial cable with BNC connectors. The SCXI-1143 Butterworth anti-aliasing filters are set with cutoff frequency at ¼ the sampling rate. There are eight filter modules per PXI-1052 chassis and 8 channels per filter module, for a total of 64 channels of analog inputs per chassis. Synchronization of up to 3 independent chassis permits up to 192 synchronized analog input channels. The DAQ sampling rate is typically 100 Hz; the DAQ is capable of up to 5 KHz when sampling all 64 channels. The DAQ assumes that all input sources are ground-referenced; therefore, it has no resistor to ground on the low (negative) side of each differential input. Testing at the HWRL has shown that the DAQ is accurate to within ±0.3mV when observing known voltages on NIST-traceably certified voltage standards.

All observed analog input signals are subject to some unwanted signals (noise). Noise is minimized through careful controls at all stages of the DAQ, including but not limited to the use of shielded cabling, isolation of instrumentation power supplies from non-instrumentation outlets, elimination of ground loops, high-quality equipment from trustworthy vendors, and regular traceable calibrations. All in-situ instruments and equipment are calibrated using methods traceable to NIST standards, and the HWRL routinely maintains calibration sheets and documentation of these traces, as described in section 8 below.
Digital communication with Vectrino systems is done over RS-232 serial ports. A 16-port PXI-8420 module controls serial data acquisition for each DAQ. Vectrino systems are triggered by TTL synchronization pulses as described in the next section.

All observed data are written continuously to a solid-state drive on the DAQ. Data is copied via `ftp` to an independent data processor (Mac Mini running macOS) that keeps a locally backed-up archive of each data file before sending a copy onward to the HWRL share. The HWRL share is located on-campus in a separate building from the HWRL, and it is maintained and backed up by the College of Engineering information technology support team. This process ensures that at least three multiply-backed-up copies are made of each data file before it is made available for post-processing and quality control.

D. Data Acquisition Synchronization and Timing

Accurate synchronization and timing of observations are important concerns. The HWRL provides several options for synchronizing its own systems with each other and with those of visitors. Options for sample synchronization and absolute timing are reviewed in this section.

Each NI PXI-6259 M-series DAQ module has an 80 MHz sample clock that is accurate to within ±50ppm (±0.005%) and a resolution of 50ns. The DAQ modules are kept in spec through routine on-site self calibration and traceable calibration every 2 years, per the recommendations of National Instruments. It is most preferable to connect instruments directly to the HWRL DAQ analog input channels, which guarantees sample-for-sample timing to within the DAQ sample clock resolution.

If it is not possible to connect an instrument to the analog inputs of the HWRL DAQ, or if multiple HWRL DAQ systems are required due to the size of a project deployment plan, then sample coherency is maintained through the use of TTL pulses generated by one master DAQ and listened to by the other slave DAQs. This method is also used to ensure sample coherency between analog observations and Vectrino systems. All Vectrinos at the HWRL are set up in sample-on-sync mode and triggered by a master DAQ. TTL pulses generated by the master DAQ are buffered and repeated by Pulse Research Labs PRL-414B 1:4 50Ω TTL line drivers. TTL pulses generated by the master DAQ are optimized for Vectrino triggering with +5V highs at 40µs widths, which corresponds to a 0.004 duty cycle when operating at 100Hz.

If connection to the HWRL DAQ and triggering will not work, then simultaneous recording of common signals can be used along with post-processing realignment to achieve synchronization. The wavemaker outputs a 5V high at the start of operations and holds it high until after the board is stopped and current span has wound down to 0. This is the *wmstart* signal described previously in examples of data files in
section 3 above. It is an analog output transmitted over 50Ω coaxial cable and recorded as an analog input channel on the HWRL DAQ, and it can be buffered and sent to other systems for simultaneous recording and then post-processed to align signals afterwards. The accuracy of this procedure is to within ±1 sample of the slowest-sampling system. This procedure can also be used with mobile instruments over rigid beds to reconstruct a synoptic data set from multiple trials.

The remaining options for synchronization rely on absolute timing: the use of timestamps. All HWRL DAQ timestamps use Coordinated Universal Time (UTC). Timestamps from HWRL DAQ system clocks are provided for the first sample of analog DAQ systems in two headers, shown below in an example:

```
% [Timing Metadata]
% StartDateTimeUTC: Wed 2015/12/16 17:36:49.808 UTC
% StartYeardayUTC: 40892.7339098172
```

The first header (`StartDateTimeUTC`) is a human-readable UTC date (YYYY/mm/DD format) and time (HH/MM/SS.uuu format) with millisecond resolution. The second header (`StartYeardayUTC`😉 has units of days with resolution of under 10µs, where 0.0000 corresponds to midnight UTC on January 1st of 1904.

HWRL DAQ system clocks are synchronized to a grandmaster clock using the National Instruments NI TimeSync implementation of the IEEE 1588-2008 Precision Time Protocol. The grandmaster clock is a dedicated PXI-based HWRL DAQ system with an NI-PXI-6682 timing and synchronization module connected to a Trimble Bullet III GPS antenna mounted on the roof of the HWRL. The GPS signal provides ±100ns accuracy relative to UTC. The grandmaster clock sends synchronization messages over the local firewalled HWRL DAQ network every 500ms. Testing shows that HWRL DAQ timestamps agree to within ±7ms when observing triggered coherent samples of the same analog signal.

Systems that lack their own GPS antenna and receiver can use NTP to set clocks to UTC. Available NTP servers are the stratum 2 server at OSU: `time.oregonstate.edu` and the United States NTP pool: `0.us.pool.ntp.org` through `3.us.pool.ntp.org`. Testing shows that this yields absolute clock accuracy to within ±50ms.

6. Instrumentation and Wiring Details

All HWRL project instrumentation deployments are tracked using wiring details spreadsheets. The purpose of the wiring details spreadsheets is to enable debugging and diagnostics of experimental setups. The spreadsheets are stored in the `docs/setup/wiring_details/` subdirectory in the project folder. The file names include the project name and a local timestamp. Each modification to the project instrumentation deployment or drivers or DAQ wiring or cabling is noted in an updated sheet. Wiring details sheets and their filenames and parent directories should not be changed or modified; doing so will break automatic scripts used for post-processing. An example of the top two rows of a wiring details sheet is shown below:

data column sensor name cable to driver driver driver channel ~~cable to DAQ DAQName~~ DAQHardwareChannels standard VSTD-8241 NA NA 1 CX-05-188 pxi2 SC1Mod1/ai0

The *data column* corresponds to the channel name recorded by the DAQ. The *sensor name* is a unique identifier for each sensor that is a combination of an abbreviated text field, such as VSTD for a voltage standard, and an abbreviation of the corresponding equipment serial number. If the sensor has a separate driver, such as a pressure gauge that consists of the submerged gauge itself and the signal conditioning module outside the tank, then that driver, driver channel, and cable between the driver and the sensor are logged in the wiring details. Finally, the rightmost columns describe the cabling between the sensor or driver to the DAQ, the name of the DAQ to which the sensor is cabled, and the input channel for that sensor. In this way, the wiring details sheet is a complete description of the project setup.

7. Surveys and Location Plans

Locations of instruments are typically found using a Nikon pulse laser station model NPL 332. This total station is precise to within ±0.5mm and accurate to within ±5mm when running in precise mode without a prism. Prior to survey, the station is leveled to within ±0.05 arc-second (or 1/7200th of a degree) and targeted at up to 8 known points around the wave tank with typical standard deviation of the resection at less than ±1mm.

All HWRL project instrumentation locations are tracked using location plan spreadsheets. The spreadsheets are stored in the `docs/setup/instm_locations/` subdirectory in the project folder. The file names include the project name and a local timestamp. Every change to instrument locations is noted in an updated spreadsheet. Examples of changes to instrument locations are: addition of sensors, removal of sensors, or moving of existing sensors. Location spreadsheets and their filenames and parent directories should not be changed or modified; doing so will break automatic scripts used for post-processing. An example of the top of a location plan spreadsheet is shown below:

data column sensor name coord space placement (X) placement (Y) placement (Z) placement (I) placement (J) placement (K) comment standard VSTD-8241 Large Wave Flume
wmstart wmstart Large Wave Flume
wmdisp TMPO-LWM Large Wave Flume 0.000
wmwg RWG-LWM Large Wave Flume 0.000
level PRES-9959 Large Wave Flume 13.961 -1.527 0.638
wg1 RWG-2260-01 Large Wave Flume 17.728 -1.269

The *data column* and *sensor name* entries must match those in the corresponding wiring details spreadsheets, as described in section 6 above. The *coord space* field describes which facility is used for this location plan, and then the following fields describe position and orientation of the sensor along with any comments or notes.

All surveys and instrument locations are reported using the HWRL coordinate system. The HWRL coordinate system is defined as follows: The x-axis is the cross-shore coordinate. Its origin (x = 0) is at a vertical plane that best fits the face of the wavemaker piston when it is neutrally positioned. The x-axis is measured in meters and positive onshore (away from the wavemaker). The z-axis is the vertical coordinate. The z-axis origin (z = 0) is at the average elevation of the tank floor. The z-axis is measured in meters and positive upwards. Finally, the y-axis is the alongshore coordinate (parallel to the wavemaker piston). The y-axis origin (y = 0) is at the alongshore centerline of the tank, i.e. halfway between two vertical planes that best fit the tank walls. The y-axis is measured in meters and positive to the left when facing onshore, so that the coordinate system is right-handed. In the Large Wave Flume, x is positive north and y is positive west. In the Directional Wave Basin, x is positive west and y is positive south.

8. Calibration

All HWRL project instrument calibrations are tracked using calibration summary spreadsheets. The spreadsheets are stored in the `data/inter/Calibration/` subdirectory in the project folder. The file names include the project name and a local timestamp. Every change to instrument calibrations is noted in an updated spreadsheet. Calibration summary spreadsheets and their filenames and parent directories should not be changed or modified; doing so will break automatic scripts used for post-processing. An example of the top of a calibration summary spreadsheet is shown below:

~~offset~~

data column sensor name driver driver channel Calibration source file slope slope units offset
units Notes

standard VSTD-8241 NA 1 NA 1.000 V/V 0.000 V wmstart wmstart LWF-WM AO1 NA 1.000 V/V 0.000 V wmdisp TMPO-LWM LWF-WM AO2 NA 0.440 m/V 0.000 m
wmwg RWG-LWM LWF-WM AO3 NA 0.400 m/V 0.000 m level PRES-9959 SG-SC-6381 1 cert_pres_9959_20131009 1.043 m/V -0.002 m wg1 RWG-2260-01 RWG-2260 1
YourProjectName_wave_gauge_calibration_20150126_1330 0.226 m/V 0.000 m

Entries in the first four columns (*data column*, *sensor name*, *drive*, and *driver channel*) must match those in the corresponding wiring details spreadsheets, as described in section 6 above. The *calibration* *source file* field describes what source file was used to generate the provided calibration. This could be "NA" for calibrations that have no source file; for example the wavemaker output calibration coefficients are set directly at the wavemaker control computer. The calibration slopes and offsets and accompanying units are in the remaining columns, along with any comments or notes. Since raw data is acquired in volts, the slopes will always be expressed as a ratio of physical units to volts, and the offset will be in the physical units. Some signals have physical units of volts, for example *standard* (a voltage standard) and *wmstart* (a wavemaker output that is set to +5 V when the wavemaker is moving and 0 V when it is not).

Most HWRL project instrument calibrations are traceable to NIST standards, and calibration certificates document that traceability. Applicable calibration certificates are referred to in the calibration source file field of the calibration summary sheet, and they are available upon request. Vectrinos are calibrated at the factory (NorTek Vectrino+, 4 m/s maximum velocity, ±0.5% ±1 mm/s accuracy) and do not require recalibration unless they are damaged or bent. Other instruments, such as acoustic range finders, laser range finders, load cells, and pressure gauges, are traceably calibrated either yearly or as needed. The HWRL DAQ, voltage standards, and associated diagnostic equipment are calibrated routinely either by the manufacturer or by NIST-certified calibration services. Finally, the manufacturer (MTS Systems Corporation) calibrates the wavemaker annually.

All wave gauges are calibrated when changing the tank water level (filling and draining). Fill and drain calibration methods are the same. While the water level is slowly changing, the HWRL DAQ observes all analog inputs over a sample period, typically sampling at 100Hz for a 1-minute duration. Sampling of analog inputs is typically done every 5 minutes for an entire fill or drain, which can take up to 9 hours. The mean voltage of every input channel is estimated for each sample period. Mean voltage estimates are then put into a wave gauge calibration spreadsheet that calculates a linear least-squares fit between the observed wave gauge voltages and the calibrated water depth observations from a traceably-calibrated pressure sensor, referred to as *level* in the HWRL DAQ and in the previous example of a calibration summary sheet, above.

In addition, some wave gauges (referred to as self-calibrating wave gauges) can be calibrated without changing the water level. The self-calibrating wave gauges are equipped with a lead screw of known pitch, a stepper motor, and a rotary encoder. Each set of self-calibrating wave gauge wires are driven up and down by the stepper motor, and the accompanying encoder position is observed. Combining the observed position of the encoder with the known pitch of the lead screw provides an observation of vertical motion of the wave gauge. The observed voltages are linearly least squares fitted to the observed vertical motion, generating a calibration slope. Self-calibrating wave gauges are typically calibrated at the beginning and end of every day.

9. Wave Generation

The wavemaker for the Large Wave Flume (LWF) is a single-channel piston-type hydraulically driven system. It consists of a vertical wall, referred to as the wavemaker piston, which is suspended from a steel support structure. The piston and its support structure travel back and forth on linear bearings that are bolted to the walls of the flume. The piston is driven by a set of counter-balanced hydraulic actuators that can exert up to 50,000 lbs of force with a maximum hydraulic flow rate of 650 gpm. The piston can move at up to 4 m/s and has a 4 m total stroke, which is defined as the distance between its most offshore and most onshore positions. The maximum still water depth of the LWF is 9 ft (2.743 m), and the maximum still water depth for running tsunamis (solitary waves) is 2 m.

The wavemaker for the Directional Wave Basin (DWB) is a 30-channel piston-type belt-driven servomotor system. It consists of a segmented vertical wall, referred to as the wavemaker piston. Each segment of the wall has a drive point on either side; there are 29 segments in total being driven by 30 drive points. Each drive point is moved by a 21.3kW servomotor and toothed belt that moves the piston back and forth on a bearing rail connected to supporting steel that is bolted into the basin floor. Each drive point can move at up to 2 m/s and has a 2.1 m total stroke, which is defined as the distance between its most offshore and most onshore positions. The maximum difference between adjacent drive points is 0.25 m. The maximum still water depth of the DWB is 4.5 ft (1.372 m), and the maximum still water depth for running tsunamis (solitary waves) is 1 m.
Each wavemaker can use built-in code to run regular (monochromatic) linear wave conditions of the desired height and period for a given water depth. Each wavemaker can also use built-in code to run solitary waves of the desired height for a given water depth. All other options for wavemaker operation are generated using MATLAB code and then provided as ASCII text input files to the wavemaker control computer as a time series of board displacement. These options are described below.

The HWRL MATLAB toolbox includes a set of routines for wavemaker theory. All routines generate time series of board displacement and free surface elevation at the wavemaker piston. For unidirectional monochromatic waves, the routine `wavemaker_reg_2d` automatically selects the best theory to generate waves that match the input height and period for a given water depth. The theory selected will be one of the following: fully nonlinear second-order Stokes wavemaker theory, ad-hoc stream function wavemaker theory, or cnoidal waves combined with shallow water wavemaker theory. For unidirectional random waves, the routine `wavemaker_nl` generates waves using fully nonlinear second-order Stokes wavemaker theory. For directional regular or random waves, the routine `wavemaker` generates waves using linear wavemaker theory. All routines generate ASCII text input files that are converted to binary files by the wavemaker control computer. Those binary files are then loaded by the wavemaker control computer and used to run waves in displacement file mode.

All custom source code used to specify and/or generate wavemaker files is stored in the `sw/wavemaker` subdirectory of the share, as described previously in section 2.4 above. All ASCII text and converted binary files are stored in the `wavemaker` directory of the share, as described previously in section 2.6 above. Source code from the HWRL MATLAB toolbox may also be provided in the `sw/toolbox` subdirectory; the section specific to wave generation would then be in the `sw/toolbox/wavemaker` subdirectory.

10. Post-processing

Post-processing is the conversion of data from a raw state to an intermediate state. Raw data is the same as recorded by the DAQ without any modification. Intermediate data is the output of post-processing. Post-processing includes the updating of metadata to include locations (section 7 above), the application of calibrations (section 8 above), despiking and data cleanup. Later steps may include estimation of incident and reflected waves, directional spectra, or statistical quantities such as significant wave height or peak wave period.

All custom source code used to post-process is stored in the `sw/data_processing` subdirectory of the share, as described previously in section 2.4 above. Source code from the HWRL MATLAB toolbox can also be provided in the `sw/toolbox` subdirectory; the section specific to post-processing data from the `data/raw` subdirectory to the `data/inter` subdirectory would then be in the `sw/toolbox/raw` subdirectory. Every processing stage retains headers from the previous stage, as described in section 3 above.

The top-level routine for post-processing is `process_raw_experiment`. It calls `process_raw_trial` for every trial in the input experiment. Both of these routines still have minor project-specific customizations, and so they are not yet in the HWRL MATLAB toolbox. The `process_raw_trial` routine loads all data found for the specified trial. Instrument locations are automatically applied from the most recent instrument location plan (section 7 above). Calibration coefficients and offsets are linearly interpolated between calibration coefficients found in summary sheets (section 8 above) for each channel of data. The system is able to handle calibration coefficients that are updated more frequently, such as the twice-daily calibration of self-calibrating wave gages. Vectrino data is cleaned up, despiked, and rotated into the HWRL coordinate system (section 7 above). Ultrasonic range finders are cleaned up and despiked.

Appendix C. Summary of HWRL Safety Plan 2020.

Job Hazard Analysis

The facility adheres to University policy and procedures for job hazard identification and control. Specific job hazards identified at the facility are as follows:

Hazard	Responses
Chemical exposure, ingestion or burns	Find a less-toxic way to complete the task Hazardous storage cabinets Safety data sheets Use required PPE for the task
Compressed gas cylinders	Proper identification and caps Regular self-inspections Secured with chains
Confined spaces	Entry to area around wave makers restricted LOTO required to go on wave makers LOTO required to go behind wave makers

Hazard	Responses
Crane accidents	Stay away from crane loads and operations Never get under or atop a load Never ride a hook or sling Only trained and certified operators allowed Do not distract crane operators Do not exceed crane or sling load ratings Regular self-inspections Annual outside inspections
Drowning	Buddy system and rescue equipment Entry to wave tanks restricted No waves running when people in tanks
Electrocution	GFI circuits near wave tanks Lockout/tagout for powered specimens
Falling	Fall protection Ladder inspections required prior to use Railings Scaffold inspections required prior to use Training for elevated work surfaces
Foot injuries	All workers required to have safety training Safety (ASTM F2413) shoes required
Heavy equipment or crane accidents	Do not approach heavy equipment Do not distract machinery operators Do not exceed machinery load ratings Regular self-inspections Annual outside inspections
Loud noises from power tools or equipment	Stay out of area Ear protection required for those in area Training required for power tools
Operating power tools, using aerosol sprays, any work that may produce chips	Stay out of area Eye protection required for those in area Training required for power tools
Overhead hazards including: LWF, cranes, forklifts, equipment, or scaffolding overhead	Stay out of area Hard hat required for those in area Do not place anything atop LWF wall Do not place anything atop scaffolding Only trained and certified operators allowed

Hazard	Responses
Temperature extremes	Heaters when cold Hydration Take breaks Wear proper clothing
Tripping	Clean up clutter Cover cords and other hazards Keep walkways clear Exercise spatial awareness
Wave maker machinery (falling, entanglement, crushing)	Entry to area around wave makers restricted Ladder inspections required prior to use Lockout/tagout required to go on or behind Only trained and certified operators allowed Training for elevated work surfaces Wear fall protection

The facility has also implemented the following standard safety rules in addition to the University policy and procedures for physical labor and material handling safety:

• Documented safety training is required before working or operating any equipment
• Be aware of and follow all safety rules, signs, and instructions
• All accidents must be reported to your supervisor
• Any hazardous condition or potential hazard must be reported to your supervisor
• Anyone is expected to call for a work stoppage if they have a safety concern
• No unescorted visitors or walk-ins for tours
• Safety (ASTM F2413) shoes, secured hair and clothing required for every worker
• Be aware of trip hazards and keep walkways clear
• Do not approach any crane, heavy machinery, or power tool use without operator clearance
• Mobile device usage prohibited while driving or operating tools or machinery
• Do not needlessly distract anyone operating tools, heavy machinery, or cranes
• Hard hats are required for all overhead hazards, including in LWF or during crane operations
• Do not place anything that might fall on someone atop the walls of the LWF
• Do not place anything that might fall on someone atop moveable roller scaffolding
• Eye and ear protection are required when working with any shop or power tools
• Eye protection required when any aerosol paints or chemicals are used
• Eye protection required during any work that may produce chips
• Use of any shop or power tools requires separate training
• Use of any heavy machinery requires separate training and documentation
• Operation of any crane requires separate training and documentation
• Operation of any wave maker requires separate training and documentation
• Do not climb on, around, or inside any wave maker when it is powered up
• Stay out of the LWF enclosure when the wave maker is powered up
• Stay out of the area behind the DWB when the wave maker is powered up

Crane and Hoist Safety
The facility has a 6-ton gantry crane over the LWF, a 7.5-ton bridge crane over the DWB, and a 20-ton bridge crane over the structures lab on the west side of the LWF. The facility adheres to University policy and procedures for crane and hoist safety for all cranes. The policy and procedures are located here:

https://oregonstate.edu/ehs/sites/default/files/pdf/si/crane_and_hoist_safety_si050.pdf

Prior to operating any cranes at the facility, everyone must participate in documented crane training. Everyone is notified of this requirement as part of the mandatory walk-through safety training session described in the Employee Participation and Safety Rules sections above. All training documentation is signed and permanently stored at the facility. An operation manual specific to the LWF gantry crane has been developed and is permanently housed at the facility. A copy of the CMAA Overhead Crane Manual is also permanently housed at the facility. The University also provides online training in bridge and gantry crane operation. Familiarity with all manuals and online training and compliance with the procedures therein is required as part of the documented crane training. Facility cranes shall be inspected monthly and annually, as described in Self-Audits and SelfInspections above. Prior to and after lifting operations, all rigging shall be inspected for wear as well as monthly as part of the self-inspection audit. Rigging shall be stored and maintained in good condition.

Drowning
An observer must be present whenever anyone enters a filled Large Wave Flume (LWF) or Directional Wave Basin (DWB). The observer will be expected to devote full attention to the person in the water and the observer must be capable of a water rescue if necessary. Rescue hooks and flotation devices are provided along both the LWF and DWB at locations marked on the facility map. Everyone is notified of these locations as part of the mandatory walk-through safety training session described in the Employee Participation and Safety Rules sections above.

Noise Exposure
The facility adheres to University policy and procedures for noise exposure. The policy and procedures for the hearing conservation program and noise control plan are located here: http://oregonstate.edu/ehs/sites/default/files/pdf/si/hearing_conservation_si044.pdf The facility is not exposed to sound levels in excess of 85 dBA in normal working conditions. If noisy tools or equipment is operated, hearing protection is recommended and is collocated at the facility with other PPE. Hearing PPE at the facility consists of foam ear plugs and earmuffs. Additionally, doors between the two wings of the facility can be closed to isolate noise.

Power Tools and Shop
Prior to operating any power tools or shop tools at the facility, everyone must participate in the applicable training. Separate training is required on each specific tool. Everyone is notified of this requirement as part of the mandatory walk-through safety training session described in the Employee Participation and Safety Rules sections above. All mandatory walk-through safety training documentation is signed and permanently stored at the facility. 19 Shop tools are inspected as part of the monthly safety self-inspection described in the SelfAudits and Self-Inspections section above. All audit and inspection documentation are signed and permanently

stored at the facility.

The following is a list of fixed power tools at the facility:

Fixed power tools	
Manufacturer	**Description**
Briggs & Stratton	Generator
Clausing	Drill press
Core Cut	Concrete Saw
Dayton	Air compressor
Delta	Drill press, band saw, bench grinder
DeWalt	Cabinet table saw, Compound miter saws (chop saws)
Fisher	Kiln
Grizzle	Cabinet table saw
Lincoln, Miller	Welders
Milwaukee	Chop saw
Powermatic	Band saw, drill press
Rod Chomper	Rebar cutter & bender
Safety Speed Cut	Vertical panel saw
Spyglass	Band saw
Thermal Dynamics	Plasma cutter
Tippman	Air driven die cutter
Wilton	Band saw and mill drill

The following is a list of handheld or mobile / movable power tools at the facility:

Handheld / mobile power tools	
Manufacturer	**Description**
Black & Decker, Bosch	Corded drills
Bosch	Cordless drills, hammer drill, sander
Campbell-Hausfield	Air compressor, air ratchet
Dewalt	Belt sander, circular saw, corded drill, cordless drills
Dewalt	Impact drivers, grinders, jigsaw, reciprocating saw
Dremel	Grinder/engraver, band saw, reciprocating saw
Hilti	Hammer drill
Husky	Air driven sander
Husqvarna	Circular saw
Ingersoll Rand, NAPA, Jet	Air driven impact wrenches
Kett	Power shear (sheet metal cutter)
Makita	Vibrating cutter

Handheld / mobile power tools	
Manufacturer	**Description**
Metabo	Grinders, sanders
Miller	Floor cutting saw
Milwaukee	Corded drills, die grinder, engravers
Milwaukee	Hammer drill, jigsaw, reciprocating saw, sander
Porter Cable	Round head framing nailer, router, belt sander
Porter Cable	Deep cut band saw, grinder, worm drive circular saw
Senco	Screw gun
Simpson	Air driven caulk gun
Skil	Circular saw
Sure-Clean NW	Pressure washer

Directional Wave Basin Steel Beach Standard Operating Procedures

The Directional Wave Basin is typically set up with a planar 1:10-sloped steel-paneled beach, either to provide wave dissipation for an offshore model or for a particular research study on a linear and constant-sloped section of bathymetry. The separate Directional Wave Basin Steel Beach Operations Manual describes unique operational features and safety hazards of the installation or recovery of the beach and its components consisting of panels, longitudinal and transverse rails, columns, base support tubes and other accessories as part of a proper assembly. The operations manual shall be reviewed by every worker prior to participating in a beach installation or recovery. As part of the manual, a checklist is provided for workers. The checklist is included for reference in Appendix A below.

Wave Maker Entry and/or Maintenance

Entry to the areas around the wave makers for both wave tanks is dangerous and permitted for authorized personnel only. These regions are marked as such on the facility map and on-site with signs. Fences and/or gates also restrict entry. No wave maker may be operated while anyone is on or inside the wave maker. Prior to operating any wave maker at the facility, everyone must participate in documented wave maker training. Restrictions on operations of the wave maker while anyone is on or inside the wave maker are part of that training. Entry to the area inside or atop any wave maker requires the use of proper lockout/tagout procedures, as described in Chapter 2 above in the section Lockout/Tagout. 24 Ladders must be used to enter the area inside either wave maker. Fall protection must also be worn by anyone entering the areas either atop any wave maker or inside any wave maker. Use of either ladders or fall protection requires proper training, as described in Chapter 3 above in the section Elevated Work.

The area inside either wave maker is a confined space. Prior to entering the area inside any wave maker, workers shall be made aware of the hazards posed by machinery that has not been properly de-energized prior to entry. Workers will be made aware of proper entry and exit point using ladders and fall protection. No worker shall enter any area inside a wave maker until the wave maker has been locked out and verified safe by facility staff. The wave maker will not be re-energized until all workers have been accounted for and verified safe, with all tools and equipment recovered from the area inside the wavemaker. All of these procedures require online training prior to starting work. Specifically, online training modules required for not only workers but also all facility staff are: “Confined Space Entry”, “Ladder Safety”, “Lock and Tag”. The University training website is located here:

https://training.oregonstate.edu

Wave Maker Operation
Prior to operating any wave maker at the facility, everyone must participate in documented wave maker training. Everyone is notified of this requirement as part of the mandatory walkthrough safety training session described in the Employee Participation and Safety Rules sections above. All training documentation is signed and permanently stored at the facility.

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Directional Wave Basin Beach Checklist

Directional Wave Basin steel beach operations manual read and understood ☐

Training requirements

- Documented crane-specific on-site training of every crane operator ☐
- Documented machine-specific on-site training of every forklift operator ☐
- Ladder safety online training of every worker ☐
- Separate training of every worker on any shop, power or air tools ☐

Personal protective equipment

- Hard hats and safety (ASTM F2413) shoes required for all workers ☐
- Waterproof shoes, gloves, and long pants or coveralls recommended ☐
- Eye protection required when working with power or air tools ☐

Staging

- Protect all basin seals with plywood; stage tool and part pallets ☐
- Use labels to correctly place all beach components ☐
- Stage base support tubes and columns in beach footprint ☐
- Stage beach panels, longitudinal and transverse rails outside footprint ☐
- Anti-seize or marine grease for all hardware connections ☐

Starting

- Place angle irons and anchor to floor, then toe panels ☐
- Anchor first base tubes; use longitudinal rails to align next base tubes ☐
- Anchor toe panel fronts ☐

Beach panel routine

- Use labelling system (A south to J north, 1 bottom to 6 top) ☐
- Work from offshore to onshore (from bottom to top of slope) ☐
- Each panel requires the next set of longitudinal rails, columns, base ☐
- Use panels to align the rails, columns, and base support tubes ☐
- Pull one panel, tighten and check all bolts, replace panel, repeat ☐
- Once all panels in a row are tight, move on to aligning next row ☐

Side panels, toe plates, grating, hole plugs

- Once all panels are done, proceed to finish work ☐
- Install side panels, toe plates, grating, hole plugs ☐

Recovery

- Beach teardown in reverse order; stage outdoors on gravel pad ☐
- Verify all labels legible; repaint any that are bad ☐
- Repair or replace any bad connection points or hardware ☐
- Put away all hardware and tools in wooden bins ☐
- Do not leave anything on lab floor or in buckets or shop ☐
- Clean all hardware with wire brush or motorized wire wheel ☐

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Daily Crane Checklists

Check the Following Prior to Running Any Crane

- **Check that crane or hoist is not locked out and not tagged as out-of-order** ☐
- **Check that all ratings and warnings and safety labels are intact and legible** ☐
- **Test correct operation and brakes for hoist, trolley, bridge motions** ☐
- **Test that upper limit switch halts lifting of unloaded hook successfully** ☐
- **Listen for any unusual sounds from crane or hoist while testing operation** ☐
- **Check for damage, cracks, nicks, gouges, deformation, wear, and twist of hook** ☐
- **Check that hook latch is intact and operating properly** ☐
- **Check that hoist wire rope is free of any damage, kinks, or deformation** ☐
- **Check that hoist wire rope is reeved properly and not twisted about itself** ☐

Check the Following in Addition Prior to Running Large Wave Flume Gantry Crane

- **Ensure that nothing is sitting atop the tank walls that could be run over** ☐
- **Ensure that no other carts or equipment will be struck by the crane** ☐
- **Ensure that nothing in the flume will be struck by the crane** ☐
- **Ensure that the hook is positioned over a point between the flume walls** ☐
- **Ensure that the painted yellow area on the west side of the wall is clear** ☐
- **Ensure that nothing is laying atop the power cord along the west side of the wall** ☐
- **Verify that the spool for the power cord is operating properly and not jammed** ☐
- **Verify that the power cord is not tangled** ☐
- **Ensure that the tie-down rod is lifted away and secured** ☐

A-3

Appendix D. Testing Images

Figure D.1 Overnight Float Test

Figure D.1. depicts the test set up for the overnight float test. This was conducted prior to adjusting the ballast weight to determine the change in still waterline overnight. Polyurethane waterproof paint was applied to the model post overnight float test to ensure that even if the exterior paint was damaged, the bulk buoyancy of the model would not change.

Figure D.2 Center of Gravity Hang Testing.

Figure D.2 depicts the center of gravity hang testing conducted at OSU. The model was suspended from each corner of the wings and a laser level was used to survey the intersection of each point to determine the center of gravity.

Figure D.3 Model Coordinate Surveying. Test Set up used in Compound Pendulum test to determine the radius of gyration.

Figure D.3 depicts the test set up used to survey the coordinate system of the model. This is used in determining the RAOs of the model via the LED markers for the PhaseSpace motion capture system. The same suspension set up was used to determine the radius of gyration in X and Y. It was confirmed that the model is axisymmetric via symmetry of the radius of gyration. Depicted in the foreground is Bret Bosma using the surveying tool to determine the coordinate grid of various points of interest on the model.

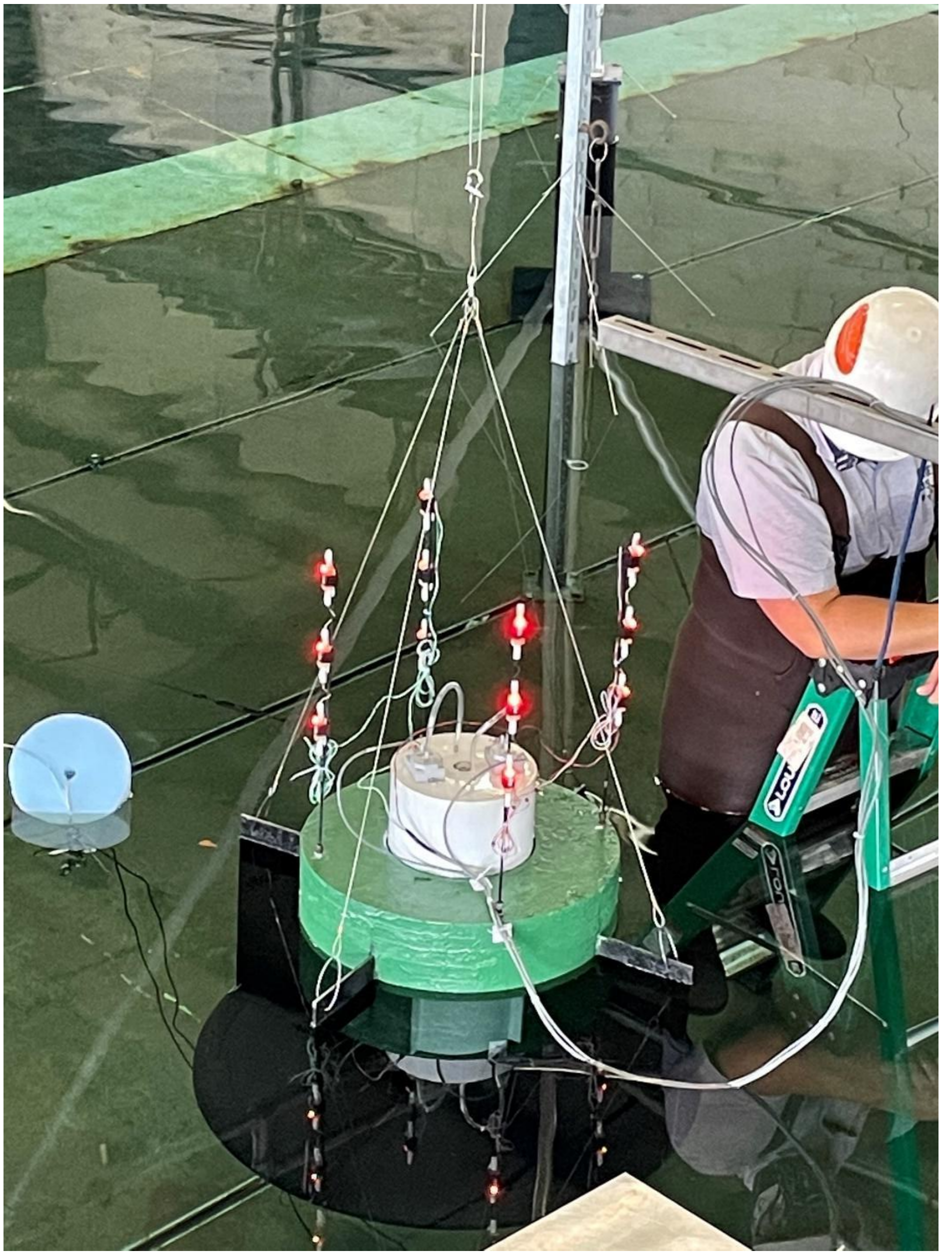

Figure D.4. Heave Decay Test Set up.

Figure D.4 depicts the test set up for the Heave Decay Tests. The model was suspended from each corner of the wave guides via 1/8” steel cable, and lifted roughly 6 cm from the still waterline. A sacrificial cable was cut via the applicant on a ladder in the basin nearby. The overhead crane was used to suspend the model above the still waterline. The PhaseSpace motion capture system observed the decay motion response.

Figure D.5. Fixed Model Surface Elevation Probe Installation.

Figure D.6. Close up image of surface elevation probe with waterproof gradation tape.

Figure D.5 and D.6. depicts the OWC chamber of the fixed model. A capacitive wave probe was affixed to the inside of the test article to measure the internal water surface. A GoPro and gradation tape were used around the OWC chamber to qualitatively verify that significant seiching did not occur.