Post Access Report

Testing the Adaptive Wave Energy Converter at Oregon State University's Large Wave Flume

Awardee: Ocean Motion Technologies, Inc.

Awardee point of contact: B. Jack Pan

Facility: Oregon State University Large Wave Flume

Facility point of contact: Pedro Lomonaco and Bret Bosma

Date: August 21st 2022

1 EXECUTIVE SUMMARY

Ocean Motion Technologies (OMT) has designed and fabricated a Wave Energy Device (WEC) for the purpose of powering data buoys.

2 INTRODUCTION TO THE PROJECT

Ocean Motion Technologies (OMT) is fabricating the Adaptive Point Attenuator (APA), an improvement on point absorber and attenuator systems, which are well-known wave energy conversion mechanisms in the industry.

Through the support from the TEAMER RFTS 1 and RFTS 2, OMT has set up the WEC-SIM models and produced preliminary results on power output. The current application aims to request for technical support for a wave tank test in order to bridge the gap between simulation and small-scale experimentation. These efforts will aid the ongoing DOE SBIR Phase II Project which will result in a field deployment with the pilot customers. This proposal is requesting support in five areas: experiment planning, pre-experiment logistics support, experiment support during the tank test, post-experiment consultation, and data analysis support.

3 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

3.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

Due to the close integration between applicant and network facilities' responsibilities, please see the description below for both sections 2.1 and 2.2.

3.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED

OMT requests for support to accomplish two weeks of testing in a wave tank. This will be the first experiment OMT has conducted in this environment and the OMT team will travel to the test location. OMT will request support in:

1. Experiment planning: based on the test plan, there will be a series of meetings to create test documents leading up to the experiment. OMT will work with the facility to draft a test plan that will cover all wave conditions and SAPA configuration variations within the two-week period that is being requested.

2. Pre-experiment support: leading up to the two-week experiment, OMT would like to request that the wave tank is set up at least one week prior to testing. OMT would ship key components ahead of the experiment to be installed by the facility. Facility hours are requested for setting up and synchronizing data acquisition systems, and installing mooring systems.

3. Experiment support: During the experiment, we will request facility personnel to operate the wave tank. We will also request personnel to ensure that the data being collected is valid and there are no significant errors that would corrupt the final analysis. The data gathered during the experiment will meet all three of the objectives of this RFTS. We expect the test to last approximately two weeks. During the first week, we will operate the SAPA device in a single configuration while sweeping wave heights and periods to develop a power matrix, and are budgeting 4-6 experiments per day. During the second week, we will vary SAPA geometry and mass parameters, and also include some irregular wave conditions to demonstrate and characterize a broader range of conditions. We expect 2-3 experiments per day during the second week due to increased setup time.

4. Post Experiment Support: To maximize experiment time during the two-week test period, OMT requests that the following week to be used for disassembling the support equipment, including the OMT device for return shipment.

5. Follow-up Data Analysis Support: After the test event, OMT will be mainly responsible for the data analysis. The data from the experiment will be compared to the WEC-SIM model simulations. A gap analysis will be conducted to determine what improvements can be made to the WEC-SIM model to increase its accuracy. OMT requests ongoing, albeit less frequent, support for this effort to ensure OMT will make the correct assumptions and process the data correctly.

4 PROJECT OBJECTIVES

OMT has been testing the SAPA device under a laboratory condition. During the 2020 pandemic lockdown, we have tested the device in swimming pools and off a pier in San Diego Bay. Additionally, the SAPA has been numerically simulated using WEC-Sim. This model is largely speculative and needs to be verified with a quantifiable wave input and experiment data. It is a necessary next step for a test of the SAPA prototype to be conducted in a wave tank so that the OMT team can gain more insights on how the prototype will respond. Through a series of wave inputs and varying the configuration of the SAPA, we will accomplish three objectives:

1. Document the kinematic response of a two-armed configuration of the SAPA in a representative wave spectrum in various configurations.
2. Document the PTO ability to harness power from the representative wave input in various configurations.
3. Select the most efficient configuration for energy harvesting with the wave spectra that closely matches the environment where it will be deployed.

<u>Key parameters that will be measured / generated and how they will map to quantifiable metrics:</u>

1. Kinetic Motion of the device
(a) Qualisys or PhaseSpace Motion capture data of arms and the main buoy.
(b) OMT will have PTO data that is being output. The method of the output can be in several forms, and it would be ideal to have it time-synchronized with the Motion Capture system data. The format of the output can be discussed during Task I.
2. Wave data
(a) The wave height, and frequency would need to be recorded and time-synced with the other data outputs. Three data probes or more for wave sampling is desired.
Note: All data to be time synced for analysis. The data rate desired is 100 Hz. Data rate can be revised depending on the capabilities of the DAQ.

5 Test Facility, Equipment, Software, and Technical Expertise

Test Facility

All testing will be conducted in the Large Wave Flume at Oregon State University's (OSU) O.H. Hinsdale Wave Research Laboratory (HWRL) in Corvallis, Oregon. The flume is 342 feet in length, is 12-foot-wide, 15 feet high and has a maximum depth of 9 feet. The flume's wave maker is a hydraulically actuated piston type wave maker, capable of making regular, irregular, Tsunami, and user defined waves in the range of periods from 1 to 12 seconds. The maximum depth for short wave generation is 2.74 m. It has a carriage for personnel access to instrumentation as well as an overhead gantry crane. Details of the Large Wave Flume and instrumentation available from HWRL can be found here: https://engineering.oregonstate.edu/facilities/wave-lab/facilities .

HWRL staff will be responsible for assisting the client in deploying their model in the facility, performing data capture of wave lab instruments (i.e., wave gauges), and providing synchronization signal(s) for syncing client data acquisition systems. HWRL staff will also be responsible for the operation of the wavemaker and providing the client with HWRL collected data in engineering units.

Wave Gauges

All wave gauges used at the wave basin are custom 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.

Motion Capture System

The HWRL uses Qualisys or PhaseSpace Systems for Motion Capture. Motion Capture (also referred to as mo-cap or mocap) is the process of digitally record the movement of objects non-intrusively. It is used in entertainment, sports, medical applications, ergonomics, robotics, and ocean engineering. Both available systems consist of a series of cameras distributed spatially around the target objects and use advanced algorithms to record the motion of weightless markers placed strategically on the body. Sophisticated post-processing transforms the spatial time series of the markers into 6DOF motions. The accuracy of the measurements is in the order of 1 mm and the time resolution will be synchronized with the wave gauges and wave machine data at 100 Hz.

Data Acquisition and Analysis

The test facility will use NI LabView for data acquisition software and MATLAB for data processing to engineering units. See section 5 for details on Data Management, Processing and Analysis.

Critical Personnel

Bret Bosma will be the point of contact and Project Manager at Hinsdale. He will overview the day-to-day activities of the project, and ensure the timely execution and progress of the project.

Tim Maddux is responsible for the day-to-day operations of the HWRL. He also serves as Safety Officer and will support the different activities along the project.

Rebekah Miller is responsible for laboratory activities, facility, and instrumentation setup. She also serves as a laboratory technician liaison and head of student support.

Pedro Lomonaco is the HWRL Director, with full oversight of the project, providing administrative, scientific, and technical advice.

Permanent and temporary staff at HWRL are 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

Ocean Motion Technologies (OMT) is fabricating the Adaptive Point Attenuator (APA). The APA is an improvement on point absorber and attenuator systems, which are well-known wave energy conversion mechanisms in the marine renewable energy (MRE) industry. The team will create the first commercial artificial intelligence (AI) aided wave energy converter (WEC) that can adapt to ambient sea states. The device uses a set of at least three mechanical arms that are radially positioned to provide omni-directional energy capture and can be integrated with existing ocean buoys and moorings. Each mechanical arm uses a gearbox to convert the wave motion to input for a generator which provides power for onboard instrument payloads. The innovation of the device is the WEC's adaptive capability, which is enabled by a machine learning model trained using reinforcement learning techniques. The learned controller will adjust the Adaptive Point Attenuators arm length and gear ratio accordingly for optimal power output.

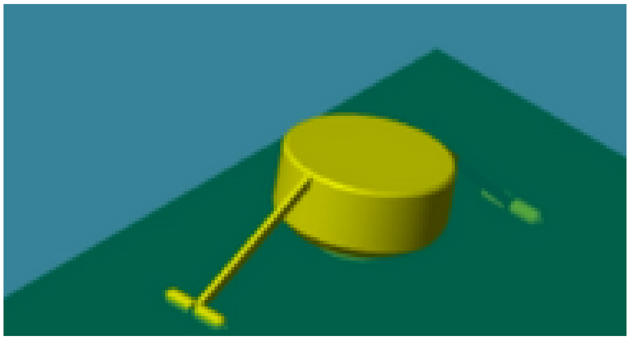
The APA device is intended to be a turn-key solution as an independent power unit that can be directly installed on most oceanographer buoys. This system integration will meet a variety of use cases in the blue economy including scientific data collection, maritime monitoring, offshore aquaculture monitoring, and powering coastal security and defense surveillance applications. Throughout the entire research & development (R&D) phase, the team is working closely with multiple system integrators and original equipment manufacturers (OEMs), who are also the pilot customers for this technology.

The device deployed during RFTS 5 at OSU will be a two-arm version of the three-arm device shown in figure below. This surrogate device will be designed to fit the dimension of the facility wave tank and also restrict the lateral motion as well as the roll and yaw axes, so that the device does not collide with the walls of the test tank. The facility will be invited to review the preliminary design of the surrogate device and participate in critical design reviews leading up to the final test.

Conceptual full-scale device

One-arm tested platform

Conceptual two-arm device for the wave tank test



Dimensions of full-scale buoy base:

https://www.nexsens.com/pdf/CB1250_drawings.pdf

Anticipated Test Article Dimensions:

Height: 2 meters, approximately 1 meter submerged

Length: 3-5 meters

Width: Not to exceed 2 meters including mooring connections

Dry weight: 200+ lbs

Description of anticipated test article: The OMT team will mount two sets of opposed arms connected to the PTO drive train on top of a NexSens buoy. We are targeting a NexSens CB1250 to match future field deployment requirements from the customers but can also select a smaller model for a scaled-down geometry if necessary.

7 Work Plan

The flume will be prepared with a 1:12 beach, wave gauges, mooring connections, and client supplied mooring lines, prior to filling. Once filled to a water depth of 2.743 m (9 feet) the device will be deployed and connected.

7.1 Experimental Setup, Data Acquisition System, and Instrumentation

At least three wave gauges will be deployed to measure incident and transmitted waves on the structure. All instruments will be connected to a main HWRL Data Acquisition System (DAQ). Additional channels include the flume water level, the board position, the board free surface, a

NIST traceable pressure gauge located just in front of the wave machine, a random LED signal used to synchronize with auxiliary DAQ systems, and other control signals for QA/QC. The minimum sampling rate will be 100 Hz, and each experiment will be comprised with not less than 50 regular waves or 300 irregular waves.

Additionally, a motion tracking system, either by Qualisys or PhaseSpace will be deployed for measuring body motions. Synchronization channels will be deployed accordingly.

Passive (Qualisys) or Active (PhaseSpace) markers will be fixed on the different parts of the device so the cameras will be able to capture and reconstruct its motions while subject to the wave action. A reference frame will be also fixed in the flume walls to provide a reference and allow the calibration procedure of the system.

7.2 Test and Analysis Matrix and Schedule

General Activities

- Operation of facility sensors and DAQ during the experiment
    - Validation of data as it is being recorded.
- Receiving the OMT SAPA device and setting up the experiment
    - The details of which components of the SAPA can be set up without OMT will be discussed leading up to the event. OMT will be mainly responsible for the setup, assistance will be required from the facility for deployment.
- Disassembling the OMT SAPA device and shipping to a designated location
    - Details of what components the facility will disassemble to be determined at a later date.
    - OMT will be mainly responsible for disassembly but request help from the facility.
- Data analysis to convert the recorded data to engineering units
- Document the kinematic response of a two-armed configuration of the SAPA in a representative wave spectrum in various configurations.
- Document the PTO ability to harness power from the representative wave input in various configurations.
- Select the most efficient configuration for energy harvesting with the wave spectra that closely matches the environment where it will be deployed.

<u>Key parameters that will be measured / generated and how they will map to quantifiable metrics:</u>

1. Kinetic Motion of the device

    (a) Camera Capture with scales so that the kinetic motion can be observed and quantified:

    (i) Cameras on the buoy pointed toward each arm or a 360-degree camera placed in the middle.

    (ii) A camera perpendicular to the device and waves mounted outside the wave tank. Scales would be behind the device and waves for quantification.

    (iii) OMT will be responsible for camera capture. Assistance with the initial setup is ideal.

(b) Motion capture data of arms and main Buoy:

(i) Using the Qualisys or Phase Space motion capture device record 6-degree of motion of the device and how it responds to wave inputs.

(ii) The facility will assist with the selection and set up of the motion capture device power output.

(c) OMT will have PTO data that is being output. There are back EMF sensors for speed as well as voltage and current sensors built into the device. These parameters will monitor the drive train functionality as well as the power production.

General Schedule

- Use of a wave tank for a period of four weeks, including setup, testing, and disassembly.
- Operation of the wave tank during the testing period
    - Each test will last 5 to 10 minutes, depending on the chosen wave period
    - Detailed experiments and duration are as follows

Week 1	
Day 1	Receive shipment
Day 2	Unboxing and set up
Day 3	On board instrumentation set up
Day 4	Trial Run
Day 5	Flex day
Week 2	
Day 1	Regular wave tests Test 1 -- 0.25 m wave height 5 second period Test 2 -- 1.5 m height 3 second period Test 3 -- 0.75 m height 4 second period
Day 2/3	Complete Table 2 shown below for irregular waves in order of numbered priority. 8 to 15 tests per day
Day 4	Test the adaptive torque feature using Table 1 for regular wave case
Day 5	Test the adaptive torque feature using Table 2 for irregular wave case

Week 3	
Day 1	Reconfigure gear boxes Regular wave tests Test 1 -- 0.25 m wave height 5 second period Test 2 -- 1.5 m height 3 second period Test 3 -- 0.75 m height 4 second period
Day 2/3	Complete the Matrix of test cases in Table 2 below for irregular waves. 8 to 15 tests per day
Day 4	Test the yellow portions of the matrix in Table 2. The wave conditions (wave height and period) will be based on the results observed during the previous experiments. Estimated 6 tests.
Day 5	Flex day.
Week 4	
Day 1	Disassembly of equipment
Day 2	Disassembly of equipment
Day 3	Packaging
Day 4	Transport to shipping
Day 5	Ship to San Diego

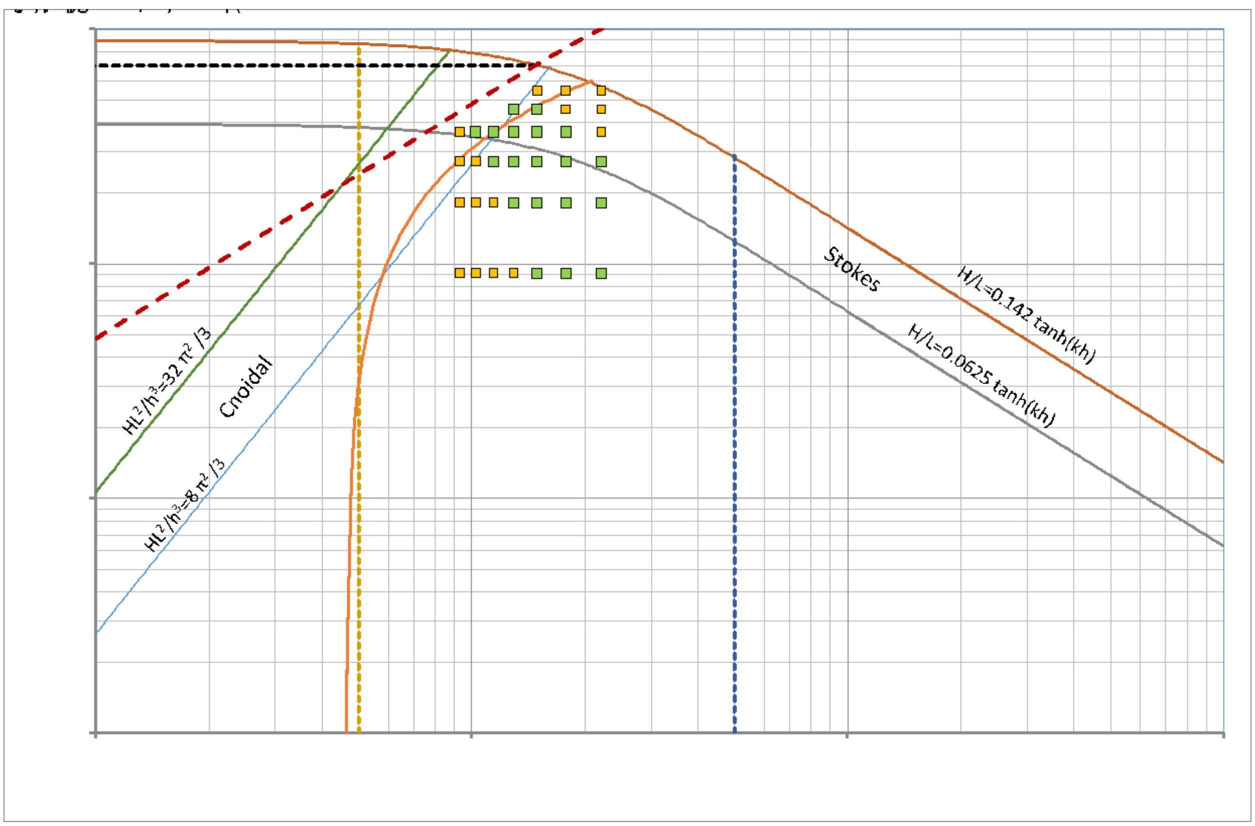
Table 1 Regular waves Matrix. Numbers within the boxes indicate priority order. Wave conditions in yellow are extra tests pending on the results of tests marked in green. Wave conditions marked in red are not feasible.

	Wave Period (seconds)							
Wave Height (meters)		3	3.5	4	4.5	5	5.5	6
	0.25	1	3	4				
	0.5	5	6	7	8			
	0.75	9	10	11	12	13		
	1		14	15	16	17	18	
	1.25			19	20			
	1.5				2			

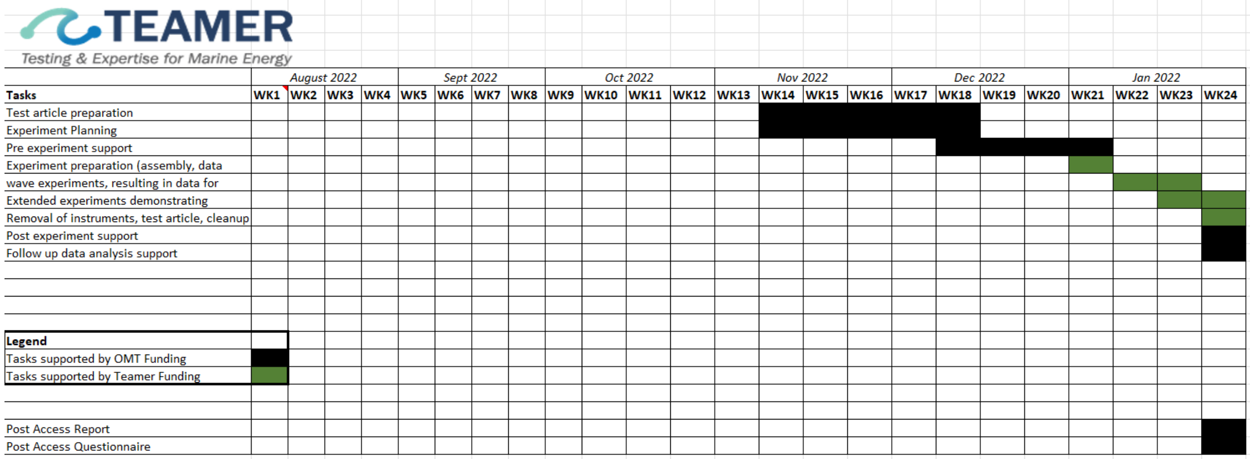
Table 2 Irregular Waves Matrix. Numbers within the boxes indicate priority order

	Wave Period (seconds)							
		3	3.5	4	4.5	5	5.5	6
Wave Height (meters)	0.25	1	3	4				
	0.5	5	6	7	8			
	0.75	9	10	11	12	13		
	0.9		14	15	16	17	18	2

The following figure presents the proposed baseline regular wave conditions to be executed in dimensionless form in Table 1. It incorporates also the theoretical limits of different wave theories, including the breaking limit due to wave steepness and depth limitations.



7.3 Test and Analysis Matrix and Schedule



7.4 Safety

The applicant and OSU facility staff will follow all relevant safety procedures and protocols outlined in the HWRL Safety Plan 2021. 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. 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 will undergo a specific and documented Safety Training, reviewing general safety procedures, rules and hazards. Temporary visitors will use yellow safety vests for best identification and awareness, and should use safety shoes at all times while working on the laboratory floor. Other safety protocols will be reviewed with the client during the Safety Training.

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

7.5 Contingency Plans

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

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

Failure of Prototype

Although it is unlikely to occur, complications in handling the prototype could result in damage to the floating test article. Should a failure of the model occur replacement parts and/or repair methods will be available should they be needed. The test article structural design and integrity is managed by the developer, who will take all countermeasures to prevent its failure or it's expedited repair. A significant delay produced by the failure or damage of the device may prevent the continuation of the experiments which will be rescheduled in consultation with the developer and TEAMER.

Failure of Sensors

Although it is unlikely to occur, complications during handling or installing the sensors could result in damage to a sensor. For this reason, we are not utilizing the full amount of sensors in the facilities possession to enable backup sensors. Replacement of HWRL standard sensors is relatively fast and the staff is prepared and trained to do it. Failure of the on-board sensors is managed by the developer, who will take all countermeasures to prevent its failure or it's expedited replacement. A significant delay produced by the failure of the on-board sensors may prevent the continuation of the experiments which will be rescheduled in consultation with the developer and TEAMER.

COVID-19 Complications

To prevent complications that may occur due to contracting COVID-19, all participants in the project will be requested to be fully vaccinated. All CDC COVID-19 guidelines will be adhered to the best of our ability to prevent such complications. Contact tracing will occur in the event that our contacts receive a positive COVID-19 test.

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

Wildfires

Recently, wildfires and extreme natural events have been identified as hazards that might impact the testing schedule. HWRL will adhere to OSU guidelines while air quality or specific measures are taken in the event of such events. HWRL will enforce following those restrictions, while work diligently with the authorities to resume operations in an expedite way.

7.6 Data Management, Processing, and Analysis

7.6.1 Data Management

- Data is to be stored locally at OSU and on hard drive backup. Raw and processed data will additionally be compressed and zipped onto Box. A ReadMe file for the data describing the data will be included with all data files. Processing of data will be conducted at OSU the day following a drain calibration of wave gauges.
- OSU has a server that will house the data on their end. They also will have a hard drive backup. At the end of the project, they will lock the directory and archive it (read only). Raw data file and raw data in engineering units will be transferred to MHK DR and then processed on site the following day.
- Raw Data: Surface elevation at wave gauge locations.
- Processed Data: Free surface elevations, wave height, wave period.
- 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.

Data to be submitted	Data types
motion capture data	ASCII logs and plots
video data	video files
power production data and drive train data	ASCII logs and plots
wave data	ASCII logs and plots

7.6.2 Data Processing

Data will be processed using MATLAB code and will be processed at OSU and OMT in between tests to enable quality assurance in the event of signal errors.

Calibration data will be provided for each sensor to address uncertainties and quantify. Repeating a standard calibration test in specific wave conditions will enable us to quantify additional uncertainties. Additionally, as we are repeating wave conditions while testing the floating test article, the results will provide a way to quantify uncertainties even further.

7.6.3 Data Analysis

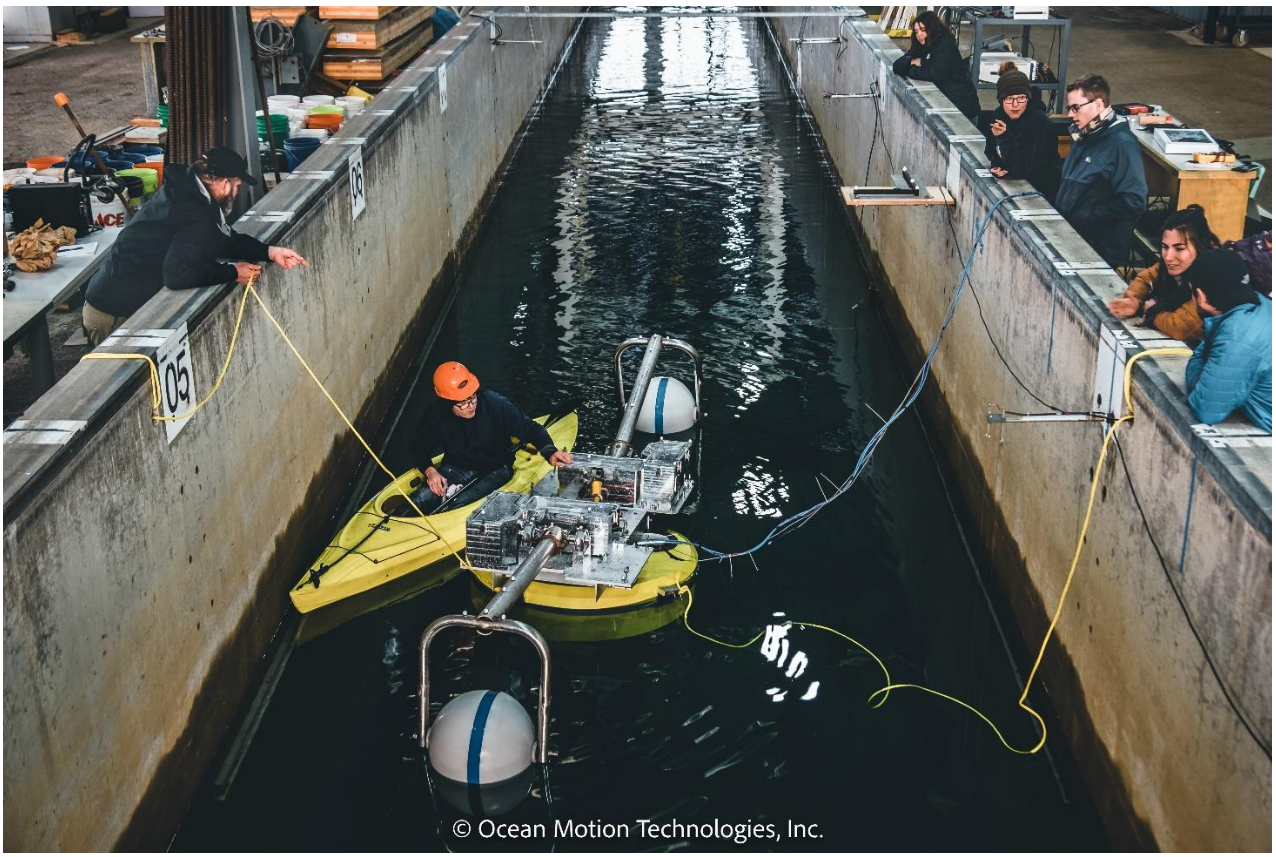
Data analysis will be performed by OMT, preprocessing of the motion capture data to be performed by OSU. All data will be from experimental tests. There is no plan to manipulate the data. The data gathered will be for validation purposes. There is no plan to eliminate data unless there is a failure in the sensor system. By gathering the wave data, motion data and power production data this will validate that the device designed will work in the initial trials at sea and produce enough energy to charge batteries over time. Any positive power production over time would be considered a successful experiment.

8 Project Outcomes

○ 8.1 Results

○ 8.1.1 Test work up 3 Jan 23 - 13 Jan 23

OMT arrived at OSU on the scheduled date of 3 JAN 2023. The first week was utilized for planning configuration of the wave tank and setting up the sensors. Additionally, there were some modifications that were needed and the second week was spent on making those modifications to the WEC. While the modifications were made, we conducted weights, CG, and moments of inertia measurements on the available/unmodified components as shown in the figures below. These measurements aid the WEC-SIM team that will start their gap analysis in RTFS 6.

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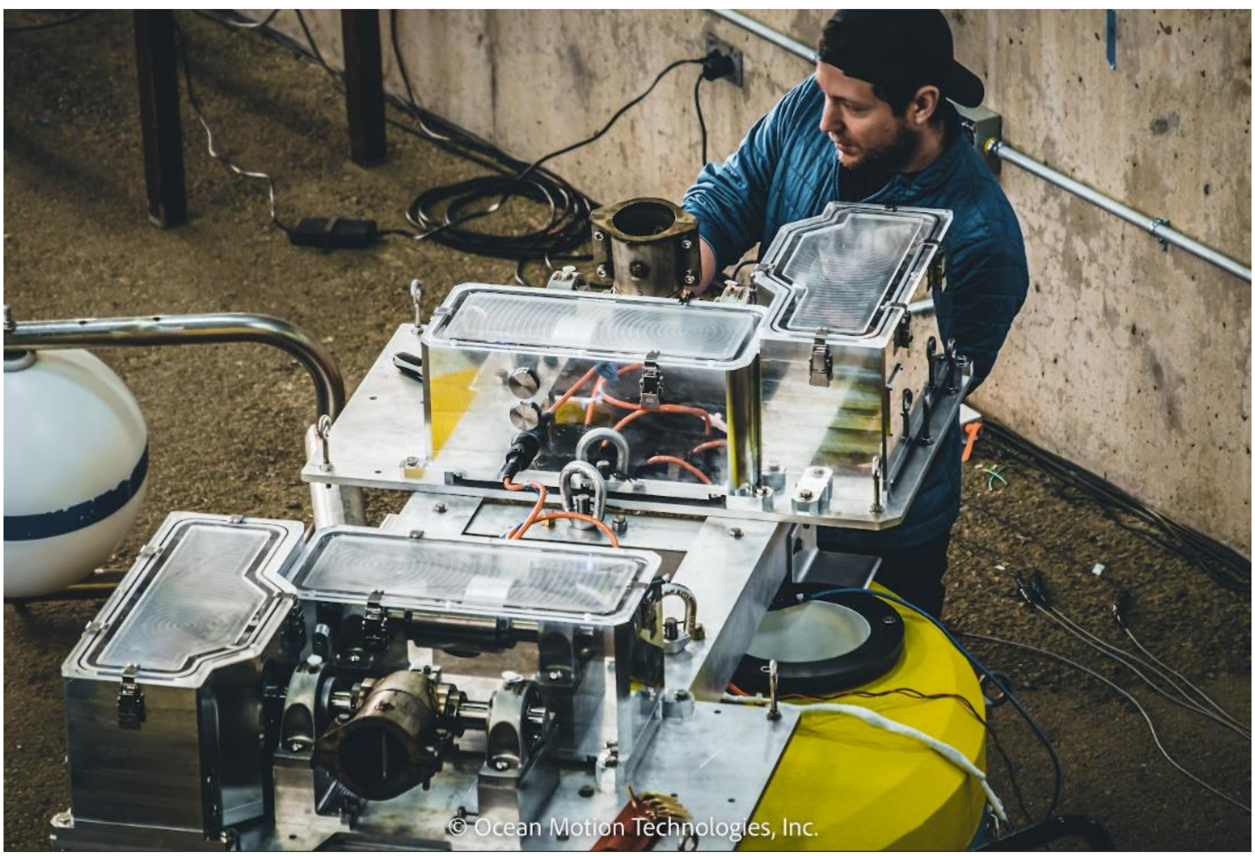
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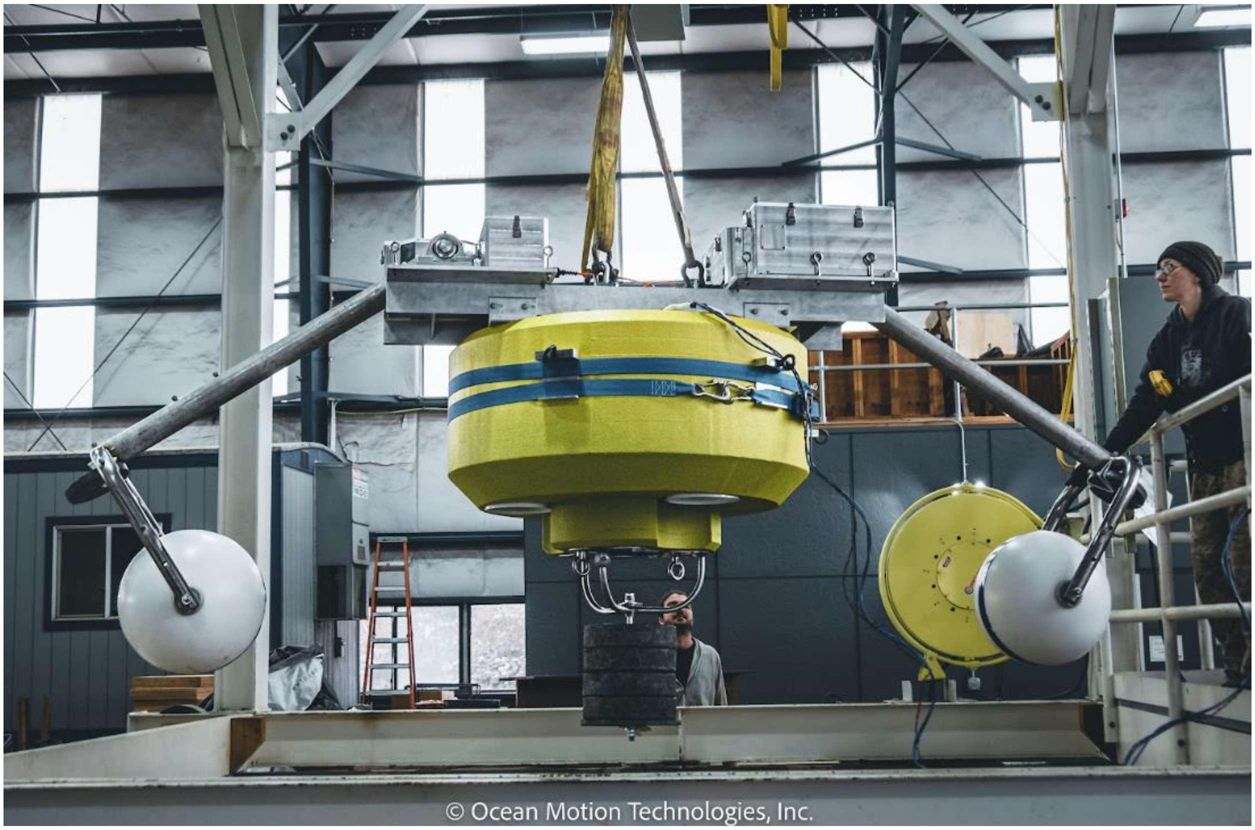
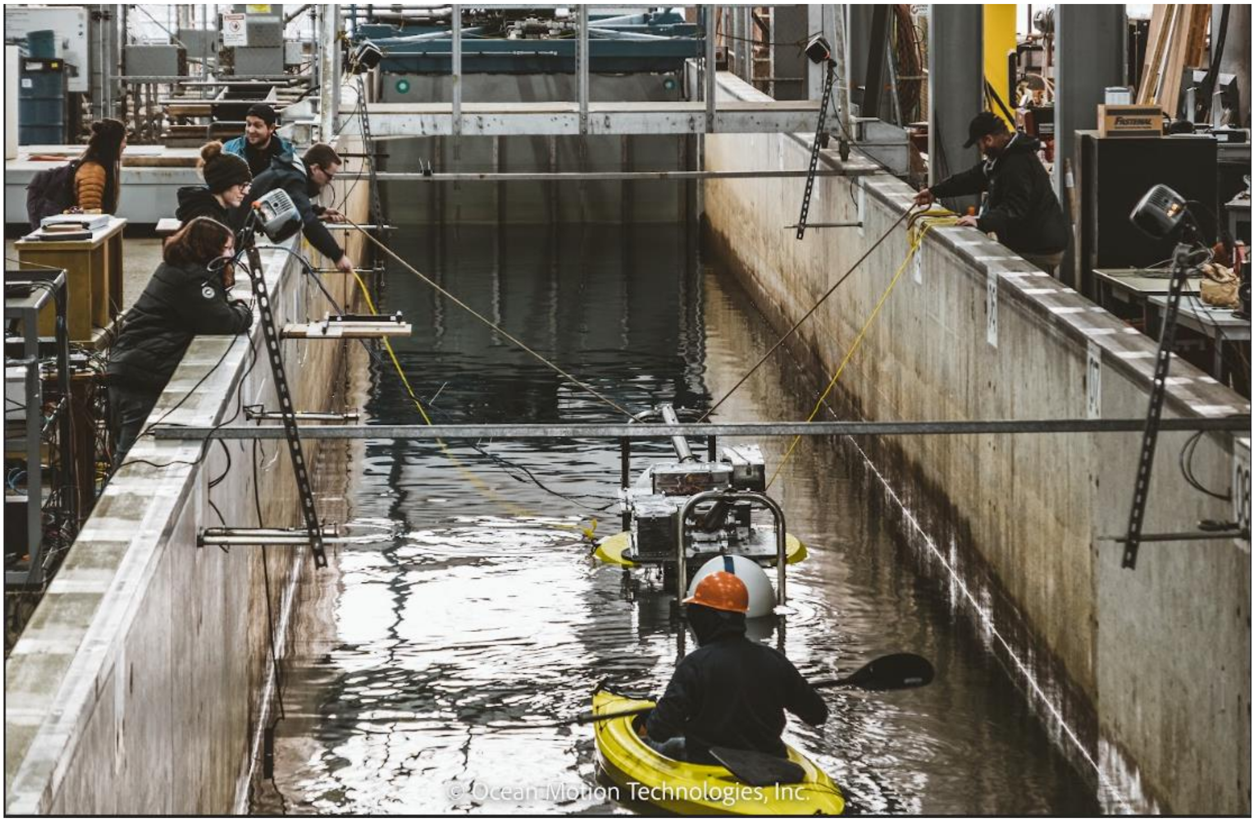
○ 8.1.2 Testing performed 17 Jan 23 - 20 Jan 23

Shown below is the start of the wave tank test, which occurred on 17 Jan 2023. The ballast and positioning of the WEC took most of the first day.

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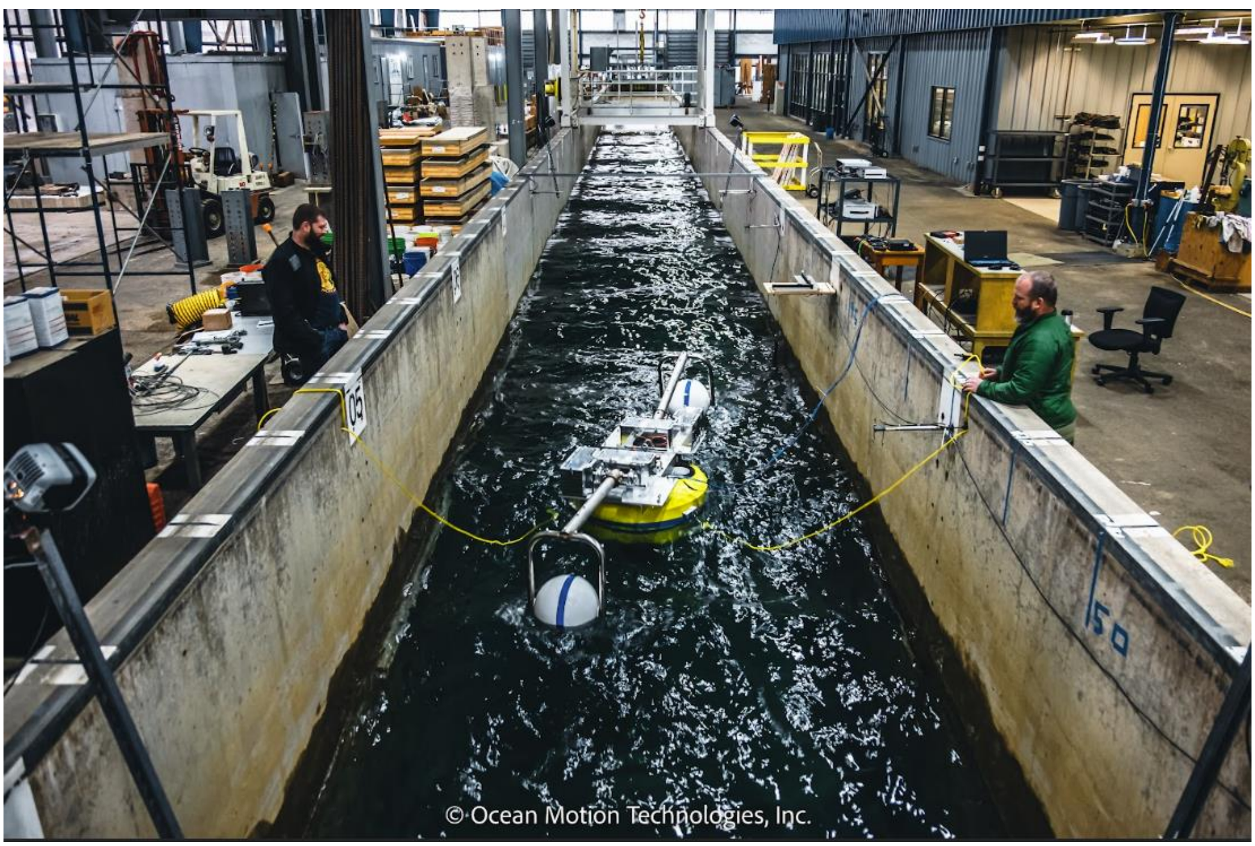
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The table below shows the date/time, and file names of all the tests that were performed during the initial week of testing. The OSU trial numbers refer to the OSU data acquisition unit (DAQ) file names; the corresponding file names from OMT are also listed. If file name is not present, it indicates that the buoy was not turned on and we were gathering unloaded data.

	Regular wave					
	Random wave					
Day of January 2023	**Regular or Random Wave**	**H (m)**	**T (s)**	**OSU Trial Number for that day/wave type**	**Start time**	**OMT DAQ filename**
17	Regular	0.25	5.0	01	15:04	N/A
17	Regular	0.35	5.0	02	15:22	N/A
17	Regular	0.35	4.5	03	15:32	N/A
17	Regular	0.45	4.5	04	15:40	N/A
17	Regular	0.45	3.5	05	15:48	N/A
17	Regular	0.35	2.5	06	15:56	OSU_1_17_2023_1555 OSU_1_17_2023_1556
17	Regular	0.35	2.0	07	16:06	OSU_1_17_2023_1605
17	Regular	0.25	1.75	08	16:24	OSU_1_17_2023_1623
17	Regular	0.25	1.75	09	16:34	OSU_1_17_2023_1631
17	Regular	0.25	1.50	10	16:40	OSU_1_17_2023_1639
17	Regular	0.20	1.25	11	16:48	OSU_1_17_2023_1645
18	Regular	0.35	2.0	01	10:21	OSU_1_18_2023_1020_combined
18	Regular	0.35	2.0	02	10:26	OSU_1_18_2023_1024
18	Regular	0.25	2.0	03	15:14	OSU_1_18_2023_1515
18	Regular	0.25	1.75	04	15:24	OSU_1_18_2023_1523
18	Regular	0.25	3.0	05	15:30	OSU_1_18_2023_1530
18	Random	0.15	2.0	01	10:44	OSU_1_18_2023_1043
18	Random	0.20	2.0	02	11:02	OSU_1_18_2023_1100_co

						mbined
18	Random	0.25	2.0	03	11:19	OSU_1_18_2023_1118
18	Random	0.30	2.0	04	11:30	OSU_1_18_2023_1129
18	Random	0.30	2.5	05	11:47	OSU_1_18_2023_1145
18	Random	0.30	3.0	06	14:15	OSU_1_18_2023_1409_combined
18	Random	0.20	1.75	07	14:32	OSU_1_18_2023_1430
18	Random	0.25	1.75	08	14:44	OSU_1_18_2023_1445
18	Random	0.30	1.75	09	14:58	OSU_1_18_2023_1459
18	Random	0.35	1.75	10	15:41	OSU_1_18_2023_1538
18	Random	0.40	5.0	11	15:59	OSU_1_18_2023_1558
18	Random	0.60	5.0	12	16:18	OSU_1_18_2023_1615
19	Regular	0.35	2.00	01	10:22	test19Jan_1021
19	Regular	0.35	2.00	02	10:34	test19Jan_1032
19	Regular	0.35	2.00	03	10:50	test19Jan23_1049
19	Regular	0.35	2.00	04	11:01	test19Jan23_1101
19	Regular	0.35	2.00	05	11:12	test19Jan23_1111
19	Regular	0.35	2.00	06	11:25	test19Jan23_1124
19	Regular	0.35	2.00	07	11:39	test19Jan23_1137
19	Regular	0.35	2.00	08	11:51	test19Jan23_1150
19	Regular	0.35	2.00	09	13:15	test19Jan23_1304_combined
19	Regular	0.35	2.00	10	13:26	test19Jan23_1326
19	Regular	0.25	1.75	11	13:35	test19Jan23_1334_combined
19	Regular	0.25	1.75	12	13:48	test19Jan23_1345
19	Regular	0.25	1.75	13	13:54	N/A
19	Regular	0.25	1.75	14	14:44	N/A
19	Regular	0.35	2.00	15	14:51	N/A
19	Random	0.700	6.000	01	15:28	N/A
19	Random	0.70	6.0	02	15:34	test19Jan23_1533_combined

19	Random	0.60	4.5	03	16:04	test19Jan23_1603_combined
20	Random	0.75	6.0	01	9:36	test20jan23_0935_combined
20	Random	0.45	2.25	02	11:05	test20jan23_1106_combined
20	Random	0.50	2.5	03	11:29	test20jan23_1128_combined
20	Random	0.60	3.5	04	11:44	test20jan23_1143_combined
20	Random	0.55	3.0	05	13:11	test20jan23_1310_combined

8.1.3. Power Matrix and Control System Tuning

During the third week of testing, we completed a power matrix and tune the control system – a major goal of the wave tank test. The power matrices below were gathered from the generator controllers and the peak mechanical wattage measured are shown. The system was found to be less dynamic than expected, resulting in restricted arm motion. The solution is to add buoyancy to the end of the arms and the main float, as well as add weight to the arms overall. We also immediately noted that the existing pressure casings were excessively heavy, and their masses will be reduced. We speculated and anticipated these changes based on our initial analyses of laboratory and simulation results.

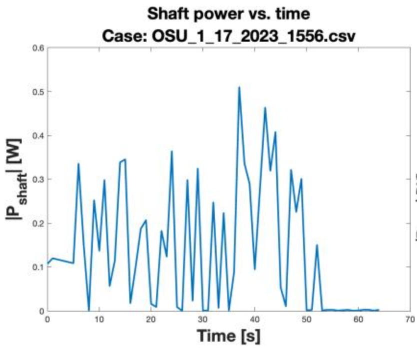
The second major goal of the wave tank tests was to tune the control system for its optimal performance. To complete this objective, we first found an optimal range when the WEC was producing consistent power. This range was found to be a period of 2 seconds and a wave height of 0.35 approximately.

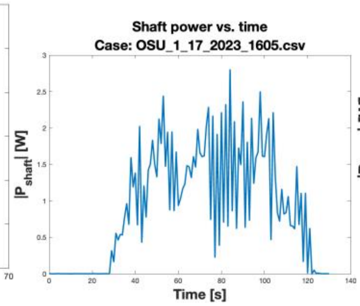
Power Matrix For Regular Waves		T (s)					
		1.25	1.5	1.75	2	2.5	3
H (m)	0.15						
	0.2	0.473					
	0.25		1.838	2.439	0.745		0.005
	0.35				3.491	0.510	

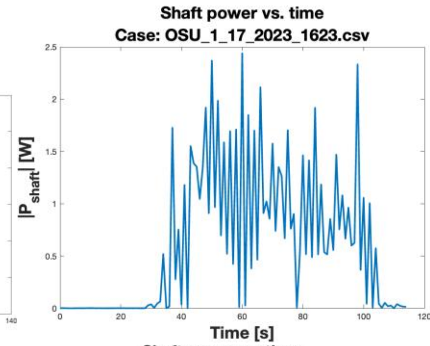
Once the control system is tuned, then the WEC is subject to more realistic wave conditions (e.g., random waves). While our first field site will be the Puget Sound, we decided to test a larger range to assess any significant differences with a tuned control system. Indeed, we found a greater power output, but this output needs some averaging; the fly wheel was intended to carry out this averaging mechanically, but we found that there is too much friction in the system for the flywheel subsystem. We will be adding a capacitor bank instead. Overall, we found satisfactory results and we have a list of to-do items that will make our deployment at sea a success in August 2023.

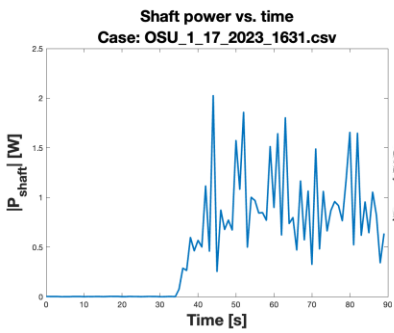
Power Matrix For Random Waves		T (s)								
		1.75	2	2.25	2.5	3	3.5	4.5	5	6
H (m)	0.15		0.914							
	0.2	0.893	0.931							
	0.25	0.820	1.290							
	0.3	0.181	1.207		1.374	0.971				
	0.35	1.308								
	0.4								0.739	
	0.45			3.472						
	0.5				4.123					
	0.55					4.103				
	0.6						3.911	0.664	2.059	
	0.65									
	0.7									2.826
	0.75									2.544

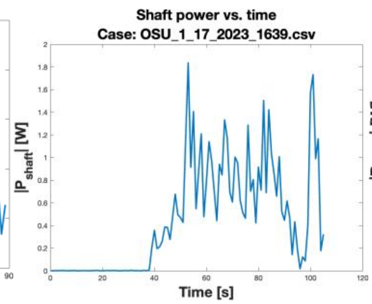
The following graphs were selected to present the results that were the most helpful for completing our power matrix as well as tuning the control system. Not all graphs are shown in this report, but all graphs and raw data will be uploaded and shared according to TEAMER requirements and guidelines. Please note no post-processing was conducted for these graphs – they are merely plots retrieved directly from the controller boards. If there were data gaps during a test (e.g., data acquisition was unintentionally shut off), the final data output from that test were combined and noted in file names within the master log.

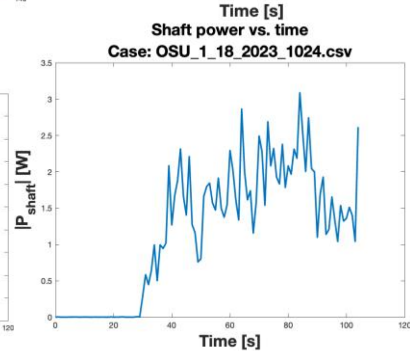

Shaft power vs. time
Case: OSU_1_17_2023_1556.csv
|Pshaft| [W]
Time [s]

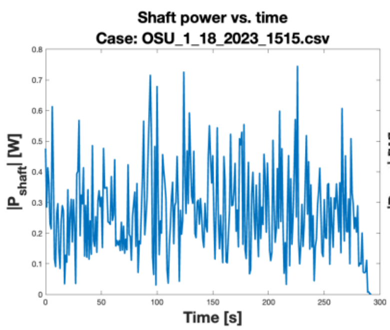

Shaft power vs. time
Case: OSU_1_17_2023_1605.csv
|Pshaft| [W]
Time [s]

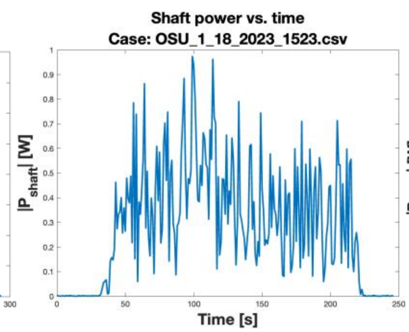

Shaft power vs. time
Case: OSU_1_17_2023_1623.csv
|Pshaft| [W]
Time [s]

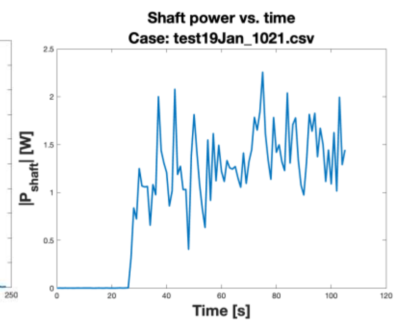

Shaft power vs. time
Case: OSU_1_17_2023_1631.csv
|Pshaft| [W]
Time [s]

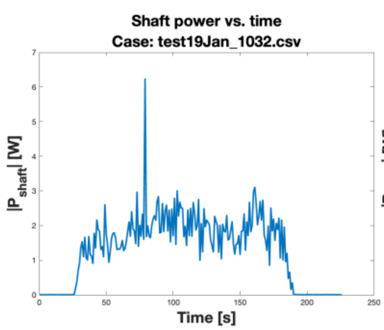

Shaft power vs. time
Case: OSU_1_17_2023_1639.csv
|Pshaft| [W]
Time [s]

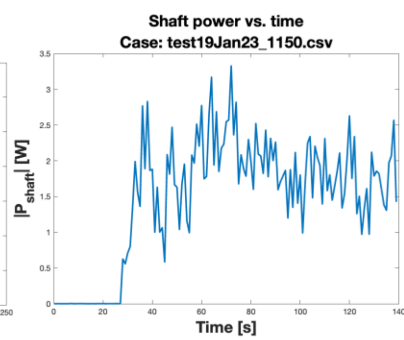

Shaft power vs. time
Case: OSU_1_18_2023_1024.csv
|Pshaft| [W]
Time [s]

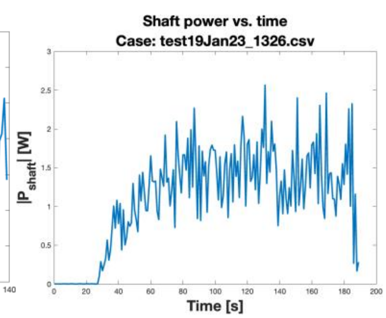

Shaft power vs. time
Case: OSU_1_18_2023_1515.csv
|Pshaft| [W]
Time [s]

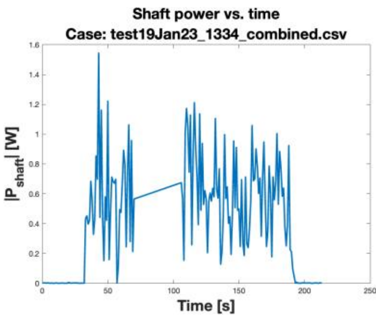

Shaft power vs. time
Case: OSU_1_18_2023_1523.csv
|Pshaft| [W]
Time [s]

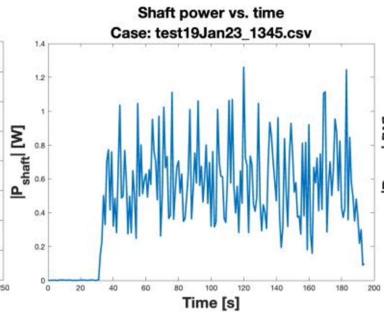

Shaft power vs. time
Case: test19Jan_1021.csv
|Pshaft| [W]
Time [s]

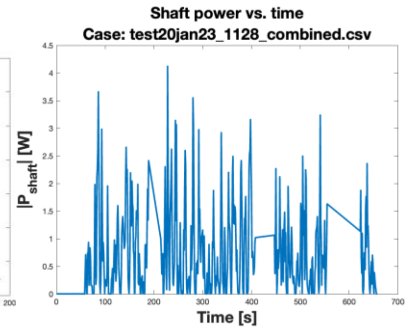

Shaft power vs. time
Case: test19Jan_1032.csv
|Pshaft| [W]
Time [s]

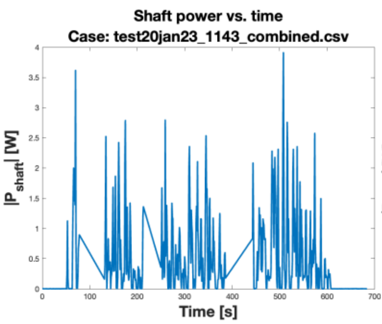

Shaft power vs. time
Case: test19Jan23_1150.csv
|Pshaft| [W]
Time [s]

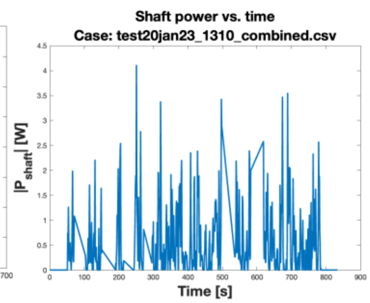

Shaft power vs. time
Case: test19Jan23_1326.csv
|Pshaft| [W]
Time [s]





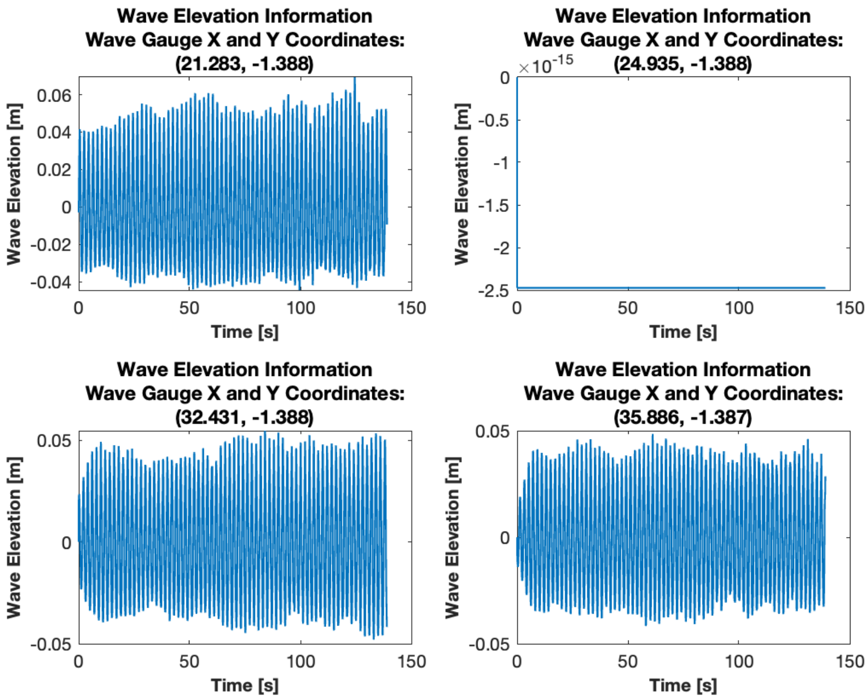


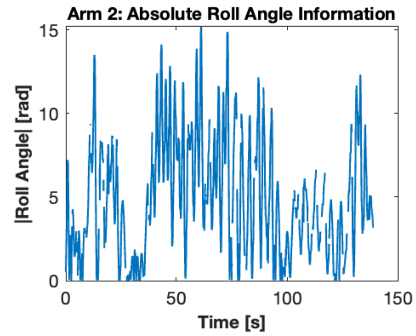


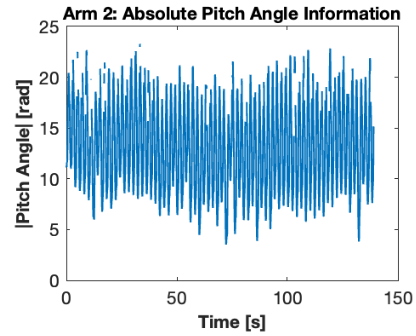


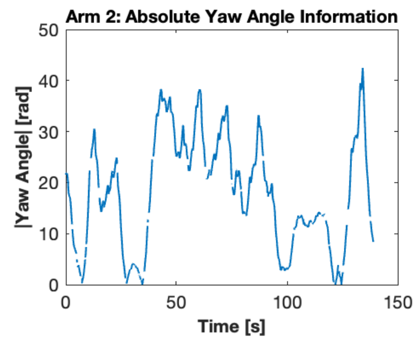
○ 8.1.3 Full Data Set 19 JAN 23 1150

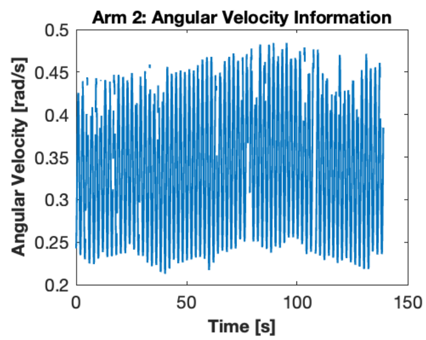
OMT used several environmental sensors including wave gauges, and motion detectors during the test to provide a full input, motion, and output dataset. This dataset will be used in RTFS 6 to evaluate the performance of the WEC-SIM simulations that have led up our current design. The results will also serve as an input to improve WEC-Sim and allow better predictions of our WEC performance for the field deployment (as part of a separate Phase II Project). The plots presented here are all raw output results obtained by OMT. There are some anomalies in this dataset that still require further investigation. It was known that one of the wave gauges malfunctioned during the test, so some datasets had results from 3 gauges while others had 4.

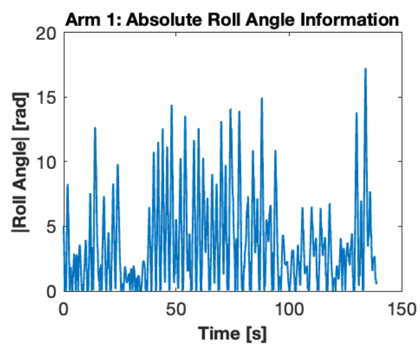

Wave Elevation Information
Wave Gauge X and Y Coordinates:
(21.283, -1.388)
Wave Elevation [m]
Time [s]
Wave Elevation Information
Wave Gauge X and Y Coordinates:
(24.935, -1.388)
×10-15
Wave Elevation [m]
Time [s]
Wave Elevation Information
Wave Gauge X and Y Coordinates:
(32.431, -1.388)
Wave Elevation [m]
Time [s]
Wave Elevation Information
Wave Gauge X and Y Coordinates:
(35.886, -1.387)
Wave Elevation [m]
Time [s]

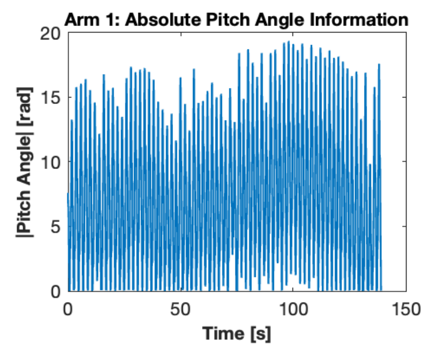

Arm 2: Absolute Roll Angle Information
|Roll Angle| [rad]
Time [s]

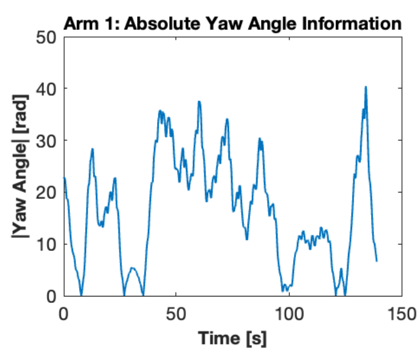

Arm 2: Absolute Pitch Angle Information
|Pitch Angle| [rad]
Time [s]

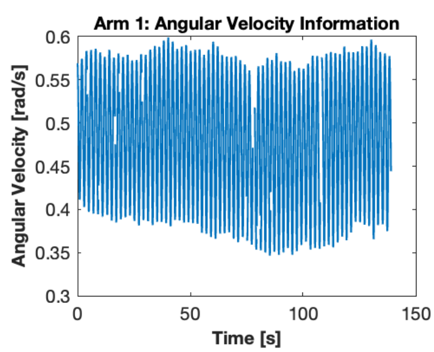

Arm 2: Absolute Yaw Angle Information
|Yaw Angle| [rad]
Time [s]

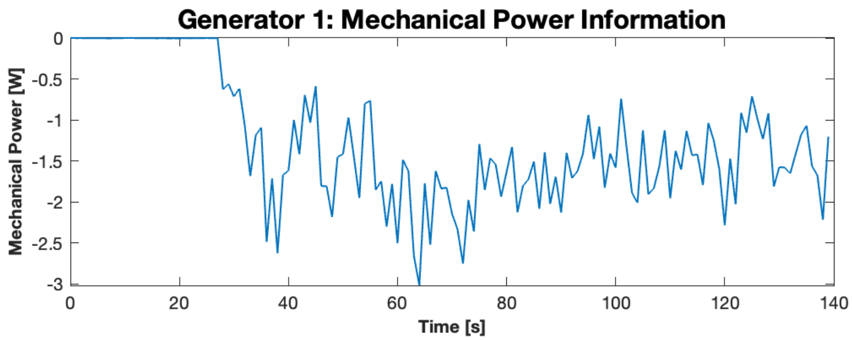

Arm 2: Angular Velocity Information
Angular Velocity| [rad/s]
Time [s]

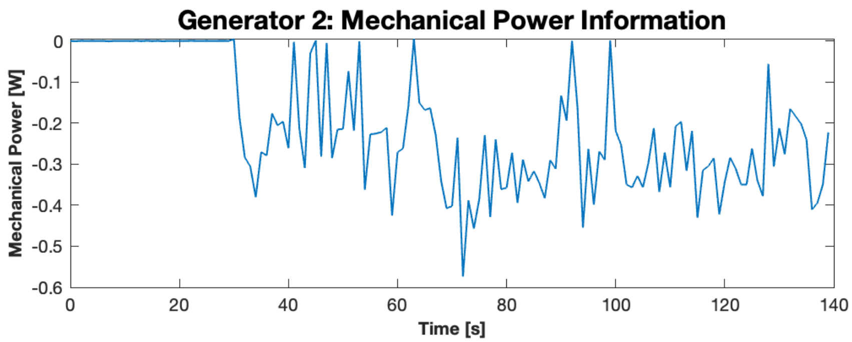

Arm 1: Absolute Roll Angle Information
|Roll Angle| [rad]
Time [s]

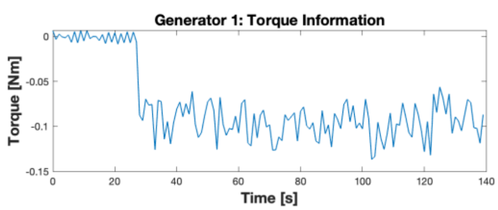

Arm 1: Absolute Pitch Angle Information
|Pitch Angle| [rad]
Time [s]

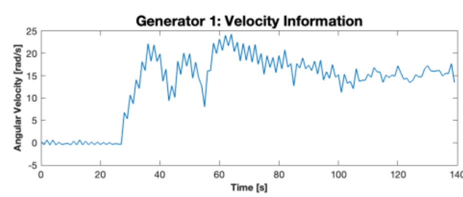

Arm 1: Absolute Yaw Angle Information
|Yaw Angle| [rad]
Time [s]

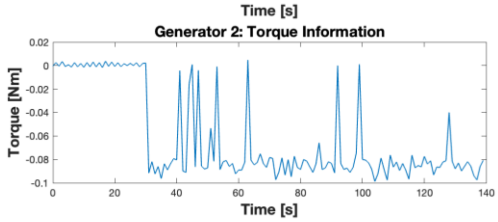

Arm 1: Angular Velocity Information
Angular Velocity| [rad/s]
Time [s]

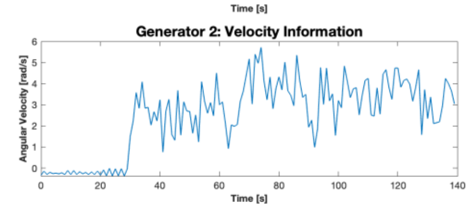

Generator 1: Mechanical Power Information
Mechanical Power [W]
Time [s]

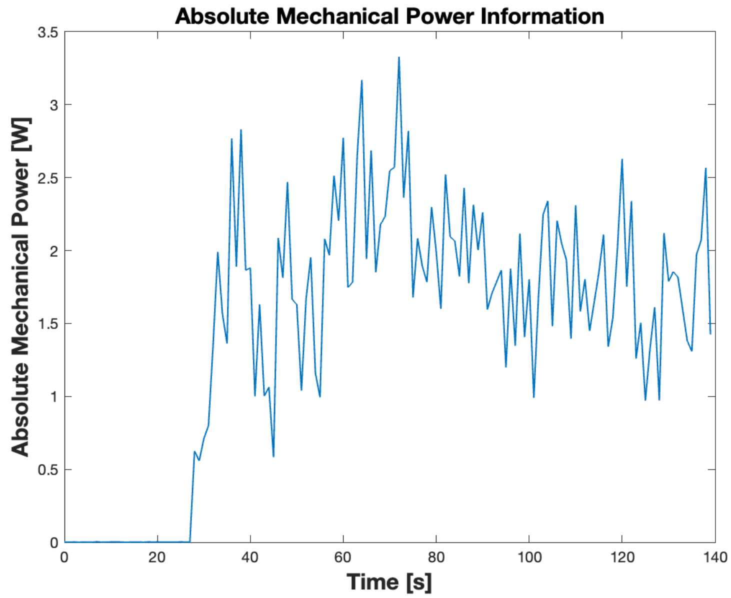

Generator 2: Mechanical Power Information
Mechanical Power [W]
Time [s]

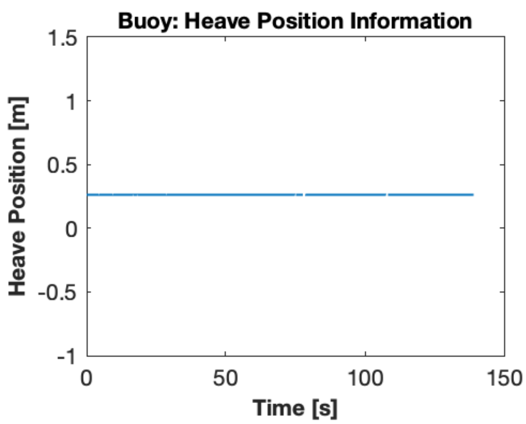

Generator 1: Torque Information
Torque [Nm]
Time [s]

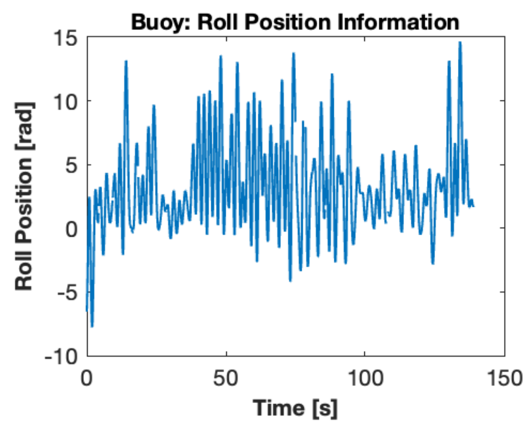

Generator 1: Velocity Information
Angular Velocity [rad/s]
Time [s]

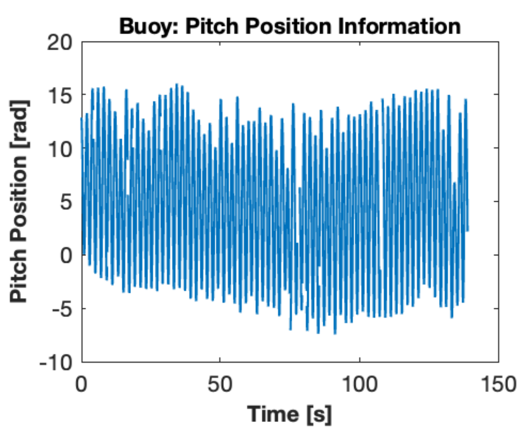

Generator 2: Torque Information
Torque [Nm]
Time [s]

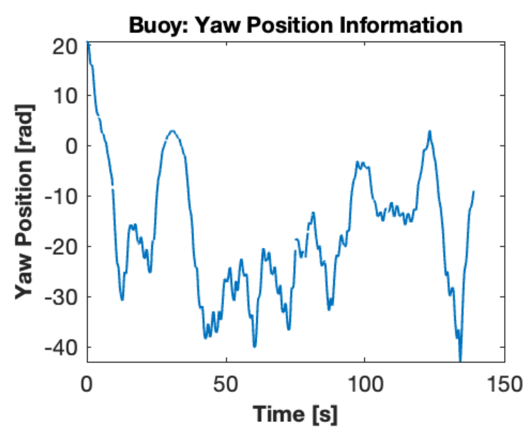

Generator 2: Velocity Information
Angular Velocity [rad/s]
Time [s]


Absolute Mechanical Power Information
Absolute Mechanical Power [W]
3.5
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
Time [s]


Buoy: Heave Position Information
Heave Position [m]
1.5
1
0.5
0
-0.5
-1
0
50
100
150
Time [s]

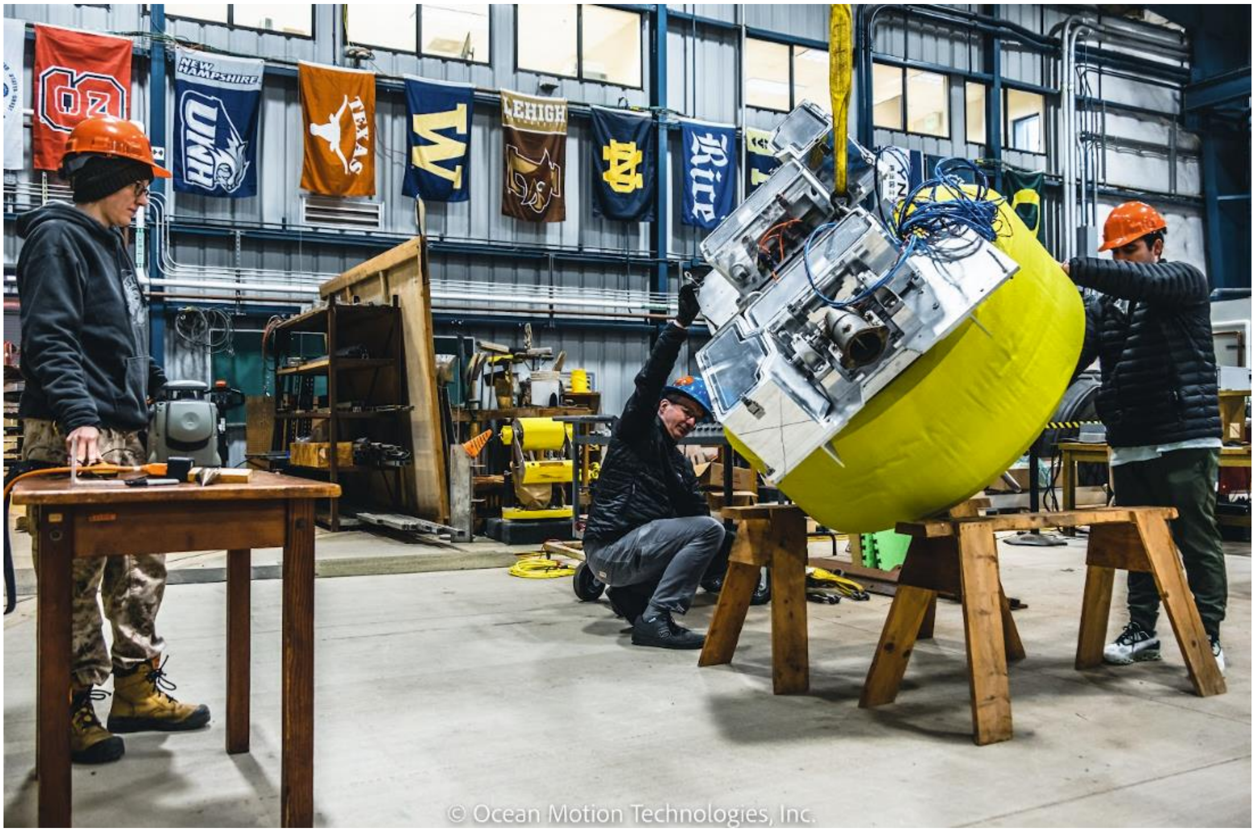

Buoy: Roll Position Information
Roll Position [rad]
15
10
5
0
-5
-10
0
50
100
150
Time [s]


Buoy: Pitch Position Information
Pitch Position [rad]
20
15
10
5
0
-5
-10
0
50
100
150
Time [s]


Buoy: Yaw Position Information
Yaw Position [rad]
20
10
0
-10
-20
-30
-40
0
50
100
150
Time [s]

- ### 8.1.5 Ancillary measurements and mobilization 23 Jan 23 - 27 Jan 23

During the last week of our test, the flume was drained and ancillary measurements of the device were conducted including CG in the Z axis and the moment of inertia in the pitch and roll axes.



8.4 Lesson Learned and Test Plan Deviation

A significant deviation was observed in the actual power matrix as compared to the initially conceived matrix. The test plan had anticipated testing the Wave Energy Converter (WEC) with steep waves, a circumstance which would have likely jeopardized both the integrity of the WEC and the wave tank walls. To address this, we swiftly adapted our approach by initiating the tests with waves of lower amplitude, gradually escalating to an optimal wave range that was both safe and efficient for our testing requirements.

An important lesson we learned relates to the production and fit check of machined components. To accommodate for potential alterations, these machined components should be assessed and validated a few weeks prior to the scheduled test. Further, the decision to conduct the test immediately after the New Year holiday proved sub-optimal to our timeline due to the ensuing shipment delays to the test facility. For future tests during winter, it would be more suitable to begin at least a week after the holiday season, ensuring that the same test duration can be effectively managed.

9 Conclusions and Recommendations

The wave tank test conducted under RFTS 5 led to significant insights regarding the ideal weight and ballasts required for optimal WEC performance. It facilitated a comprehensive understanding of the system dynamics, which has been instrumental in achieving the most efficient tuning parameters for our control system.

For future research, it would be beneficial to consider the lessons learned during this test, particularly with regards to the power matrix formulation, production timelines of machined parts, and scheduling considerations around holiday periods. Incorporating these insights can result in improved testing efficiency, leading to more robust, reliable, and optimized WEC devices.

10 Acknowledgements

The Ocean Motion team would like to thank the faculties and staff at the Oregon State University's Hinsdale Wave Research Laboratory, namely Pedro Lomonaco, Tim Maddux, Bret Bosma, and Rebekah Miller, as well as the undergraduate research assistants. Adam Keester from the Sandia National Laboratories is also acknowledged for his participation during our wave tank test and supporting the validation and improvement of our WEC-Sim performance. Special thanks to the Department of Energy Water Power Technologies Office and the Pacific Ocean Energy Trust, namely Sam, Quinn, Devan Kochersperger, Matt Sanders, for making the TEAMER Program possible.