Post Access Report

Uncertainty analysis and performance comparison in tank testing of a floating OWC Project

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Testing & Expertise for Marine Energy

EXECUTIVE SUMMARY

In a recent collaboration with TEAMER and the MaREI Research Centre for Energy, Climate and Marine research (the University College Cork, Ireland), Ohmsett conducted tank testing of the Ocean Energy (OE) 1:15 scale model prototype of a floating oscillating water column (OWC) wave energy converter (WEC). OE is an Irish Wave Energy Developer (https://oceanenergy.ie/) who are specialists in the development of wave energy technology. The WEC absorbs energy from ocean waves to generate green, sustainable electricity. The results from the testing of the scaled model prototype will be used to optimize the development of a much larger WEC device at a later stage.

The scale model device has been in development for over a decade and has successfully been tested at the Lir National Ocean Test Facility at the University College Cork (Ireland) and École Centrale de Nantes (France). The model is instrumented with several sensors for the measurement of water pressure and level at various locations on the device.

Testing was carried out at the Ohmsett test facility between the 1st and 12th May 2023, to study the operational and structural performance of the OE wave energy converter model. The model device was anchored between the main bridge and the auxiliary bridge, and was subjected to a mix of irregular and regular waves. Over 40 tests were carried out in the tank for a range of different CPM and stroke values, with and without the OE device in the water. All data was acquired and stored on the Ohmsett data acquisition system.

The acquired tank test data is currently being analyzed at MaREI. The output of the testing on the OE model WEC device and subsequent data analysis, will be utilized to provide input to the design, development, modelling and optimization of the full-scale OE WEC device, referred to as the OE35 WEC device, which is being developed as part of an international project called "WEDUSEA" (Wave Energy Demonstration at Utility Scale to Enable Arrays). The WEDUSEA project will demonstrate a grid connected 1MW floating WEC which will be deployed when completed at the European Marine Energy Centre's test site in Orkney, Scotland.

1 INTRODUCTION TO THE PROJECT

This project proposed originally proposed to extend and enhance the c tank testing for wave energy devices across different facilities, building on the learnings of the Marinet2 (www.marinet2.eu) programme on tank testing standardization for wave energy devices and utilizing the guidance documents generated from that project. The project involved examining the performance of a 1:15th Scale floating oscillating water column (OWC) wave, the OE Buoy, which had previously been tested previously in Lir NOTF Ireland and ECN Nantes France.

However, due to greater than expected differences in wave making and DAQ capabilities a direct comparison between Ohmsett and the other facilities was not possible. Instead the focus of the testing programme shifted to examining the performance of the test article in a range of wave conditions in an outdoor saline tank.

2 Roles and Responsibilities of Project Participants

2.1 Applicant Responsibilities and Tasks Performed

UCC MaREI researchers (and partners in Ireland Ocean Energy, OE) provided the WEC model to be tested at the Ohmsett test facility. Prior to the testing at the Teamer network facility, the WEC was tested at the Lir NOTF facility (Cork, Ireland) in 2022. With collaboration and support from staff at the Ohmsett test facility, UCC MaREI staff were responsible for setting up the model in Ohmsett and selecting the test programme and for the subsequent post processing data analysis and reporting.

2.2 Network Facility Responsibilities and Tasks Performed

The Ohmsett facility provided the test tank, along with test and data acquisition equipment. A testing period of 10 days was proposed for the setup, tank calibration, and demobilizing time. The Ohmsett wave tank is 203 m long, 20 m wide, and 2.4 m deep, and can create a variety of sea states including sine waves up to one meter high and simulating harbor chop waves. Waves are generated by varying the stroke length (inches) of the hydraulic arms and the cycles per minute (CPM) of the stroke movement. A series of over 40 tests were carried out in the tank for a range of different CPM and stroke values, with and without the OE device in the water. All data was acquired and stored on the Ohmsett data acquisition system.

3 Project Objectives

The main aim of the project was to improve the quality, robustness, and accuracy of physical modeling and testing practices implemented by marine renewable energy test infrastructures globally. The primary objectives of this test program were to:

1. Gain an understanding of the differences between tank testing methodologies in Europe and the US.
2. Examine structural implications of the hull of a floating OWC under a variety of loadings.
3. Investigate the performance of the device in a salt-water test environment and compare with the performance in previous fresh-water tests.
4. Compare analysis methods between facilities for quantifying uncertainty in tank testing of wave energy devices.
5. Generate a dataset for calibration with numerical modeling.

There were two levels to the quantifiable metrics for this proposed research project, one as a round robin comparison activity and the second as a device performance improvement activity. By undertaking a comparison between test facilities and repeating the same test plan, the understanding and quality of tank testing can be improved. This applies to both the facility operator who would gain knowledge of how their tank performs compared to others but also for developers who may test various iterations of their technology at different facilities. It was envisaged that the outputs from the campaign would also add to the global improvement of technology development by providing guidance on standardizing approaches based on these inter-facility comparisons. The proposed outputs expected were:

- A quantifiable comparison based on tank characterization, such as how tank reflections impact performance;
- An evaluation of uncertainty in saltwater testing compared to freshwater;
- An evaluation of the impact of different data acquisition techniques and test setup methodologies.

The outcomes would be new, robust and representative sets of standardized testing procedures and the delivery of open access datasets for virtual laboratory calibration and verification.

It was proposed that the results from the work carried out would expand the standardization and guidance assessment undertaken during the MaRINET2 testing project by applying the same principles to a facility outside of the original round robin activity, which examined bias between four European facilities (Centrale Nantes (ECN), University College Cork (UCC), University of Plymouth (UoP), and University of Edinburgh (UoE)). Bias errors found included differences in test set-up, calibration, wave parameters and spectral shape, and tank effects. Each facility bias was included as part of a guidance document for both developers and facility managers. Expanding this to cover tank testing in the US would allow for improved quality, robustness, and accuracy of physical modeling and testing practices globally. However as stated earlier the differences in wave making capability including the inability to produce irregular spectrum to a defined shape (PM, Brettshneider, JONSWAPP) the comparison of tank performance is not possible.

The preliminary dissemination of the activity is being undertaken through a paper in University Marine Energy Research Community 2023 Conference. Further results may be disseminated through academic publications and conference presentations. Postprocessed datasets will also be provided to TEAMER -- Specific results published from the proposed tests at TEAMER network facility may include for example:

- Calibration wave data comparison (no model);
- Academic journal article detailing wave tank test results;
- UCC master’s thesis (to be confirmed)

As data analysis post testing is still ongoing, it is envisaged that the output results from the test campaign will (in terms of improving the OE Buoy subject device), provide valuable parameters related to internal pressure of the plenum chamber at various sea states, which has a direct consequence for LCOE of the full-scale device. Undertaking tank testing in both saltwater and freshwater as well as developing a numerical model can be used to validate the next generation of full-scale devices to be developed by Ocean Energy.

4 Test Facility, Equipment, Software, and Technical Expertise

Ohmsett has similar wave-making facilities and tank width and depth to Lir NOTF, but is significantly longer, which provides for an excellent comparison of results. The longer length allows for mitigated reflection effects during wave testing. Placing the device close enough in the tank to the wave paddles provides an opportunity to get enough data to analyze before reflected waves reach the model.

The Ohmsett facility uses salt water with an open ocean salinity of 30-33 parts per thousand (ppt) NaCl, which will enable a direct comparison of buoyancy effects between fresh water (in the Lir NOTF tank) and salt water for tank testing. The facility also has the benefit of multiple instruments for measuring wave conditions, including acoustic and underwater cameras to monitor device motion.

The Ohmsett test tank is equipped with three movable bridges with tow speeds of up to 6 knots, programmable to 1/100th knot increments to simulate ocean current flow. The robust tow bridges can accommodate the torque and forces of a wide range of turbines and wave energy converter (WEC) equipment. Controls are fully computerized and data from various sensors and video cameras are collected for synthesis and analysis.

Wave Making Capabilities

- The wave generator system consists of dual bottom hinged 10,000-pound flaps located at the south end of the tank.
- The wave flaps have independent hydraulic drives that allow for programmable amplitude, frequency, and wavelength control.
- Wavelengths up to 30 meters are achievable.
- A retractable wave damping beach system is present at the north end of the tank.

Sensors & Instrumentation

- Wave height altimeters
- Wave height - capacitance probes
- Pressure transducers
- Acoustic ranging
- Acoustic Doppler Velocimeter
- Load and strain gauges
- Torquemeter

The Ohmsett staff members have multiple years of experience performing in-tank tests under a variety of wave and weather conditions. Support facilities at Ohmsett include a machine shop that provides a complete range of materials, fabrication and welding services to support testing. The facility can lift equipment into the tank via crane or other suitable devices. Sufficient indoor and outdoor workspace is available to prepare and modify test equipment. A complete meteorological station allows for continuous weather measurements.

Equipment needed for the project consists of:

- load cells for internal wall loading
- Mooring load cells
- Pressure gauges
- Motion detection identifiers.

5 Test or Analysis Article Description

This TEAMER project and Ohmsett tank testing, proposed to extend and enhance the comparative analysis of tank testing for wave energy devices across different facilities, building on the learnings of the MaRINET2 program (www.marinet2.eu) for tank testing standardization for wave energy devices among European facilities, and utilizing the guidance documents generated from that project.

A key element of the proposed project was a set of round robin tests where the OE floating OWC wave device was tested in two different tanks to assess the impact the facility itself has on the experimental results.

The OE model device/Buoy is a floating oscillating water column wave energy converter (WEC). The device is based on the backward bent duct concept where the water column is held in the chamber facing away from the incident waves. This device uses wave energy to compress air in a plenum chamber and pump it through an air turbine system. The mouth of the OWC is facing away from the wave direction; this results in high energy efficiencies at the operating point because of the motions of the float system relative to the waves.

The buoy, figure 1, is a fiberglass 1:15 scale model with an aluminum tray for ballasting, with an open orifice for pressure measurement and separate hull access. Its dimensions are 0.9 m x 2.0 m x 1.0 m, with a dry weight of 250.0 lbs.

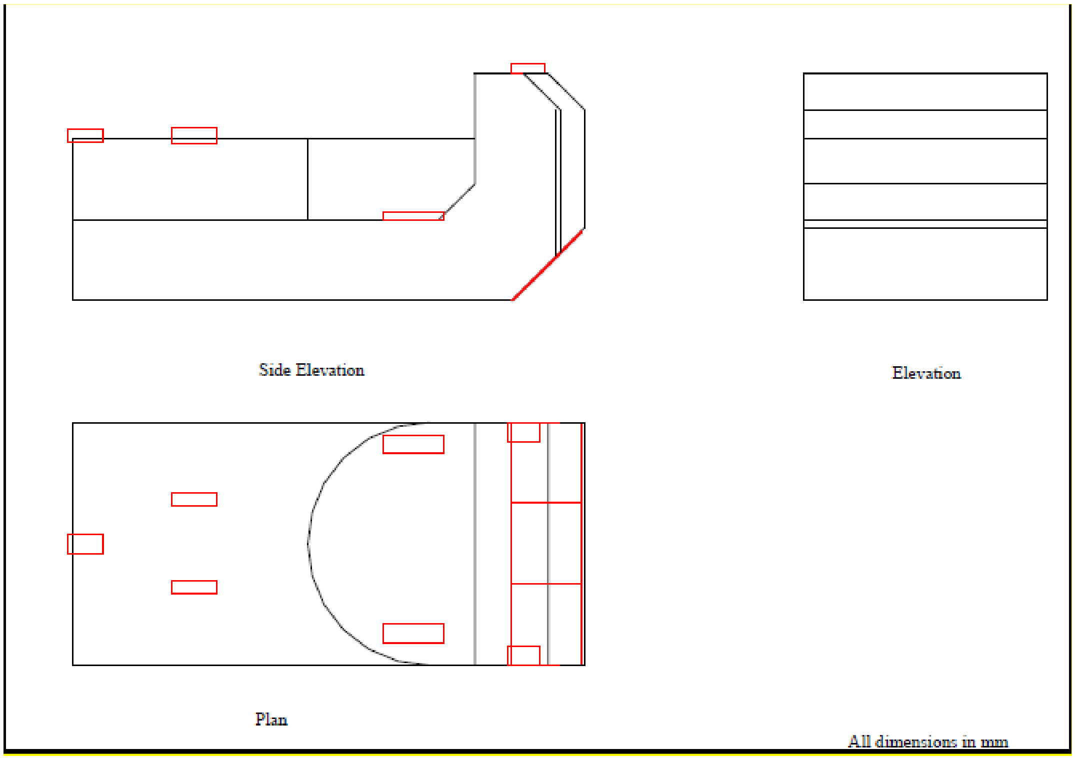

Figure 1 OWC Plan

The buoy has been developed to full scale previously, but this Ohmsett tank testing focused on improving the tank testing accuracy of a 1:15 scale device, Figure 2, while also investigating the operational and structural performance of the device. The joint test campaign's aim was to gather data to enable analysis and critical load parameter quantification that will ultimately be incorporated into a second-generation full-scale OE buoy.

Figure 2 Previous OE Testing at 1/15th scale

The OE Buoy has undergone many component and subsystem tests throughout its 20-year development including most notably on the FP7 funded Cores project, where a 1:4 scale model was subject to an open sea-based deployment in Galway Bay 1/4th scale test site. The project focused on components including data recording and acquisition, mooring and cabling, as well as device performance.

The focus of the wide variety of tank testing during the OE Buoy's development has been on improved performance, from a TRL 1-2 1:50 scale, to 1:15 scale testing in ECN in 2004, and on to sea trials at 1:3 and full scale. It has undergone several open water tests at various scales: A 1:4 scale OE Buoy device was subject to eight months of sea trials between 2007 and 2008 at the Marine Institute/Sustainable Energy Authority of Ireland Wave Energy Galway Bay Test Site, Ireland. During the trial period, the device was subjected to a wide range of wave conditions including a severe storm with wave heights of 8.2 m. It was found that the mooring system had no difficulty coping with these conditions and the device did not suffer any defects from the extreme waves. The project ended in 2011. More recently a full-scale prototype has been built in Oregon and is currently at the U.S. Navy's Wave Energy Test Site in Oahu. It is due to connect to the island of Oahu's electric grid in the near future. The 749-metric-ton, 1.25-megawatt device will undergo a year of performance tests. It will be moored to a 60-meter-deep berth, with a subsea cable link to Hawaiian Electric's grid.

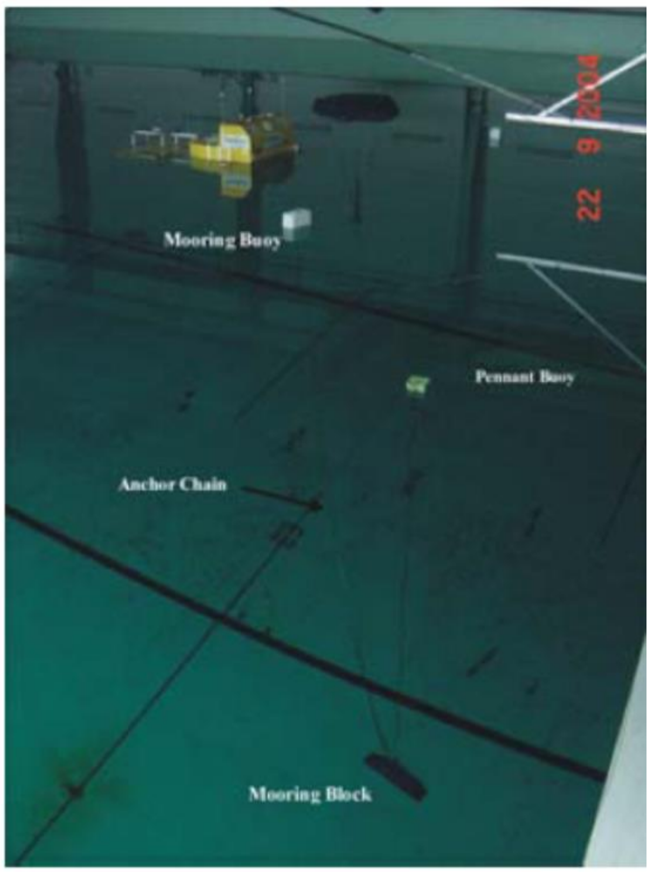

Figure 3 Mooring Configuration

6 Work Plan

6.1 Experimental Setup, Data Acquisition System, and Instrumentation

Six water pressure sensors (Keller Series 26Y piezoresistive level probes for hydrostatic pressure measurement) and three water level (resistance wire) gauges located on the OE WEC model device, were used for the measurement of both water pressure and water levels at different parts of the model. These sensors were interfaced to the Ohmsett data acquisition system, where data were acquired and stored.

The sensors above are summarized in the following table:

Table 1 List of sensors used on the OE buoy.

Sensor Ref #	Sensor	Description/Position/Name	Type
1	Water Level Gauge	Centre	Resistance Gauge
2	Water Level Gauge	Port	Resistance Gauge
3	Water Level Gauge	Starboard	Resistance Gauge
4	Keller Pressure sensor	Plenum Starboard (CM)	4-20 mA output
5	Keller Pressure sensor	Midship Port External (CM)	4-20 mA output
6	Keller Pressure sensor	Starboard Aft External (CM)	4-20 mA output
7	Keller Pressure sensor	Plenum Port (CM)	4-20 mA output
8	Keller Pressure sensor	Port Aft External (CM)	4-20 mA output
9	Keller Pressure sensor	Starboard Midship External (CM)	4-20 mA output

The Ohmsett test facility's Data acquisition (DAQ) system consists of the following National Instruments (NI) DAQ card modules for use with NI's CompactDAQ/CompactRIO Systems.

Table 2 Ohmsett National Instruments (NI) DAQ card modules

DAQ card Module	Description	Quantity / Number of DAQ chs.
NI 9207 (781068-01)	Provides 24Bit ADC Sampling, with input ranges of ±10.2 V or ±21.5 mA (depending on voltage or current measurement) with sampling rates up to 500 sps.	Qty: 2 Each module provides 16 analogue input channels (8 voltage and 8 current)
NI 9219 (779781-02)	Provides 24Bit ADC Sampling, with input ranges of ±60 V, ±15 V, ±4 V, ±1 V, ±125 mV, with sampling rates up to 100 sps.	Qty: 1 Each module provides 4 input analogue channels. A second 9219 module was available but was not completely wired up for testing.

The sensors listed in Table 1 were interfaced to the NI module 9207. For the Ohmsett DAQ system, each input channel is configured with a 249Ω (ohm) sensor to convert the measured signals into an output voltage in the range of 1 to 5 Volts (V).

Additional sensors for the OE buoy model including four other pressure (Honeywell 24PC/170PC series gauge and differential) sensors and two load cells were also to be interfaced to the Ohmsett DAQ system. These sensors ideally required a 4-wire resistance measurement, which could be facilitated using the Ohmsett NI-9219 module, whose datasheet lists the availability of such functionality, as summarized in the table below.

Table 3 Ohmsett National Instruments (NI) 9219 DAQ module

Measurement Type	Nominal Range(s)	Actual Range(s)
Voltage	±60 V, ±15 V, ±4 V, ±1 V, ±125 mV	±60 V, ±15 V, ±4 V, ±1 V, ±125 mV
Current	±25 mA	±25 mA
Thermocouple	±125 mV	±125 mV
4-Wire and 2-Wire Resistance	10 kΩ, 1 kΩ	10.5 kΩ, 1.05 kΩ
4-Wire and 3-Wire RTD	Pt 1000, Pt 100	5.05 kΩ, 505 Ω
Quarter-Bridge	350 Ω, 120 Ω	390 Ω, 150 Ω
Half-Bridge	±500 mV/V	±500 mV/V
Full-Bridge	±62.5 mV/V, ±7.8 mV/V	±62.5 mV/V, ±7.8125 mV/V

However, with only a single active 9219 module, it was not possible to interface all these additional sensors to the 9219 module.

The three water level gauges would have been connected to the 9219. Each of these sensors required interfacing to a 4-wire measurement but as we were limited in the number of channels available, some basic Wheatstone bridge circuits were made using a selection of resistors and wired to the corresponding channels on the 9207 module.

The other modification to be made to the existing DAQ system was that it was configured/wired in the DAQ rack to provide +24VDC. However, sensors required powering or excitation at lower values of for example < 10V DC. Therefore, some basic potential divider networks were made up using a selection of resistor component (and connected to the appropriate connectors and pins for the 9207 module), to provide the required voltages for the sensors.

Data acquired from the nine (9) sensors connected to the 9207 module were acquired on the Ohmsett NI LabVIEW software measuring system.

An additional sensor, namely an IMU (Inertial Measurement Unit) was used to measure the linear acceleration and angular velocity of the OE device. The IMU data was acquired and recorded on the Ohmsett data acquisition laptop.

Figure 4 Ohmsett Test Facility staff and OE WEC model device

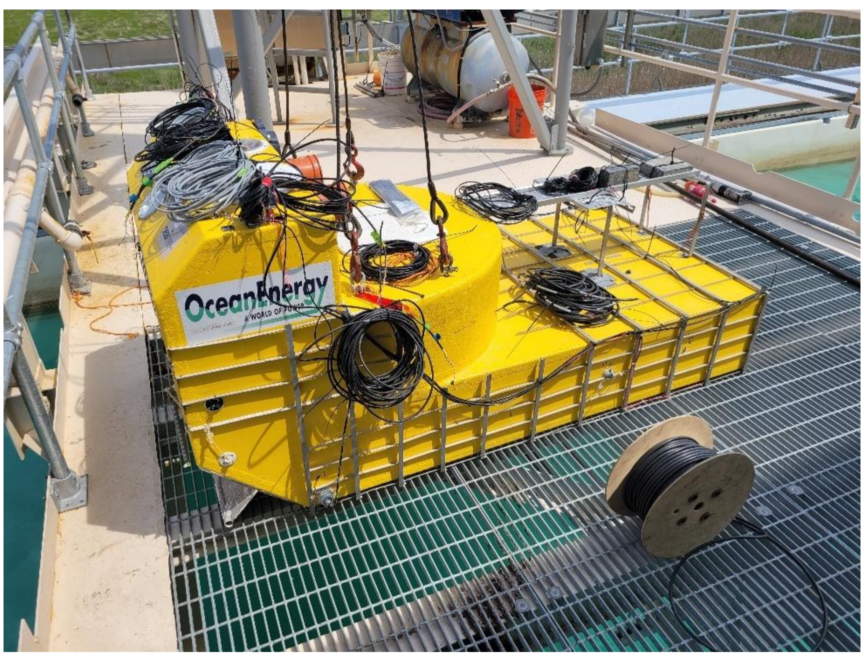

Figure 5 OE WEC model device on deck of bridge

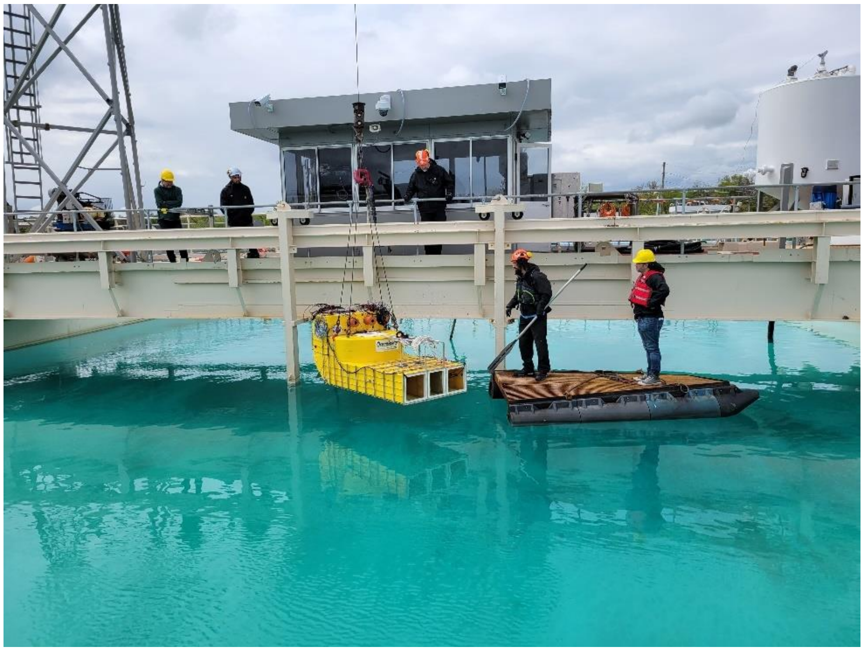

Figure 6 OE WEC model device being lowered into test tank.

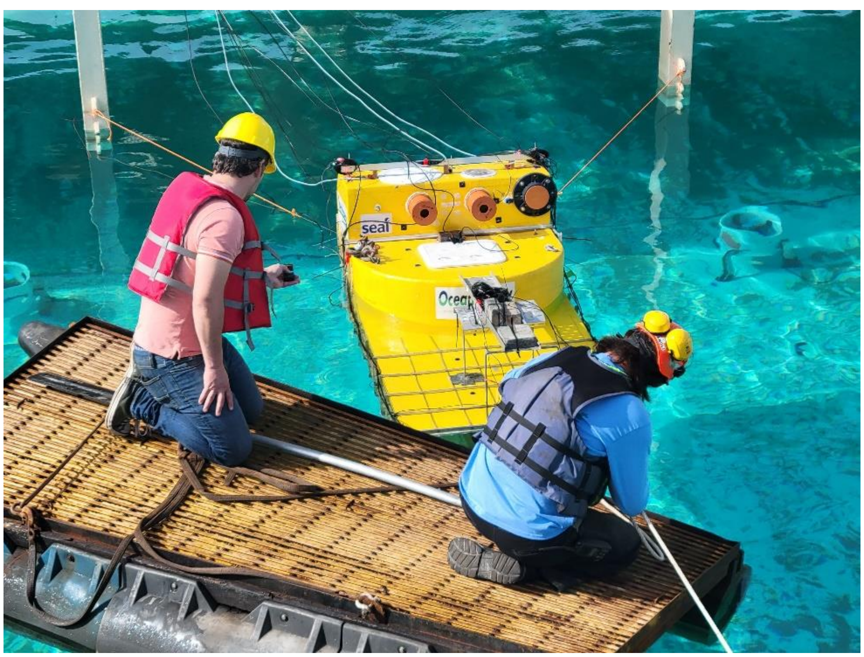

Figure 7 OE WEC model device in test tank - 1

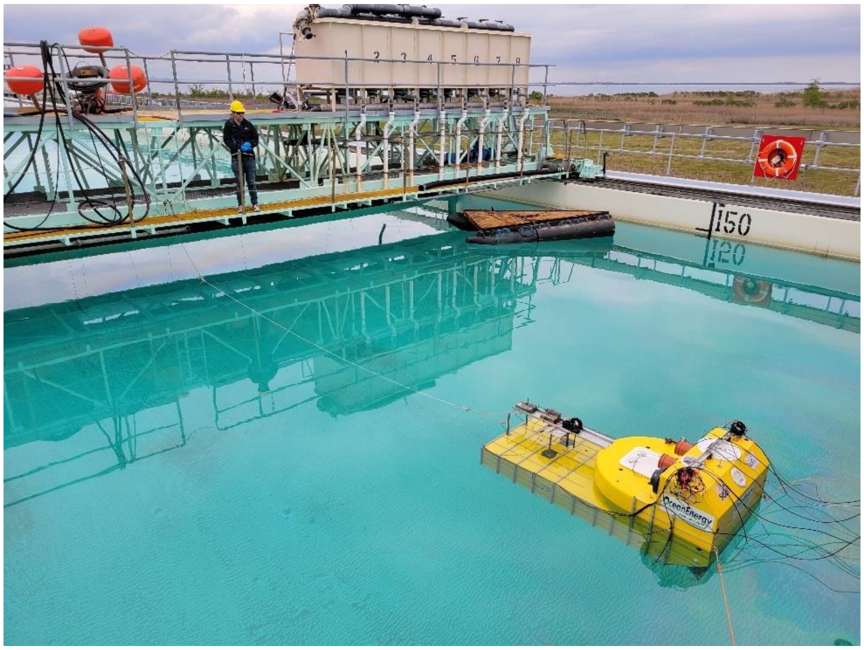

Figure 8 OE WEC model device in test tank - 2

Figure 9 Example of wave tests on OE WEC model device in test tank.

Wave height altimeters were mounted on the movable main bridge of the Ohmsett facility at two locations in close proximity to the OE buoy to collect data for documenting wave profiles during each test. The actual locations of the OE buoy and movable tank bridges were recorded during testing.

6.2 Numerical Model Description

The OE Buoy has previously been numerically modeled, with a focus on OWS loading examinations, by Ocean Energy, Ltd., through the TEAMER project in the first TEAMER RFTS at Sandia National Laboratories.

Recently, UCC MaREI performed CFD analysis of the OE Buoy using Flow3D. This modeling was run in RANS solver and has 2-phase flow capability. The focus of the modeling was on describing the internal air pressure and quantifying water loads on the structure. The model developed for the OE device may be validated the with physical data generated during both the tank testing previously carried out at the UCC LIR NOTF facility, and the recent tank testing at Ohmsett.

6.3 Test and Analysis Matrix and Schedule

The test campaign occurred during the period of the 1st to the 12th of May 2023. The overall testing sequence of events was based on a programme of Regular waves. The device also underwent a series of static calibration and decay tests initially and was exposed to a variety of specific wave forms.

Preparation of the OE device and associated sensors, cabling and interfacing with the Ohmsett test facility's data acquisition system was carried out during the first week (1st to the 5th May) of the test campaign. Installation of the OE device in the test tank was carried out on the 3rd May. Initial calibration and static tests on the OE device (while positioned in the tank, Test#1 to 22) took place on the 4th and 5th of May. The actual tank testing for the OE device utilizing several different waves (test# 23 to 63) was carried out from the 5th to the 12th May. These tank tests are summarized in the table below.

Table 4 - Summary test plan of Ohmsett wave testing on the OE WEC device

Test #	Date	Approximate Time (hrs)	Wave #	Wave Generator Settings	Nominal Wave Characteristics*	Comments
23	05/05/2023	1341	Reg Wave 1	15 cpm @ 4.5-in stroke	H(avg)=6.9 cm; Period=4.3 s; λ=19.1 m	Bridge location=158.9 m (521.2 ft); Water Depth=2.62 m (130.12 ft); These parameters are constant for the duration of the test period.

24	05/05/2023	1358	Reg Wave 2	15 cpm @ 3.0-in stroke	H(avg)=5.4 cm; Period=3.3 s; λ=13.8 m	
25	05/05/2023	1411	Reg Wave 3	40 cpm @ 3.0-in stroke	N/A	This test was repeated later as Test 52 due to uncertainty regarding the wave generator setting.
26	05/05/2023	1424	Reg Wave 4	25 cpm @ 4.5-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	
27	05/05/2023	1439	Reg Wave 5	35 cpm @ 3.0-in stroke	H(avg)=13.7 cm; Period=1.8 s; λ=5.0 m	
28	05/05/2023	1455	Reg Wave 6	10 cpm @ 15.0-in stroke	H(avg)=13.8 cm; Period=4.5 s; λ=20.2 m	
Large Wave 1	08/05/2023	1050	Lg Wave 1	18 cpm @ 18-in stroke	H(avg)=38.2 cm; Period=3.0 s; λ=12.0 m	Large wave tests performed for data outside of test matrix. IMU data recorded on labp top, not on DAQ. **Note: Large wave 2 broke a USB cable to the unit.**
Large Wave 2	08/05/2023	1055	Lg Wave 2	30 cpm @ 12-in stroke	H(avg)=47.8 cm; Period=1.8 s; λ=5.2 m	
Large Wave 3	08/05/2023	1100	Lg Wave 3	20 cpm @ 18-in stroke	H(avg)=47.5cm; Period=2.7 s; λ=10.4 m	
29	08/05/2023	1416	Lg Wave 1	18 cpm @ 18-in stroke	H(avg)=38.2 cm; Period=3.0 s; λ=12.0 m	38 cm (15-in) Wave Height Series
30	08/05/2023	1425	Lg Wave 3	20 cpm @ 18-in stroke	H(avg)=47.5cm; Period=2.7 s; λ=10.4 m	48 cm (19-in) Wave Height Series
31	08/05/2023	1445	N/A	25 pm @ 15-in stroke	H(avg)=52.5 cm; Period=2.2 s; λ=7.1 m	
32	08/05/2023	1502	Reg Wave 3	40 cpm @ 3.0-in stroke	N/A	
29 R	09/05/2023	0929	Reg Wave 1	15 cpm @ 4.5-in stroke	H(avg)=6.9 cm; Period=4.3 s; λ=19.1 m	Open Water Tests Although instrumentation was out of the water, they were still connected to the buoy. Therefore, significant
30 R	09/05/2023	N/A	Reg Wave 2	15 cpm @ 3.0-in stroke	H(avg)=5.4 cm; Period=3.3 s; λ=13.8 m	

						drift in the data was noted.
N/A	10/05/2023	Changed damaged springs and conducted tension tests accordingly. Proceeded with triplet tests centred around and approximate average wave height.				
33	10/05/2023	1438	Triplet Around 13 cm Avg H	25 cpm @ 4.5-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	
34	10/05/2023	1455		35 cpm @ 3.0-in stroke	H(avg)=13.7 cm; Period=1.8 s; λ=5.0 m	
35	10/05/2023	1511		10 cpm @ 15.0-in stroke	H(avg)=13.8 cm; Period=4.5 s; λ=20.2 m	
N/A	11/05/2023	Conducted mooring calibration tests in the AM.				
36	11/05/2023	0920	Repeat of 13 cm triplet.	25 cpm @ 4.5-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	Blank turbine covers in-place (not vented). Repeat of 13 cm triplet run as 600 second spectral wave generation.
37	11/05/2023	0945		35 cpm @ 3.0-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	
38	11/05/2023	1009		10 cpm @ 15.0-in stroke	H(avg)=13.8 cm; Period=4.5 s; λ=20.2 m	
39	11/05/2023	1030	Triplet Around 21 cm Avg H Spectral	20 cpm @ 9.0-in stroke	H(avg)=21.6 cm; Period=3.0 s; λ=12.2 m	Blank turbine covers in-place (not vented). 600 second spectral 21 cm triplet.
40	11/05/2023	1045		40 cpm @ 6.0-in stroke	H(avg)=20.7 cm; Period=1.8 s; λ=4.9 m	
41	11/05/2023	1108		11 cpm @ 22.0-in stroke	H(avg)=21.5 cm; Period=5.0 s; λ=23.1 m	
42	11/05/2023	1129	13 cm Triplet, Spectral	25 cpm @ 4.5-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	Vented turbine covers in-place (vented). 600 second spectral, 13 cm triplet.
43	11/05/2023	1322		35 cpm @ 3.0-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	
44	11/05/2023	1348		10 cpm @ 15.0-in stroke	H(avg)=13.8 cm; Period=4.5 s; λ=20.2 m	
45	11/05/2023	N/A	21 cm Triplet, Spectral	20 cpm @ 9.0-in stroke	H(avg)=21.6 cm; Period=3.0 s; λ=12.2 m	Vented turbine covers in-place (vented).

46	11/05/2023	1427		40 cpm @ 6.0-in stroke	H(avg)=20.7 cm; Period=1.8 s; λ=4.9 m	600 second spectral, 21 cm triplet.
47	11/05/2023	1446		11 cpm @ 22.0-in stroke	H(avg)=21.5 cm; Period=5.0 s; λ=23.1 m	
N/A	11/05/2023	N/A	The following tests are "re-do's" of lost data from May 8, 2023.			
48	12/05/2023	0955	Lg Wave 1	18 cpm @ 18-in stroke	H(avg)=38.2 cm; Period=3.0 s; λ=12.0 m	Re-do of Test 29.
49	12/05/2023	1009	Lg Wave 3	20 cpm @ 18-in stroke	H(avg)=47.5cm; Period=2.7 s; λ=10.4 m	Re-do of Test 30.
N/A	12/05/2023	N/A	At approximately 213 seconds into test, the mooring starboard mooring spring came off the mooring line. No spring damage. Re-ran Test 49 below.			
50	12/05/2023	1025	Lg Wave 3	20 cpm @ 18-in stroke	H(avg)=47.5cm; Period=2.7 s; λ=10.4 m	Re-do of Test 49 (and Test 30).
51	12/05/2023	1040	N/A	25 pm @ 15-in stroke	H(avg)=52.5 cm; Period=2.2 s; λ=7.1 m	Re-do of Test 31.
52	12/05/2023	1105	Reg Wave 3	40 cpm @ 3.0-in stroke	N/A	Re-do of Test 32
N/A	12/05/2023	The following is the Breaking Wave test. Bridge location was at approximately 300 feet on the tank.				
53	12/05/2023	1146	Recipe from Still Water: 1.) 5 cycles @ 30 cpm and 12-inch; 2.) 5.5 second delay; 3.) 4 cycles @ 20 cpm and 18-inch.			
54	12/05/2023	1151	Repeat of breaking wave test.			
55	12/05/2023	1157				
N/A	12/05/2023	N/A	The following tests are open water tests with the buoy removed completely. Tests performed at 512.2 feet on the tank.			
56	12/05/2023	1327	13 cm Triplet, Open Water	25 cpm @ 4.5-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	Open Water Triplets
57	12/05/2023	1346		35 cpm @ 3.0-in stroke	H(avg)=13.2 cm; Period=2.2 s; λ=7.2 m	
58	12/05/2023	1352		10 cpm @ 15.0-in stroke	H(avg)=13.8 cm; Period=4.5 s; λ=20.2 m	

59	12/05/2023	1358	21 cm Triplet, Open Water	20 cpm @ 9.0-in stroke	H(avg)=21.6 cm; Period=3.0 s; λ=12.2 m	Open Water Triplets
60	12/05/2023	1408		40 cpm @ 6.0-in stroke	H(avg)=20.7 cm; Period=1.8 s; λ=4.9 m	
61	12/05/2023	1419		11 cpm @ 22.0-in stroke	H(avg)=21.5 cm; Period=5.0 s; λ=23.1 m	NOTE: This test was inadvertently run at the previous wave genny settings of 40 cpm @ 6.0-in stroke. The test was re-run at Test 63 below.
62	12/05/2023	1428	Lg Wave 2	30 cpm @ 12-in stroke	H(avg)=47.8 cm; Period=1.8 s; λ=5.2 m	Repeat of the Large Wave 2 test that broke the USP connector. This test produced no adverse effect upon the buoy, instrumentation, or connectors and communications.
63	12/05/2023	1438	Repeat	11 cpm @ 22.0-in stroke	H(avg)=21.5 cm; Period=5.0 s; λ=23.1 m	Repeat of Test 61, above.

6.4 Safety

The Ohmsett facility provided an overview of general hazards that may be encountered, potential hazards related to the proposed testing, and procedures, protocols, and personal protective equipment to mitigate hazards and risks.

6.5 Contingency Plans

The Ohmsett facility staff routinely perform tests under a variety of environmental conditions. The only time outside work is stopped is on those occasions when lightning or other severe weather conditions occur. Testing was carried out as planned and not hampered by local weather (rain) conditions.

6.6 Data Management, Processing, and Analysis

6.6.1 Data Management

Data was collected via the Ohmsett 24 channel LabVIEW data acquisition system. Data files along with video, photo and support documentation were uploaded to a UCC data portal on SharePoint.

6.6.2 Data Processing

The raw data acquisition files acquired by the Ohmsett DAQ system, were converted into .csv files for use in MaREI UCC analysis tools. Both the *.csv and the IMU data files (*.mtb) were uploaded to the UCC data portal.

6.6.3 Data Analysis

Analysis of the acquired data is currently ongoing. Data analysis will focus on (1) analysis of the IMU data to derive the rotational (Roll, Pitch and Yaw) and translational (Surge, Sway, Heave) degrees of freedom of the OE WEC device and (2) pressure and water level gauge sensors.

7 Project Outcomes

7.1 Results

Data analysis is currently ongoing and as such no official results are currently available at this time.

Initial analysis of results has been focused on the motion analysis of the OE model device, and deriving the translational and rotation degrees of freedom, using the data acquired from the IMU sensor. The Xsens IMU MTi-100 sensor comprises a tri-axial accelerometer, tri-axial gyroscope and tri-axial magnetometer, providing measurements of acceleration [m/s^2], angular velocity [rads/s] and arbitrary units [a.u] for the magnetometer respectively. The IMU does not provide any information on the six degrees of freedom (Roll (θ), Pitch (ϕ), Yaw (ψ), Surge (η), Heave (ϖ), Sway (ζ)) representing the motion of the OE model device. These parameters need to be calculated based on the acquired sensor data above. An example of the derived Pitch (ϕ) and corresponding Sway (ζ) values for one of the wave tests are shown here for reference only.

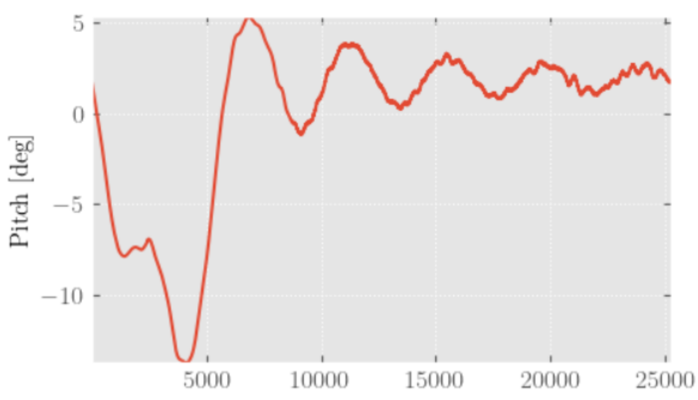

Figure 10 Example of derived Pitch response during tank testing.

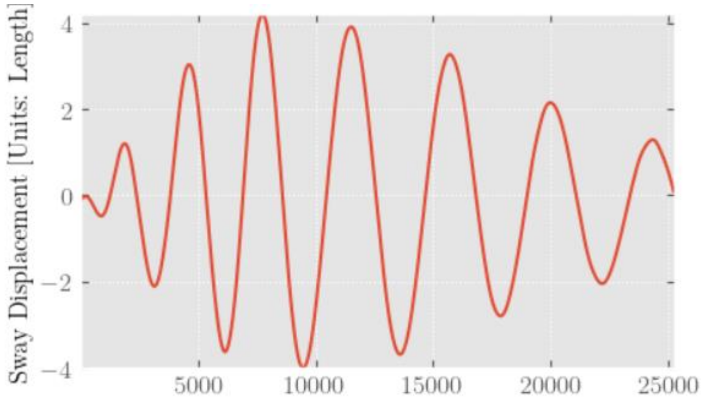

Figure 11 Example of derived Sway response during tank testing.

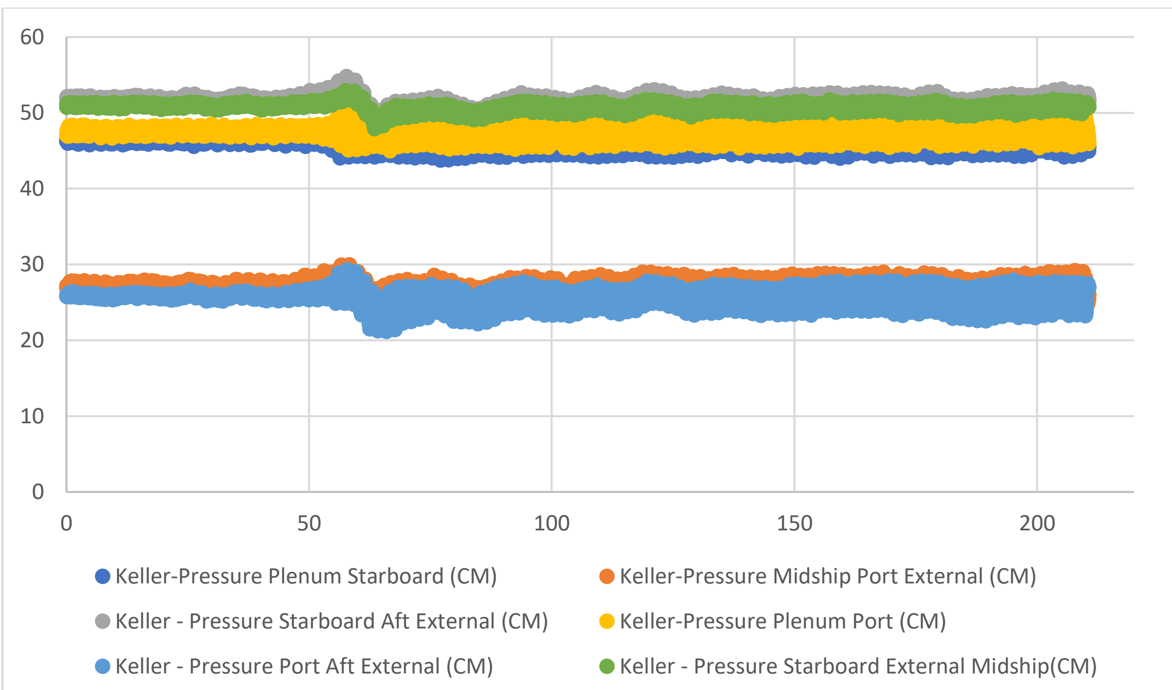

Figure 12 Example of measured pressure on OE model during tank testing.

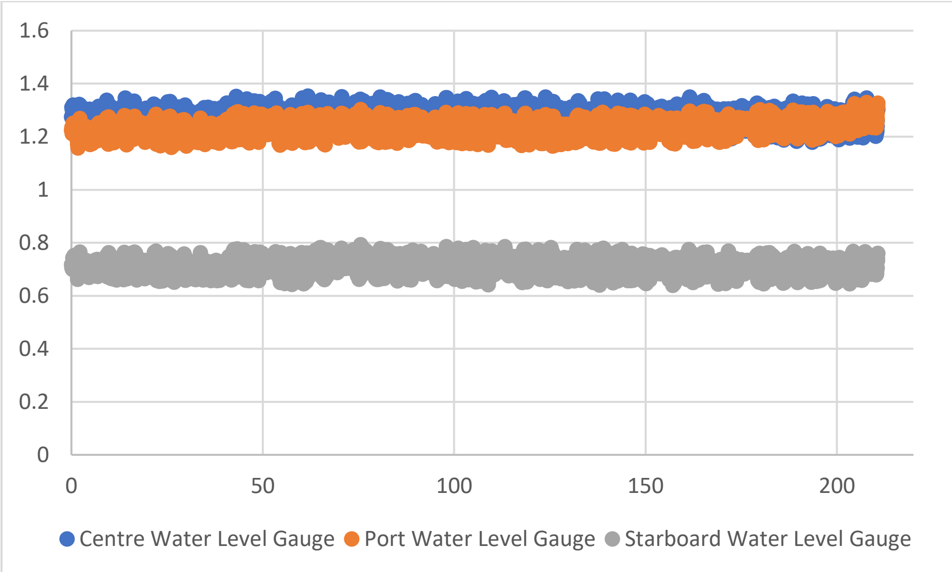

Figure 13 Example of measured water level on OE model during tank testing.

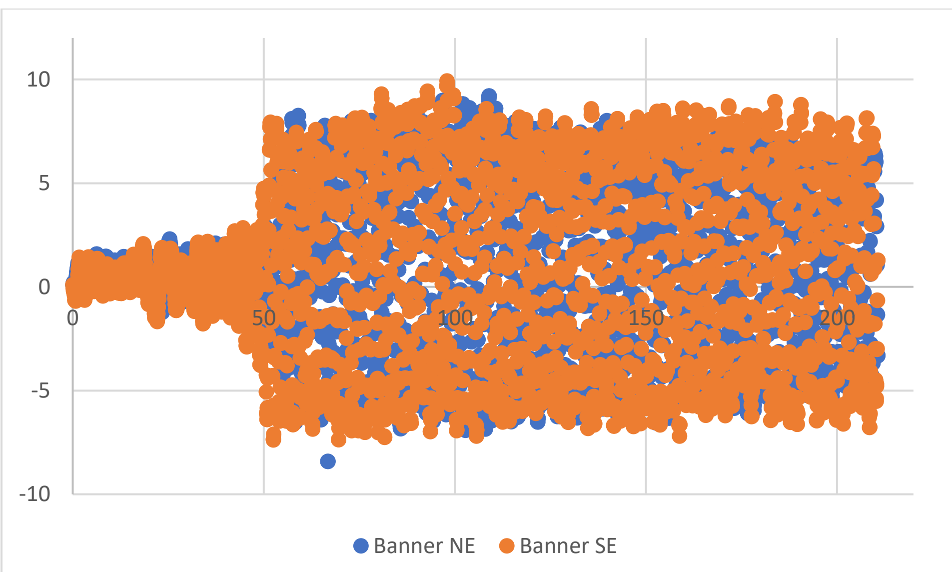

Figure 14 Example of measured wave height during tank testing.

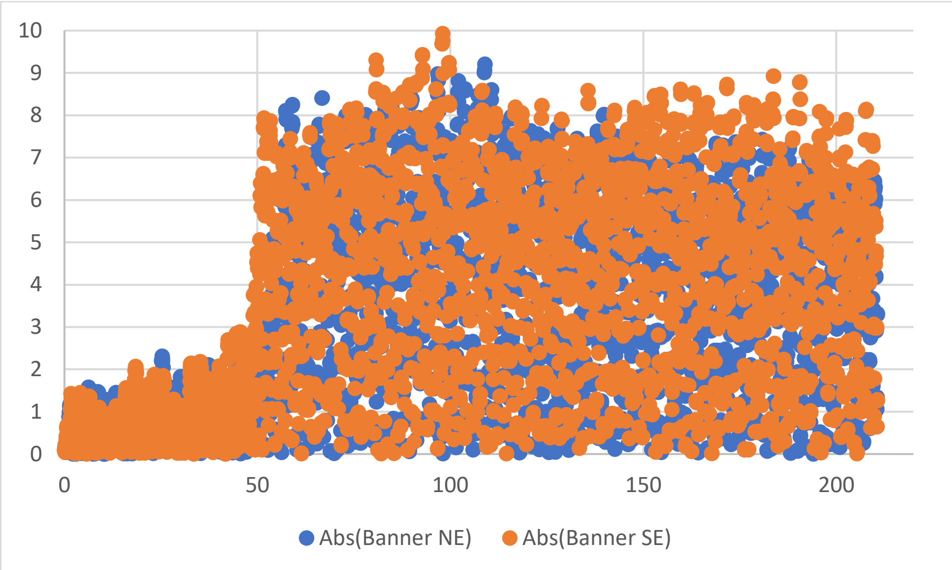

Figure 15 Example of measured wave height during tank testing (Absolute values).

7.2 Lesson Learned and Test Plan Deviation

A portion of the test plan for the wave tank testing on the OE WEC model device was altered due to limitations and difference in the capability of the Ohmsett paddle/wave generation. The Irregular spectrum waves were not undertaken due to this. Instead, the testing programme was focused on regular waves and in particular waves that could cause structural damage to such a device.

In terms of the instrumentation and data acquisition system at Ohmsett, the current DAQ system is currently not optimized to perform low voltage signal measurements, as required for differential measurements. This is particularly the case for sensors with low signal outputs requiring for example 4-wire, strain and bridge type measurement capability, which require more sensitive and specialized low noise signal conditioning and acquisition instrumentation /equipment to perform such measurements.

Without the ability to perform such measurements during the Ohmsett testing, no load cell or gauge/differential pressure readings for the OE WEC model device were acquired. Similarly for the resistive water level gauges on the OE device, for signal conditioning and acquisition purposes, these would have been better connected to an active 4-wire bridge measurement system, but as this wasn't possible, an improvised solution, using several discrete resistor components to construct a simple Wheatstone bridge was done. Data analysis is currently ongoing.

8 Conclusions and Recommendations

Testing was carried out at the Ohmsett test facility between the 1st and 12th May 2023, to study the operational and structural performance of the OE wave energy converter model. The model device was anchored between the main bridge and the auxiliary bridge and was subjected to regular waves. Over 40 tests were carried out in the tank for a range of different CPM and stroke values, with and without the OE device in the water. All data was acquired and stored on the Ohmsett data acquisition system.

The test plan for the wave tank testing on the OE WEC model device was carried out as planned. In terms of the instrumentation and data acquisition system at Ohmsett, the current DAQ system is currently not optimized to perform low voltage and low noise signal measurements, as required for low amplitude differential measurements. This would require a specialized DAQ system setup to be installed and configured to provide such sensing capabilities for future testing.

The acquired tank test data is currently being analyzed at MaREI.

9 REFERENCES

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F. Judge, E. Lyden, M. O'Shea, B. Flannery, J. Murphy, Uncertainty in Wave Basin Testing of a Fixed Oscillating Water Column Wave Energy Converter, ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering, 7(4), 040902 (11 pp) (2021)

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11 APPENDIX

Ohmsett Facility Specifications

DEMONSTRATE PROOF-OF-CONCEPT WITH PROTOTYPE TESTING AT OHMSETT.

Facility:
- Controlled reproducible conditions
- Test protocol development
- HD underwater video/viewing capabilities
- 32 Channel National Instruments LabVIEW DAQ
- On-site fabrication/work shop
- Certified welders
- Meteorological station
- On-site divers

Wave Making Capabilities:
- Programmable flap travel and frequency
- Wave spectrum capable
- 59 cm height ($H_{1/3}$, at λ=7.1m, 2.16 sec)
- 83 cm height ($H_{1/3}$ Harbor Chop)
- Wave length 25.3 m (at $H_{1/3}$=29.4 cm, 5.48 sec)
- Wave damping beach system

Sensors & Instrumentation:
- Wave height altimeters
- Wave height - capacitance probes
- Pressure transducers
- Acoustic ranging
- Acoustic Doppler Velocimeter
- In-situ fluorometery
- Particle size distribution (laser and optical)
- Load and strain gauges
- Torquemeter
- Surface thermal imaging
- Accelerometers

Wave Tank:
- 203.3 meters (667 feet) long
- 19.8 meters (65 feet) wide
- 3.4 meters (11 feet) deep; 2.4 meters (8 feet) nominal operating water depth
- 9.8 million liters of water maintained at open ocean salinity (32-35 ppt)
- Tow bridge speeds up to 3.1 meters/sec (6 knots)
- Indexed drive system
- 3 equipment/instrumentation tow bridges

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Ohmsett

https://ohmsett.bsee.gov

Ohmsett - Basic Specifications	
Overseeing Organization	U.S. Department of Interior's Bureau of Safety and Environmental Enforcement
Hydrodynamic Testing Facility Type	Tow Tank, Wave Basin
Length(m)	203.3
Beam(m)	19.8
Depth(m)	2.44
Water Type	Saltwater
Cost(per day)	Contact: 732.866.7183
Special Physical Features	Accommodates full and meso-scale equipment under a realistic sea environment, multiple traveling bridges, underwater video, computer controlled bridge and wave generator settings, onsite fabrication, viewing windows, scuba diver support, test equipment integration support.
Towing Capabilities	
Towing Capabilities	Yes (±0.005 m/s)
Maximum Velocity(m/s)	3.1
Length of Effective Tow	160
Wavemaking Capabilities	
Wavemaking Capabilities	Yes
Max Wave Ht. ($H_{1/3}$) Achieved (m)	0.59 (at λ=7.1 m, 2.16 sec)
Max Wave Lgth. Achieved (m)	25.3 m (at $H_{1/3}$ = 29.4 cm, 5.48 sec)
Wave Period Range (sec)	1.4 – 5.5
Wave Maker Description	Dual bottom hinged flaps; independent hydraulic drive
Programmable	Yes: menu driven/user defined;
Wavemaking	programmable flap travel and frequency; wave spectrum capable
Wave Direction	Uni-Directional
Simulated Beach	Yes
Description of Beach	Downstream lift and diffuse; retractable
Control and Data Acquisition	
Description	National Instruments LabView
Number of channels	32
Bandwidth(kHz)	DC level
Cameras	Yes
Number of Color Cameras	3
Description of Camera Types	Underwater full-pan, tilt, zoom with data overlay
Available Sensors	Acceleration, Flow, Turbulence, Velocity, force, temperature, other by request
Test Services	
Test Services	Yes
Utility Services Available	480 VAC, 3Ph; municipal water; steam; ice and chilling capability
On-Site fabrication capability/equipment	On-site fabrication/work shop; contracted local machine and fabrication
Special Characteristics	
Specializations, Capabilities, and Key Facility Attributes Not Covered Elsewhere	Available Sensors: Wave height; In-situ Fluorometry; In-situ laser particle size distribution. Underwater ROVs, underwater acoustic and sonar instrumentation. Specialized Characteristics: Hazardous materials operations.

https://ohmsett.bsee.gov/brochures/Ohmsett%20Fact%20Sheet%20_2021.pdf