Post Access Report for Public

Numerical Analysis of Two-Body Floating Attenuator WEC (Waveberg)

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RFTS: 9

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EXECUTIVE SUMMARY

This TEAMER RFTS 9 award was used to develop a numerical model of the Waveberg floating attenuator wave energy converter (WEC) using the Wave Energy Converter-Simulator (WEC-Sim). The Waveberg is designed to generate power in the smaller waves (for wave heights of 1 - 2 meters) predominant in the world. It is simple and inexpensive, therefore applicable in low resource settings.

A previous TEAMER RFTS 8 award was used to complete wave tank testing on the Waveberg WEC at Steven's Institute of Technology. Analysis of these tests on a new 1:25 scale model supports a valuable understanding of Waveberg's dynamics in real wave conditions. The tank testing included an initial characterization of dynamics using free decay and response amplitude operator (RAO) tests. More advanced testing was also carried out to characterize power output and test novel improvements including hydrofoils to increase lift. The tank test results provided validation data for the WEC-Sim numerical model developed in this TEAMER RFTS 9 award.

WEC-Sim is developed for the purpose of simulating, analyzing, and optimizing WEC dynamics and power performance. It provides simulation framework for modeling the Waveberg WEC. An accurate numerical model that has been validated by tank testing results supports the Waveberg Development team going forward as an inexpensive way to demonstrate the WEC's capabilities and efficiently create new design iterations. The numerical model will be vital in Waveberg Development's goals of attracting the $3 million required to complete testing of a full-scale prototype.

1 Introduction to the Project

The Waveberg device is a floating attenuator that uses a piston pump to pressure seawater as the Power Take-off (PTO). The pressurized water is piped to shore to be utilized in reverse osmosis, power generation or sea water supply for aquaculture. An array of devices would be situated near shore (15 to 25 m water depths). The Waveberg generates power in the smaller waves (for wave heights of 1 - 2 meters) predominant in the world. A numerical model of the Waveberg WEC has been developed in WEC-Sim to support characterization of the dynamics and future design iterations.

The outcome of this TEAMER award is first and foremost a working and validated WEC-Sim model (hosted on a private GitHub repository) of the 1:25 scale Waveberg Floating Attenuator WEC which can be used to test the WEC in different wave conditions and extract desired results. The specific metrics used to verify the accuracy of the WEC-Sim model and provide reference for the performance of the device are the body responses, relative pitch motions, and power take-off output in terms of both pumped water and mechanical power in various wave conditions. The modeling process is separated into multiple tasks:

0. Sharing of existing Waveberg dimensions and parameters:

This task simply refers to the initial phase in which Waveberg shared the existing design with the WEC-Sim team to begin the modeling process. The shared design included relevant dimensions and parameters in sufficient detail to create an accurate model.

1. Boundary Element Method (BEM) development:

During this phase of modeling, Waveberg provided design details were used by the WEC-Sim team to create a CAD model and mesh representing the Waveberg WEC. The mesh was then used to calculate the hydrodynamic data using an open-source BEM solver Capytaine. This process required multiple iterations with varying degrees of mesh refinement to ensure accuracy.

2. Baseline WEC-Sim model development:

The BEM data is used as an input to WEC-Sim to support a baseline WEC-Sim model. The initial model consists of the Waveberg WEC without power take-off (PTO) and mooring systems, which was used to verify stability using free-decay and regular wave tests. Then, PTO and mooring systems were incrementally added according to Waveberg's provided design. The final design has been run in the desired wave conditions to assess performance.

3. Data analysis and post-processing:

Data from the baseline WEC model required post-processing to assess the desired metrics and effectively communicate model results.

4. Model verification and validation:

This phase of modeling is vital to the reliability of the WEC-Sim model of the Waveberg WEC. The model results were compared to tank test results in various free decay and wave conditions to ensure the real-world dynamics are accurately captured by the model. The results comparison included comparing to encoder data for the top hinge, IMU data for the main body, and the observed water output. Multiple iterations of variable tuning were required to achieve a more accurate numerical model.

5. **Dissemination and technology transfer:**

Lastly, the results of the TEAMER award are presented to the Department of Energy (DOE) in this post-access report and the model was handed off to Waveberg Development after a technology transfer meeting.

2 Roles and Responsibilities of Project Participants

2.1 Applicant Responsibilities and Tasks Performed

The applicant provided geometric and mass/inertia parameters of the existing design and results from tank testing at the Stevens Institute of Technology (Stevens) in May 2023. The applicant provided details on the power take-off being used in the wave tank model to improve model accuracy. The applicant defined sea states of interest including regular wave simulations for a range of relevant wave heights and periods. The applicant also shared previous results analyzing power performance in previous tank testing at HMRC, including an equation that predicts that performance.

2.2 Network Facility Responsibilities and Tasks Performed

The WEC-Sim facility was responsible for building a WEC-Sim model of the Waveberg WEC that represents the device tested in the Stevens Institute of Technology wave tank. This included meshing the geometry of the two rigid bodies comprising the Waveberg WEC, running a hydrodynamic analysis to generate linear hydrodynamic coefficients (i.e. WAMIT, Capytaine, NEMOH), and building the baseline WEC-Sim model. The facility then simulated the Waveberg WEC under no waves (check for hydrostatic stability), free decay (check energy dissipation), and regular waves to estimate performance at different locations. The simulations in various conditions were compared to tank test results as validation. Lastly, the facility was responsible for communicating performance results to the applicant and providing access to the WEC-Sim model.

3 Project Objectives

OVERALL OBJECTIVE

Waveberg Development seeks to optimize the device configuration for future iterations of the Waveberg WEC, and a baseline numerical model is required. The numerical model allows the Waveberg physical dimensions to be adjusted and evaluated under regulars to determine the geometry and mass properties leading to improved power capture. However, the accuracy of the model must be established before outputs from the numerical tool can be trusted. The results from the Stevens Institute of Technology wave tank testing campaign provided a validation data set that was used to tune the WEC-Sim model.

The current design was first created by John Berg in 2007 at Hydraulics and Marine Research Centre (HMRC) and then modified by Paul Wegener for further testing at HMRC in 2009. Tank testing shows it works well, despite shortcomings in the model power takeoff. A completely new model was fabricated for the tank testing at Stevens Institute under the TEAMER program, which was completed in June 2023. Combined with the test results of the physical device, the verified numerical model will provide Waveberg with accurate modeling capabilities. The WEC-Sim model can guide Waveberg on future design decisions and improvement efforts. A successful numerical model also benefits WEC-Sim by furthering the verification and validation of the software specific to an attenuator WEC, a type of device which has limited previous verification in WEC-Sim. Lastly, the Waveberg WEC presents an opportunity to advance the marine energy industry through the development of its simple and inexpensive design.

PHYSICAL ATTRIBUTES BEING INVESTIGATED

The physical attributes investigated include first and foremost the Waveberg's hydrodynamic response to incoming wave conditions. The response was validated against tank testing results in various conditions. The device performance (power output as watts) across a representative range of waves, both regular and irregular, was also investigated. The power take-off and mooring forces were also captured in the model and provide important reference for future design iterations.

PERFORMANCE METRICS

- Residual error between WEC-Sim model and tank test results in all free decay and regular wave conditions identified in Table 2.
- Average and peak power output across the range of regular wave conditions modeled.
- Average and peak PTO and mooring forces across the range of regular wave conditions modeled.
- Phase delay between numerical model results and wave tank test results in regular wave conditions.
- Capture width of device across the range of regular wave conditions modeled.

4 Test Facility, Equipment, Software, and Technical Expertise

The numerical simulation tool utilized for the modeling to be carried out on the Waveberg Floating Attenuator WEC is the Wave Energy Converter-Simulator (WEC-Sim). WEC-Sim is an open-source software for simulating wave energy converters (WECs) jointly developed by the National Renewable Energy Laboratory and Sandia National Laboratories in the United States. WEC-Sim is developed in MATLAB/SIMULINK framework utilizing Simscape Multibody to solve the multi-body dynamics problem. WEC-Sim predicts WEC dynamics through time domain simulations based on the radiation and diffraction method using hydrodynamic coefficients obtained from frequency-domain boundary element methods (e.g., WAMIT, NEMOH, Aqwa, Capytaine). WEC-Sim is developed for the purpose of predicting, analyzing, and optimizing WEC dynamics and power performance and will provide an ideal approach for modeling the Waveberg WEC.

A basic CAD model was developed using Dassault System's SolidWorks, which was then defeatured and meshed to prepare for the boundary element method (BEM). Capytaine, a Python package based on the solver NEMOH for linear potential flow wave theory, was used to complete the boundary element method and output the hydrodynamics required for WEC-Sim's BEMIO (boundary element method input output). WEC-Sim takes inputs from BEM as well as user-defined inputs which can be used to define the simulation settings, wave conditions, body properties, PTO format, mooring configuration, etc. WEC-Sim derives the design and model format from a user-defined Simulink Model, which can specify body constraints and interactions. After solving using the Simscape Multibody solver, WEC-Sim can output desired results including wave forces, body response (position, velocity, acceleration), etc. Specific user-defined results which can be derived from the basic outputs for this model include power performance and capture width.

5 Test or Analysis Article Description

The Waveberg Floating Attenuator Wave Energy Converter (WEC) (Figure 1) consists of two bodies: the main body and the float. The main body makes up ~60% of the mass of the WEC and is connected to the float via an arm containing a single-action piston pump power take-off (PTO). The approaching crest raises the arm float, filling the pump; the arm float begins its power stroke and descends the backside of the wave crest as the crest lifts the nose of the main body. The crest then tilts up the rear of the main body, lowering the nose, just as the next crest is approaching the arm float. The Waveberg uses a pump to deliver energy to shore as pressurized seawater. An array of Waveberg WECs is intended to be connected by a manifold of pipes to deliver power to one processing plant onshore which uses this output to generate electricity or fresh water. Undersea piping manifolds are commercially available, as used in the gas industry. The estimated cost of a complete array is $3,000 per KW, with a delivered cost of energy under $0.20 per kWh including debt repayment.

The body and float of the Waveberg are constructed of composites and foam commonly used in yachts. The body can be constructed locally, while the pumps, valves and controls are shipped from a central plant. Simplicity is key to low cost and high durability. By supporting the further development of a potential low-cost durable WEC design, this testing will promote the industry further toward broader scale commercialization.

6 Work Plan

SPECIFIC APPROACH TO ACHIEVE OBJECTIVES

This project required a succinct set of tasks to achieve the desired results. First, the initial preparation was completed to detail the device to be tested. This will included providing of a model drawing, specification of body properties, PTO setup, mooring configuration, and results expected. Once the geometry was agreed upon, the CAD model and a mesh were created and run through Capytaine (BEM) to achieve the necessary WEC-Sim inputs. Next, a baseline WEC-Sim model was created and verified through static and free decay simulations. The baseline model was assessed in wave conditions specified by Waveberg and the results processed to achieve the desired metrics. Results from tank testing were compared directly to processed WEC-Sim results for verification and validation purposes. Lastly, a technology transfer was formally completed to ensure Waveberg has access and ability to utilize the model, and the final documentation was completed.

TASK 0: Waveberg share device properties and existing CAD models of concept

- **Waveberg completed the following:**
  - Define the mass and moment of inertia of both bodies.
  - Provided the geometric parameters of the 1:25 scale wave energy converter (WEC).
  - Shared PTO information to determine if PTO-Sim needs to be used.
  - Provided details on mooring cables or station keeping system to determine if a linear stiffness matrix is sufficient or MoorDyn will be needed.
  - Define up to three quantities of interest to be measured and reported to evaluate model performance. These could include:
    - Device response
    - Power performance
    - Capture width ratio
    - Device lag to the wave (phase delay) to estimate friction in the physical model.

TASK 1: Develop BEM models of the Waveberg device

- **WEC-Sim completed the following:**
  - Defeatured the device geometry (in CUBIT).
  - Meshed the device geometry (in CUBIT).
  - Ran the geometry in BEM solver (Capytaine).
- **Waveberg completed the following:**
  - Waveberg provided a model of the device to the WEC-Sim team.
  - Waveberg met with the WEC-Sim facility bi-weekly to provide regular updates and answer questions about modeling decisions.

TASK 2: Develop baseline WEC-Sim model of the Waveberg device

- **WEC-Sim completed the following:**
  - Developed baseline WEC-Sim model of the Waveberg device based on Waveberg provided device parameters.
    - Completed static water cases to verify hydrostatic stability.
    - Completed free decay tests to verify the correct energy dissipation mechanisms are in place and the model is stable.
    - Completed a frequency domain analysis by sending waves across a range of wave periods and two wave heights to verify model operation.
    - Ran final wave conditions that were defined by Waveberg to evaluate the performance metrics defined by Waveberg.
  - Shared WEC-Sim model development with Waveberg through private GitHub repository.
  - Met with Waveberg bi-weekly to provide updates on model development.
- **Waveberg shall complete the following:**
  - Waveberg provided relevant device parameters necessary to develop the WEC-Sim model, e.g., mass properties, PTO dynamics, mooring configuration, still water line, etc.

- Waveberg defined the wave conditions relevant for estimating the desired performance metrics (i.e., device motion, power performance, loads, etc. defined in Task 0).

TASK 3: Data analysis and post processing

- **WEC-Sim completed the following:**
  - Post process WEC-Sim results based on Waveberg provided metrics.
  - Shared data with Waveberg through private GitHub repository.
  - Met with Waveberg bi-weekly to provide updates on data analysis.
- **Waveberg completed the following:**
  - Waveberg provided feedback on the reported desired metrics, e.g., power output, motion response, mooring loads.

TASK 4: Model verification and validation

- **WEC-Sim completed the following:**
  - Compared WEC-Sim model results to Waveberg experimental data provided.
  - Share Verification & Validation results with Waveberg through private GitHub repository.
  - Meet with Waveberg bi-weekly to provide updates on data analysis.
- **Waveberg completed the following:**
  - Waveberg provided relevant experimental and historical data for Verification & Validation, e.g., experimental data, simulated data.
  - Waveberg provided curated tank test data for WEC-Sim model verification.

TASK 5: Dissemination and technology transfer

- **WEC-Sim completed the following:**
  - Hosted technology transfer meeting(s) with Waveberg, to go through work completed during the TEAMER award, and answer any WEC-Sim questions.
  - Provided the following to DOE.
    - An initial abstract suitable for public release at the time of the CRADA is executed.
    - A final report, within thirty (30) days upon completion or termination of this CRADA, to include a list of Subject Inventions.
    - Other scientific and technical information in any format or medium that is produced as a result of this CRADA.
- **Waveberg completed the following:**
  - Waveberg collaborated with the WEC-Sim facility on development of manuscript, final report, and participated in tech transfer meeting.

6.1 Numerical Model Description

The numerical simulation tool utilized for the modeling to be carried out on the Waveberg Floating Attenuator WEC is the Wave Energy Converter-Simulator (WEC-Sim). WEC-Sim is an open-source software for simulating wave energy converters (WECs) jointly developed by the National Renewable Energy Laboratory and Sandia National Laboratories in the United States. WEC-Sim is developed in MATLAB/SIMULINK framework utilizing Simscape Multibody to solve the multi-body dynamics problem.

WEC-Sim predicts WEC dynamics through time domain simulations based on the radiation and diffraction method using hydrodynamic coefficients obtained from frequency-domain boundary element methods (e.g., WAMIT, NEMOH, Aqwa, Capytaine). A comprehensive mesh refinement study was completed to ensure the BEM results accurately represent the dynamics. The model was also validated against tank testing data provided by Waveberg, which will further ensure accuracy.

6.2 Test and Analysis Matrix and Schedule

Table 1: Task List and Schedule

Task No.	Task Title	Duration (Estimated Starting & Ending Project Month)	Responsible Parties
0	Waveberg share device properties and existing CAD models of concept	1	Waveberg
1	Develop BEM models of the Waveberg device	1-3	Sandia/NREL/Waveberg
2	Develop baseline WEC-Sim model of the Waveberg device	2-5	Sandia/NREL/Waveberg
3	Data analysis and post processing	5-9	Sandia/NREL/Waveberg
4	Model verification and validation	5-8	Sandia/NREL/Waveberg
5	Dissemination and technology transfer	8-9	Sandia/NREL/Waveberg

6.3 Safety

The project will not require any in-person or physical testing and analysis will be completed as a desktop study. Applicable office safety standards will be followed.

6.4 Contingency Plans

Wave tank tests of the Waveberg were completed at Stevens Institute of Technology. The results of these tests are used to complete validation of the WEC-Sim model. If the tank testing is delayed for any reason, Waveberg shall notify WEC-Sim and will need to request a TEAMER extension if they desire to focus on including the tank test data in the validation/verification effort.

6.5 Data Management, Processing, and Analysis

6.5.1 Data Management

The data from the modeling and simulation of the WEC will be collected into a zip file weekly and uploaded to be stored on GitHub. The data and plotted results for the numerical model tested in the wave conditions identified in Table 2 will be submitted to the Marine Hydrokinetic Data Repository (MHKDR).

6.5.2 Data Processing

Data processing was completed for both the WEC-Sim simulation results and the existing tank test data provided for comparison. Data processing will be completed in the post-processing of the WEC-Sim simulations. MATLAB scripts will be used to extract the WEC response, PTO force, mooring force, and PTO power. Meaningful directory and file names will be used for clarity and figures will be provided with accompanying post processing scripts attached for complete traceability and reproducibility. The verification against tank test results and identification of residual errors will support uncertainty quantification.

6.5.3 Data Analysis

To analyze the data from the numerical model, various metric will be plotted in the time domain. This includes the WEC response (position, velocity, acceleration), PTO and mooring forces, and power output. These results will be compared to 1:25 tank testing results completed at Stevens Institute of Technology. The primary sea states to be investigated in-depth are shown below.

Table 2: Sea states in which to compare numerical model to tank test results

Type:	Tp (s)	Hs (mm)	Purpose (tank test comparison)
Regular	1.28	30	comparison
Regular	1.4	40	comparison
Regular	1.56	50	comparison
Regular	1.7	60	comparison
Regular	1.84	70	comparison
Regular	1.98	80	comparison
Regular	2.12	90	comparison
Regular	2.12	90	comparison
Regular	2.4	110	comparison
Regular	1.4	80	comparison
Regular	1.4	100	comparison
Regular	1.4	60	comparison

The dataset from the tank testing used as comparison includes the timeseries for:

a. Wave inputs from wave maker time series, spectra, and wave gauges along flume
b. 6 DOF motion from onboard IMU
c. Pressure and power from PTO
d. Time-domain data from the encoder located at the top hinge of the main body

The primary goal of this comparison is to validate and verify the numerical model to provide a sufficient match between numerical and experimental results.

7 Project Outcomes

7.1 Results

The objective of this project was to develop a numerical model of the Waveberg WEC using WEC-Sim and validate the model with results from a previous TEAMER award for tank testing of the Waveberg at Stevens Institute of Technology.

To create a WEC-Sim model, the team needed to first understand the design and relevant dynamics of the Waveberg WEC (Figure 1). The device is defined by a "main body" and a "front float" with the front float placed in front of the main body with respect to the wave propagation. Thus, the two bodies are impacted by the waves at different times; the front float encounters the wave first then the main body. This leads to the two bodies oscillating out of phase and the relative motion can be used to generate power. In understanding the WEC dynamics, the WEC-Sim team created the diagram shown in **Error! Reference source not found.**. Essentially, the front float rotates about the point on the main body labeled as the pitch rotational constraint at [0.68, 0, 0.122]. This causes the piston (hinge on both ends) to extend and collapse. Water is taken in by the piston during extension and then pumped through a pressured PTO during compression. Based on this diagram, the WEC-Sim team was able to understand the dynamics and move on to developing the model.

Next, a geometric model of the Waveberg WEC design was created in SolidWorks and the geometry was meshed using Cubit. Capytaine was utilized to calculate the hydrostatics and the hydrodynamic coefficients, an input to WEC-Sim necessary for modeling the dynamics. At this stage, an obstacle was reached. When analyzing the tank test results, the team found that ballast was being added and removed to the WEC for many of the runs. Changing the ballast alters the drafts and rotations of each body and leads to different hydrodynamic interactions. To resolve this obstacle, the WEC-Sim team worked with Waveberg Development to decide on one specific ballast combination for the numerical model. These updated ballast values are displayed in

Table 3 and were chosen because they are both relatively close to the middle of the range of ballasts tested and were used for a significant number of the tank tests. **Error! Reference source not found.** shows the updated PTO and constraint locations when considering the draft and rotational changes due to the ballast.

Table 3: Ballast and corresponding draft and rotation for each body

	Ballast Mass (kg)	Ballast Location (m) (with respect to center of gravity)	Draft (m)	Angle of Pitch Rotation (degrees)
Front Float	0.909	[0, 0, 0.38]	0.003	0
Main Body	2.5	[0.06,0.6715,0.076]	0.0044	0.376

To model them, the WEC-Sim team converted the ballast masses into effective drafts and angles of rotation. For the front float, this was very simple to calculate as the ballasts were centered. Unfortunately, this led to an unexpected result in which the theoretical draft is much larger than the draft observed in the tank tests (Figure 4). Thus, the WEC-Sim Team, in coordination with Waveberg Development, made the decision to estimate the draft of the front float based on images from the tank tests. It is likely that the estimated draft is incorrect, and because the team was modeling the device from experiments, using the estimated experimental draft made intuitive sense. Furthermore, any discrepancies in results are likely to be resolved when tuning the WEC-Sim model later in the project.

For the main body, the placement of the ballasts toward the rear of the body meant an iterative process was needed to calculate the equilibrium rotation of the body (Table 3, columns 3 and 4). To find the equilibrium rotation, the equilibrium draft was found for each respective angle of rotation and the known center of gravity location compared to the calculated center of buoyancy (Figure 5). The point at which the x-location of the center of gravity was equal to the x-location of the center of buoyancy is known as the metacentric stability. This iterative analysis led to a draft value 0.004 m and a rotation angle of 0.04°, like the expected draft from Figure 4.

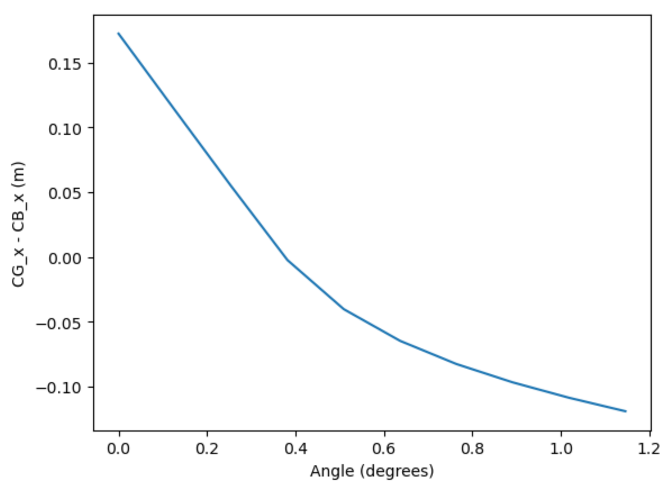


Figure 1: Difference between the x-location of the center of gravity and center of buoyancy vs. rotation angle. Used to find the point of equilibrium (where x-location of center of gravity is equal to x-location of center of buoyancy)

After determining the equilibrium draft and angle of the Waveberg WEC with the defined ballast, the BEM results were run in Capytaine. A mesh convergence study was completed, where the mesh was refined iteratively to determine the appropriate mesh refinement. A very fine mesh was required to compute the hydrodynamic coefficients accurately due to the very small draft values. The mesh elements needed to be sufficiently smaller than the draft itself. An element size of 0.005 m for the front float and 0.01 m for the main body was deemed sufficient. With these mesh sizes, the computation time was relatively significant and Sandia's High Processing Compute servers were used to run Capytaine. The results for the original WEC-Sim model, loaded and plotted by WEC-Sim's BEMIO feature, can be found in Appendix 1.

After loading the BEM results into WEC-Sim, the WEC-Sim baseline model was created.

Model picture and considerations redacted.

It is important to start simple and ensure the model is stable. First, both bodies were examined without waves first using the standard calculation and second using the convolution integral calculation (CIC). When using the CIC method, the front float was found to cause the model to go unstable. This is something that is not uncommon in WEC-Sim and is likely associated with inaccuracies in the BEM results due to the small ballast. To resolve this, a linear damping of 10 Ns/m was added to the front float and led to a stable model. Linear damping is often present in the physical models but not fully captured by BEM. Thus, the addition here is not unexpected and will also be tuned in future tasks. Next, free decay tests were completed for both bodies (no PTO present) to ensure stability and estimate the natural frequency. The values of the natural periods of the main body and front float in pitch and heave are confirmed to be similar to what was expected by Waveberg Development.

After confirming the stability and natural periods of the two bodies independently, it was time to develop the PTO model based on the water pressure system in the tank tests. The physical model relies on a piston pump which intakes water during an expansion phase and pushes water out during the compression phase. A back pressure valve and gravity pressure system are used to create the desired pressure for each tank test. A small (0.5 L) hydraulic accumulator was also used to smooth the resulting force. A diagram of the system, drawn by Waveberg Development, is shown in Figure 7.

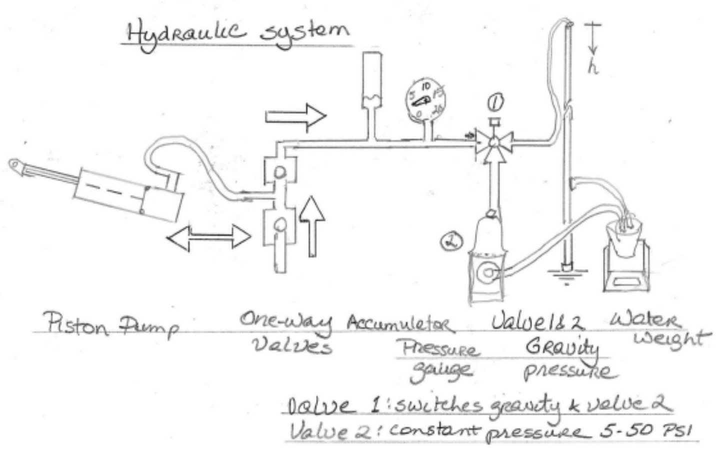


Figure 2: PTO diagram

Based on the above information, two PTO models were created in Simulink. First, a complex PTO using Simscape was developed to represent the hydraulics (Figure 8).

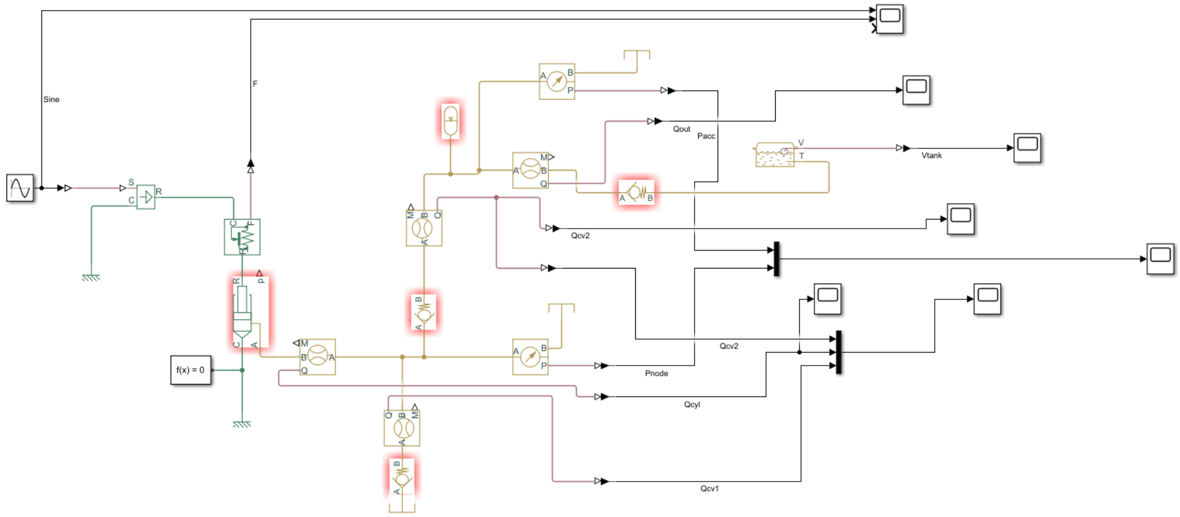


Figure 3: Complex PTO Model

Second, a MATLAB script was developed as a simplified model of the PTO. During the expansion phase, no pressure force is applied. During the compression phase, the pressure force applied is equal to the set pressure times the piston cross-sectional area. Throughout the entire oscillation, a PTO friction force is also applied, which is defined as a damping coefficient (to be tuned). The mechanical power in this case is the pressure force multiplied by the velocity at each timestep. Due to the complexity of the Simscape model, it required a larger computation time than the baseline model. Thus, the simplified MATLAB script model was used for efficiency while still providing accurate results. The complex PTO model will still be provided to Waveberg Development during the technology transfer. The Simulink PTO model (Figure 9) and accompanying MATLAB function (Figure 10) that were used for the remainder of the project can be seen below.

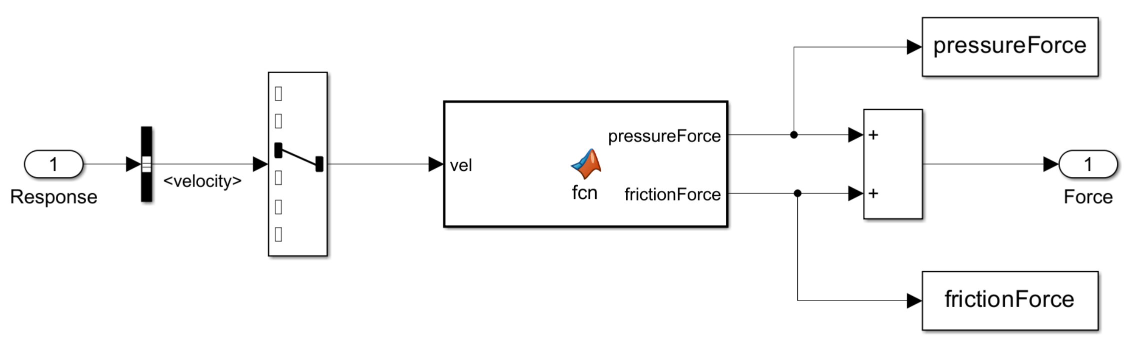


Figure 4: Simplified Simulink PTO model

```
function [pressureForce, frictionForce] = fcn(vel, setPressure, pistonArea, pistonDamping, transitionVel)


    if vel < -transitionVel
        %timeCount = timeCount + dt;
        %if timeCount > timeTransition
        pressureForce = setPressure*pistonArea;
        %else

        %end
    elseif vel < 0
        damping = (1/transitionVel)*setPressure*pistonArea - pistonDamping;
        pressureForce = -damping*vel; % -(timeCount/timeTransition)*setPressure*pistonArea
    else
        pressureForce = 0;
    end
    frictionForce = -pistonDamping*vel;
end
```

Figure 5: Simplified MATLAB script model

The water output was recorded for each wave tank test by placing a bucket at the output of the pump system and measuring the weight of water at the end of the test. This was incorporated within WEC-Sim by first calculating the piston displacement of the piston arm for each interval of maximum extension and compression. This displacement difference is multiplied by the piston area to find the water output of each interval. These intervals are summed to find the cumulative water output. This unit of water volume is cubic meters and can be multiplied by 1000 to find the output water volume in liters. In the tank tests, the water output was measured as the water weight in pounds. A simple conversion factor could be used to convert the water volume to the weight of water to verify the water output. Mooring was also added using WEC-Sim's mooring class, which then initialized stiffness, damping, and pretension matrices. Waveberg has very simple mooring system with essentially a stiffness and damping value applied in the surge direction.

Next, the comparison to the tank test is vital to ensuring an accurate model. The tank test runs were divided into two groups based upon the input pressure, which was either 3.5 or 4 psi. These values were selected as they were the two most frequently used input pressures for tank test runs with a front ballast of 0.909 kg and rear ballast of 2.5 kg. The period from each run was recorded and an input wave height was calculated for each run using that runs' wave wire data. The period and wave height were used as inputs for multiple condition runs (MCR). To most accurately compare the WEC-Sim results with those of the tank test, a RAO (response amplitude operator) of the hinge angle measure was developed for both, using the tank test data and the MCR results. The hinge angle measure was a recording of the pitch at the hinge that connects the top arm to the top of the main body (constraint(2) in WEC-Sim). This measurement was used as it was the most reliable piece of data produced from the tank tests. Initially, the RAO produced from the WEC-Sim results showed a different trend than that of the tank test data, as seen below in Figures 11 and 12.

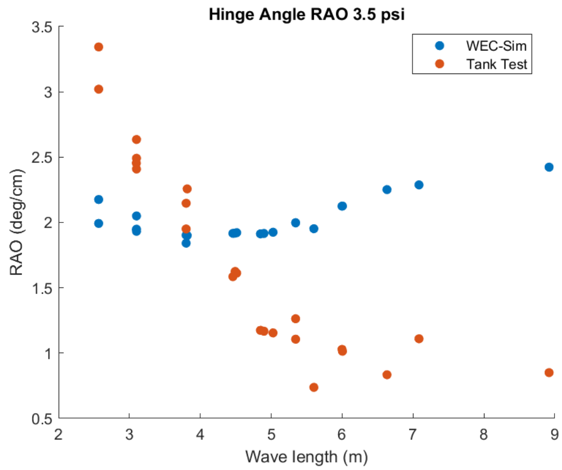


Figure 6: Hinge Angle RAO Comparison 3.5 psi

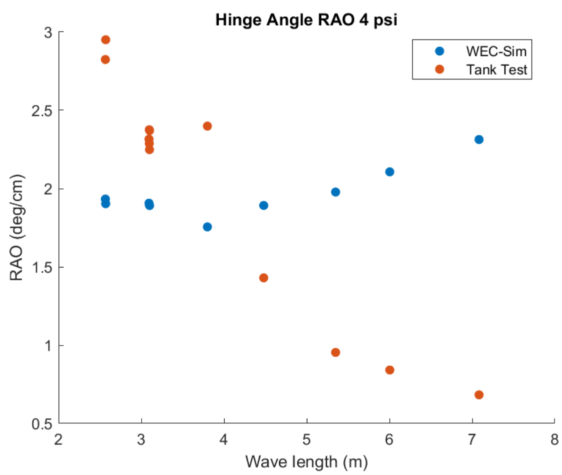


Figure 7: Hinge Angle RAO Comparison 4 psi

Tuning of WEC-Sim input parameters did not change the trend of the WEC-Sim RAO and thus did not improve the results. Experimentation with manually altering the hydrostatics in the .h5 file (contains the hydrodynamics and hydrostatics for WEC-Sim to use) produced a hinge angle RAO with a trend that more closely resembled the tank test data. This led to an investigation into the hydrostatics and hydrodynamics output from the BEM code. It was determined that the hinge motion was largely controlled by hydrostatics more so than hydrodynamics. This is evident when manually changing the coefficients within the hydrostatic matrix in WEC-Sim. Figure 13 shows hydrostatic matrices and their corresponding hinge angle response, which differ greatly in amplitude.

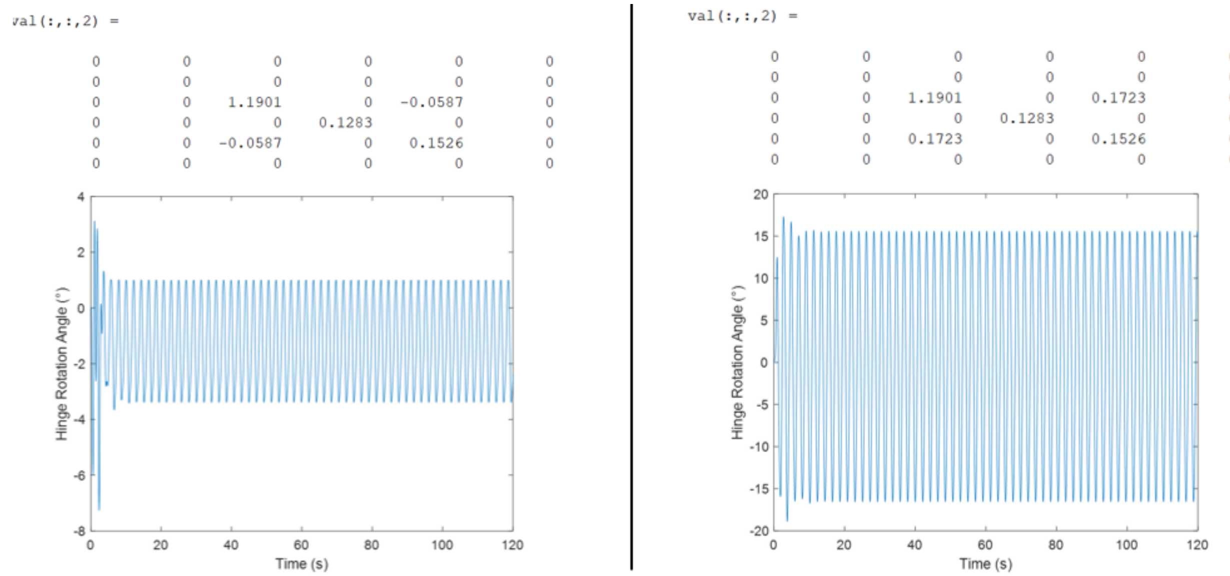


Figure 8: Hydrostatic Stiffness Matrix and Hinge Rotation Angle Response

Characteristics of the main body within the BEM code affect the resulting hydrostatic matrix. One such characteristic is the location of the ballast. As seen below in Figure 14, slight changes to the x coordinate of the ballast location result in large changes to the hinge angle RAO from WEC-Sim. This test manually changes the x coordinate of the ballast location while not changing anything else. This was very valuable to understand the trend, but not realistic. If the ballast's x-location changes, the main body pitch angle would also need to change and the hydrodynamic coefficients (excitation, added mass, etc.) will also change. Thus, we needed to complete a multi-variable study to find the configuration which (with consistent changes across ballast x-location, pitch angle, and BEM coefficients) achieves the closest match while maintaining accurate physics.

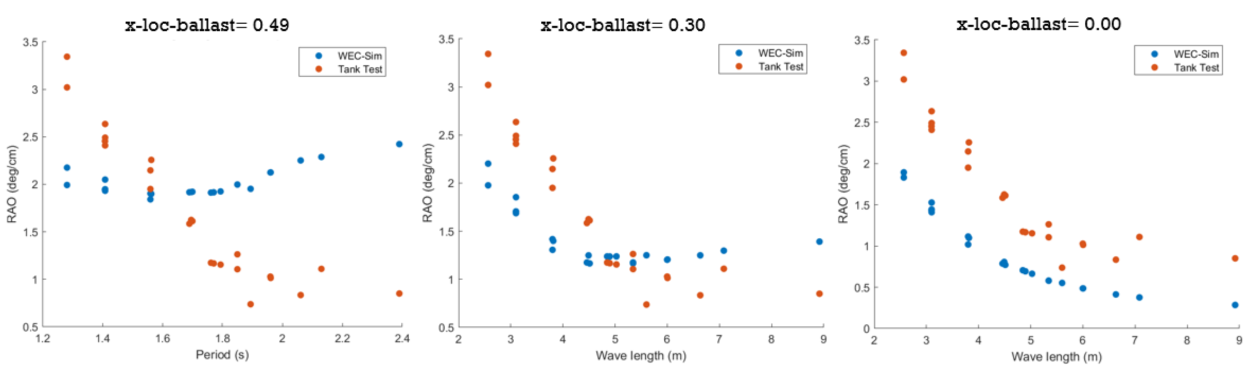


Figure 9: Effect of ballast location on hinge angle RAO

Subsequently, the ballast parameters in the BEM code were altered to adjust the hydrostatics. The values of draft, pitch, and the x coordinate of the ballast location of the main body were not absolutely determined, so altering these terms could more accurately represent the hydrostatics within WEC-Sim. First, the coefficients within the hydrostatic matrix were determined that resulted in a hinge angle RAO that exhibited greater agreement. Figures 15 and 16 show a manually altered hydrostatic matrix and a resulting RAO with greater agreement between the tank test and WEC-Sim results.

```
val(:,:,2) =

     0         0         0         0         0         0
     0         0         0         0         0         0
     0         0    1.0240    0.0000   -0.0172         0
     0         0    0.0000    0.1274    0.0000         0
     0         0   -0.0172    0.0000    0.0935         0
     0         0         0         0         0         0
```

Figure 10: Improved hydrostatic matrix through manual manipulation

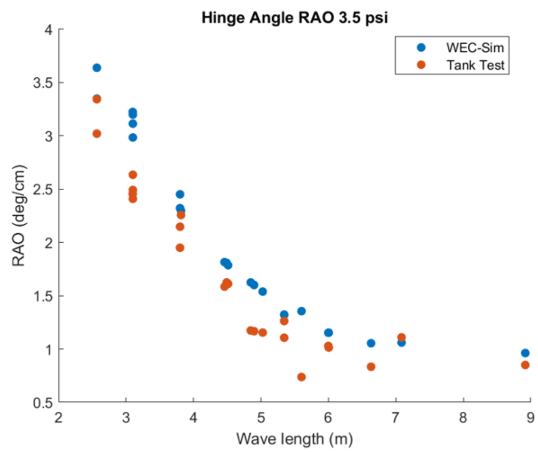
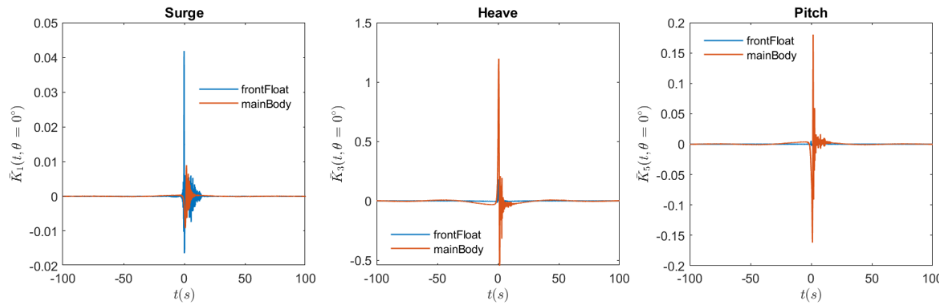


Figure 11: Improved RAO as result of manually manipulated hydrostatic matrix

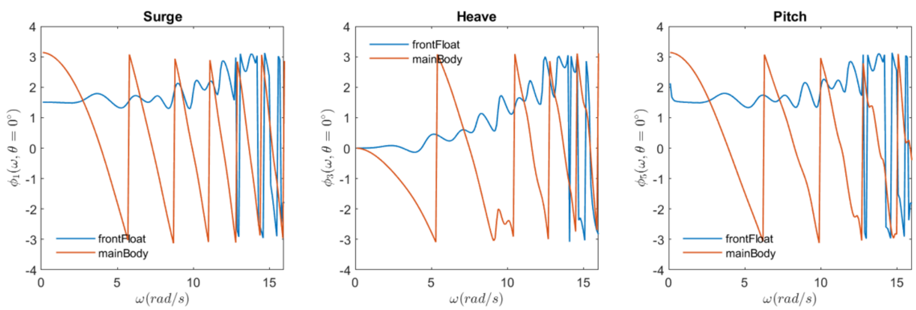
The next step was to alter the inputs within the BEM code, so the resulting hydrostatics matched those that produced a more optimal RAO. To do this the draft, pitch, and x location of the ballast values were manually adjusted until the coefficients were sufficiently close to those in the matrix above. The improved hydrostatics were generated and used within BEMIO to create a new .h5 file. This .h5 file was used to rerun the WEC-Sim MCR with updated hydrostatics and the resulting RAO resembled that in Figure 16. As the parameters within the BEM code had been changed, the entire BEM code needed to be rerun so that hydrodynamics along with the hydrostatics could be regenerated. The results from the BEM for the updated WEC-Sim model were loaded and plotted by WEC-Sim's BEMIO feature and can be seen in Figure 17.

Normalized Excitation Impulse Response Functions: $\bar{K}_i(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{X_i(\omega,\theta)e^{i\omega t}}{\rho g} d\omega$

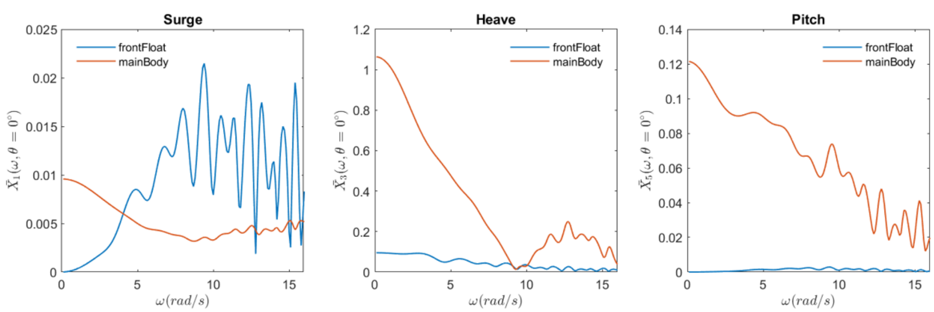


Notes:
• The IRF should tend towards zero within the specified timeframe. If it does not, attempt to correct this by adjusting the ω and t range and/or step size used in the IRF calculation.
• Only the IRFs for the first wave heading, surge, heave, and pitch DOFs are plotted here. If another wave heading or DOF is significant to the system, that IRF should also be plotted and verified before proceeding.

Excitation Force Phase: $\phi_i(\omega, \theta)$



Normalized Excitation Force Magnitude: $\bar{X}_i(\omega, \theta) = \frac{X_i(\omega, \theta)}{\rho g}$



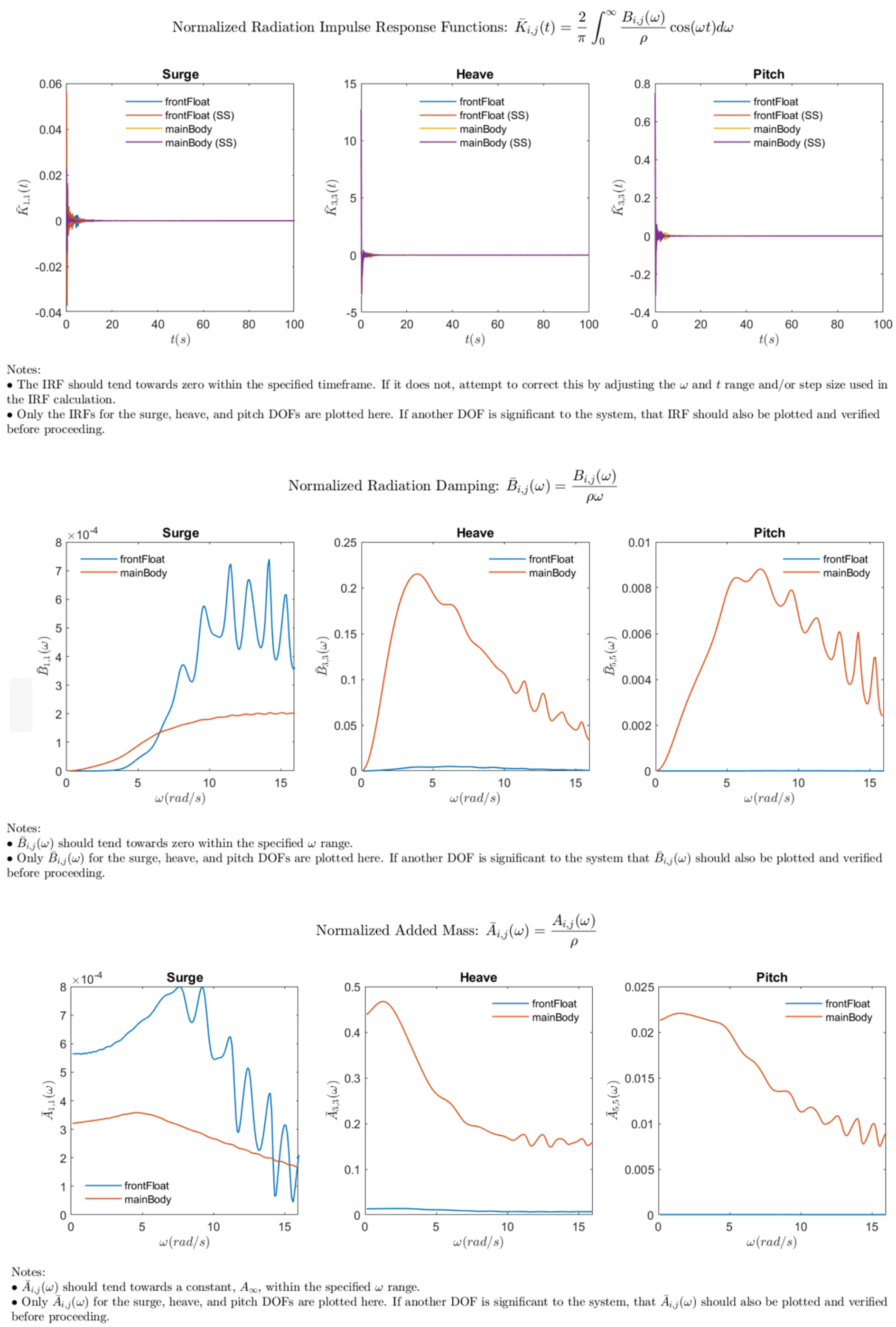


Figure 12: BEMIO plots for final BEM run

Multiple Conditions Runs (MCR) for the 3.5 psi case were completed. There was still a slight deviation between the WEC-Sim and tank test results with the WEC-Sim RAOs being slightly overdamped. To improve the agreeability between the results, the damping applied to both bodies in heave and pitch was decreased within the WEC-Sim input file. The resulting hinge angle RAO showed significant agreement between the WEC-Sim and tank test results for both the 3.5 psi and 4 psi cases, as seen in Figures 18 and

19. Note that Figures 18 and 19 show the tank test results using encoder calibration factors of 0.1951 and 0.176 (conversion from encoder units to degrees). The WEC-Sim model was tuned to match the results with a calibration factor of 0.1951, but later analysis indicated a calibration factor of 0.176 so both are shown for reference. A number of sources of error are present including the uncertainty in main body rotation, front float draft, and wave conditions.

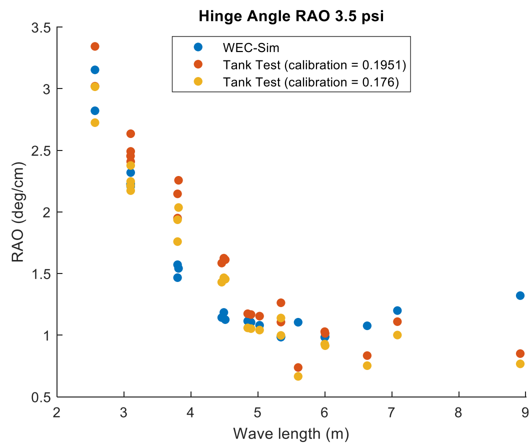


Figure 13: Final hinge angle RAO at 3.5 psi

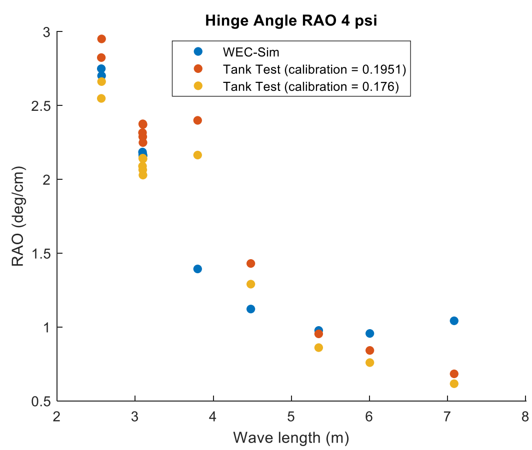


Figure 14: Final hinge angle RAO at 4 psi

The heave and pitch RAO plots differed slightly between the WEC-Sim and tank test results (from inertial measurement unit (IMU) data), as can be seen below in Figure 20. The heave response of the WEC-Sim model was more damped than the tank test results, and the pitch response of the WEC-Sim model was less damped than the tank test results. Altering the location of the ballast within the BEM code changed the location of the center of gravity of the main body in the WEC-Sim model. The tank test results were measured using an IMU on the main body. Changing the center of gravity in the WEC-Sim model means that the WEC-Sim measurements are taken from a location different than that of the IMU in the tank tests. Although a coordinate transformation could be used to move the response to the IMU reference point, the uncertainty in the exact IMU location presents another challenge, so the response was compared as is. This difference in measurement location likely results in additional pitch motion at the

IMU location leading to a greater heave response than at the center of gravity. The discrepancy between the pitch RAO results is likely caused by multiple factors. First, the gyration in pitch was measured during the tank tests and those values were later integrated to find the angular position in pitch. In doing this, offset error is likely to be present resulting in differences between the WEC-Sim and tank test pitch readings. It is also likely that drag uncertainty (not accounted for in BEM) plays a part in this discrepancy between the results.

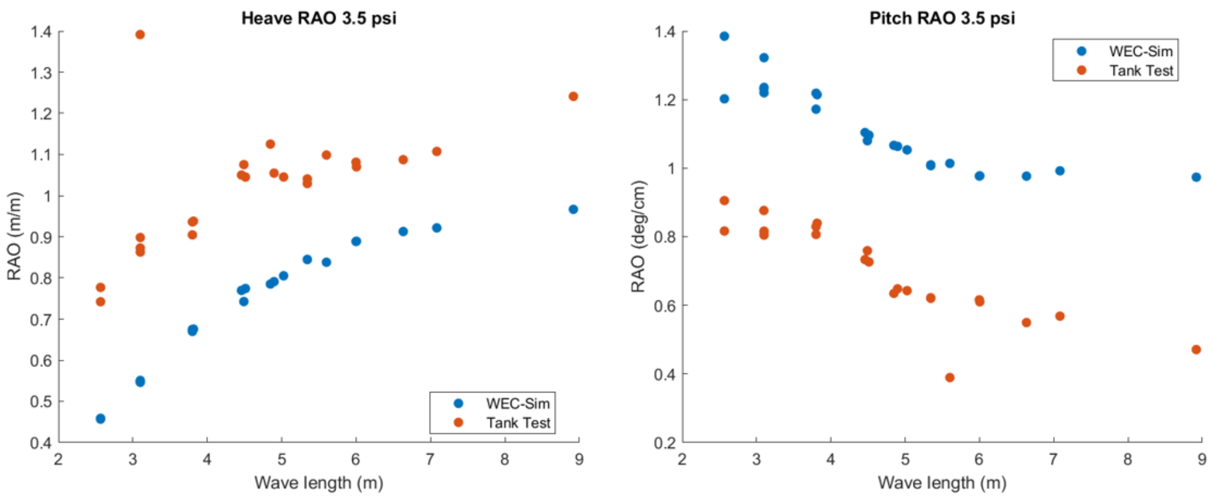


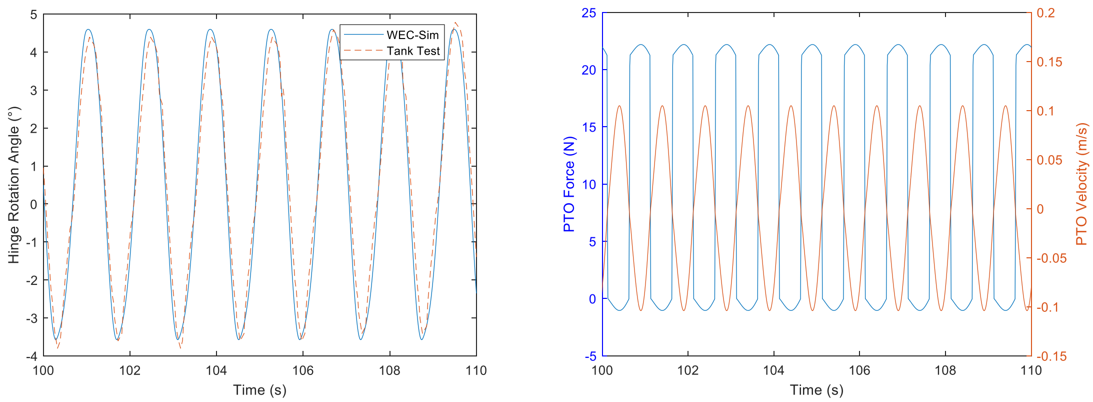
Figure 15: Final heave and pitch RAO comparison between WEC-Sim and Tank Test

As a characterization of the model to determine the natural periods of the bodies a free decay test was performed. To determine the natural period of both devices in heave, the `noWave` condition was used while specifying a wave period of 1 second and an initial displacement of positive 1 meter was applied to both bodies about their centers of gravity (no PTO damping included). For the natural periods in pitch, the same wave conditions were used, and a .5 radian initial rotation was applied to both bodies about their centers of gravity. The results from these free decay tests are shown below in Table 4. The plots used to calculate the values of natural periods can be found in Appendix 1. The natural period of the mainBody in heave is longer than that of the frontFloat, but both bodies have similar natural periods in pitch.

Table 4: Natural periods of the frontFloat and mainBody

frontFloat		mainBody	
Heave	Pitch	Heave	Pitch
0.885 seconds	0.66 seconds	1.2933 seconds	0.6825 seconds

Figure 21 shows the response of the tuned model in regular waves with a set pressure of 4 psi. This is setup to match conditions from run 166 from the tank testing with a measured wave height of 0.0358 m and wave period of 1.4084 s. The hinge rotates within a range of about 8 degrees. The results from WEC-Sim match those from run 166 very well in terms of the hinge angle rotation (Figure 21a). The PTO force (Figure 21b) reaches just over 20 N during the compression phase with only a small contribution due to friction. Although the PTO force was not measured explicitly in the tank testing, this value is within the expected range.



a b

Figure 16: Response of the WEC simulation from 100 to 110 seconds in terms of the a) hinge angle b)PTO piston velocity and force

MCR runs were completed to demonstrate a power matrix and the capture width of the Waveberg wave energy converter. The wave conditions used included wave heights ranging from 0.01 to 0.1 meters with a step size of 0.01 meters and wave periods ranging from 1 to 2 seconds with a step size of 0.1 seconds. The power matrix with a PTO pressure of 4 psi can be seen below in Figure 22. At this pressure, the Waveberg WEC performs best within wave periods of 1 and 1.1 seconds. Likewise, Figure 23 shows that the capture width is the greatest at lower wave periods, with 1.1 second waves maximizing this metric. Piston displacement is directly connected to power production, as such a wave period of 1.1 seconds maximizes the piston displacement shown in Figure 24. For the MCR runs with a set pressure of 32 psi, a similar trend could be observed. Figure 25 displays the power matrix at 32 psi showing that the device generates the most power at wave periods of 1 and 1.2 seconds. The difference in power production between the shorter and longer waves becomes more drastic as PSI increases. Figure 26 shows the capture width for 32 PSI, which differs from the plots for 4 PSI because the capture width value is relative to the incoming wave power. Piston displacement also appears to slightly change with the increased pressure as a wave period of 1.2 seconds maximized the piston displacement for the 32 PSI runs, which can be seen in figure 27. Additional results from the MCR runs can be found in Appendix 1.

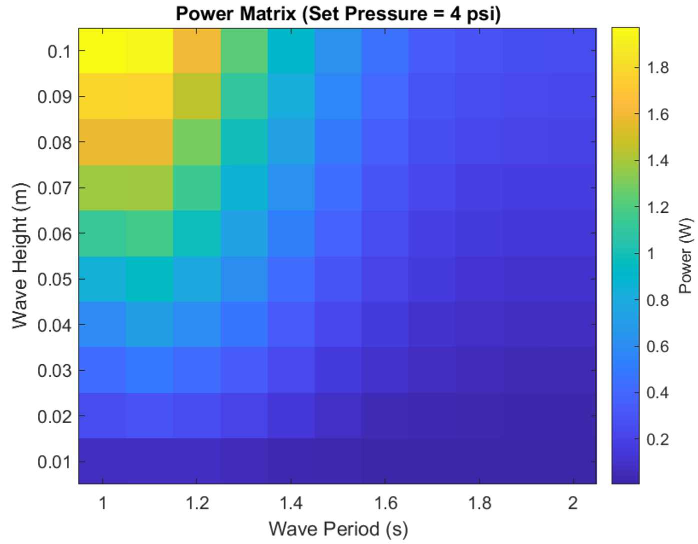


Figure 17: Power Matrix (Set Pressure = 4 psi)

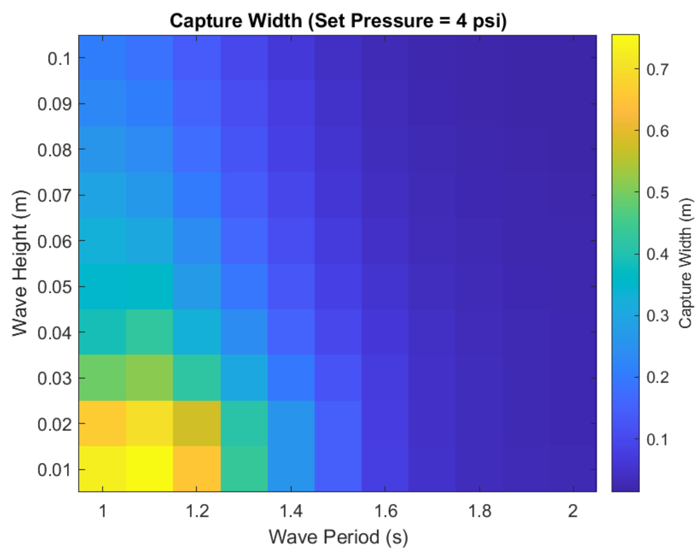


Figure 18: Capture Width (Set Pressure = 4 psi)

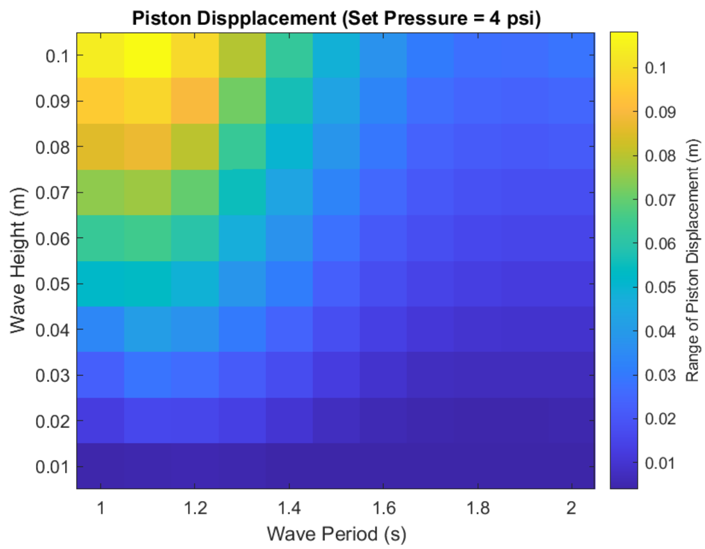


Figure 19: Piston Displacement (Set Pressure = 4 psi)

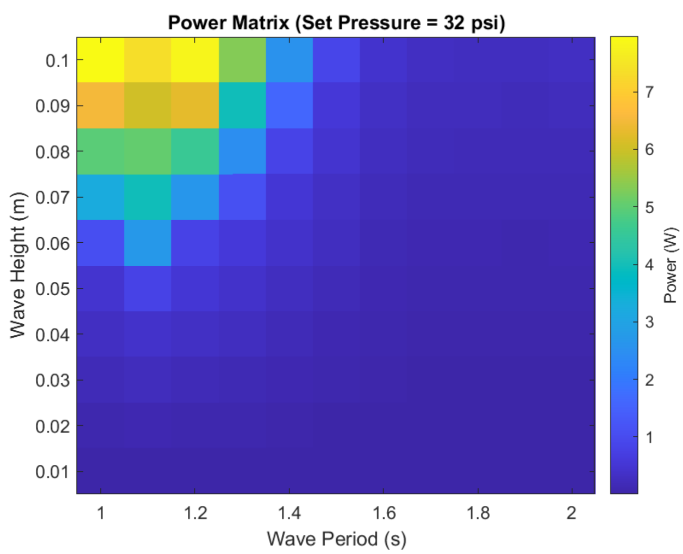


Figure 20: Power Matrix (Set Pressure = 32 psi)

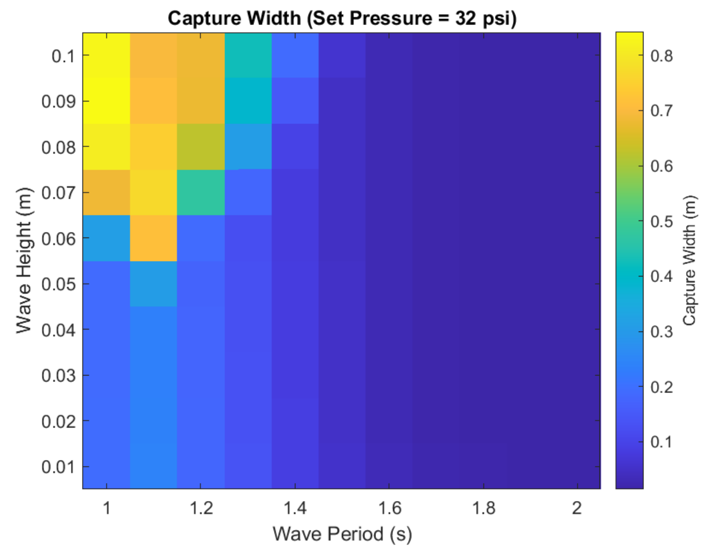


Figure 21: Capture Width (Set Pressure = 32 psi)

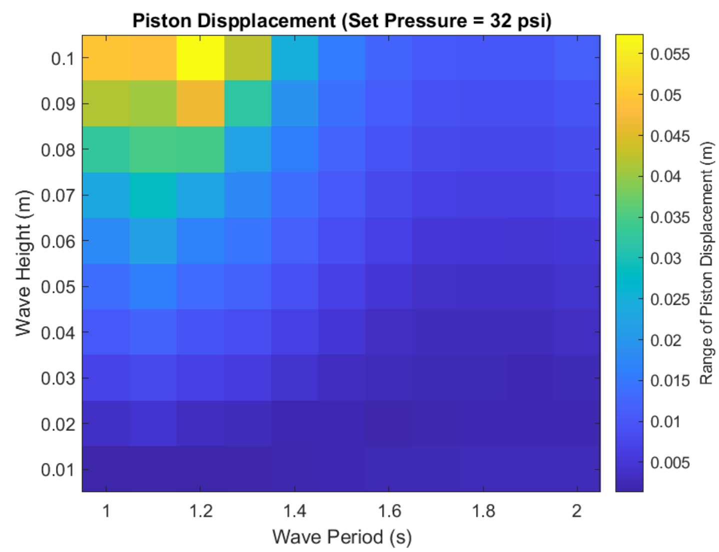


Figure 22: Piston Displacement (Set Pressure = 32 psi)

7.2 Lesson Learned and Test Plan Deviation

This project ran into some challenges that hindered the progress at times. Because the goal was to develop a validated WEC-Sim model, the project relied on adequate design information, tank test data, and data processing from Waveberg. These challenges are detailed below:

- Tank test data processing should be completed to a sufficient level before beginning a validated WEC-Sim model.
    - Because the goal was to develop a validated WEC-Sim model, the project relied on adequate tank test data and data processing from Waveberg. This data processing is still

being completed during the development of the WEC-Sim model. This meant that some of the processed tank test data was updated during the time that the WEC-Sim facility was completing the tuning. Some model development and tuning had to be repeated due to updates in the comparison data. The lesson here is that the WEC-Sim facility should communicate in more detail the processed data that is needed for validation and the TSR should have this processing completed before the award begins.

- Boundary element method is sensitive to small-thickness surfaces and features.
    Model description redacted.
- The provided design information should be sufficiently detailed and consistent.
    - The design information provided by the TSR consisted of a hand-drawn model of the WEC at 1:25 scale and an excel spreadsheet with some of the dimensions. The hand-drawn sketch was measured in Adobe Acrobat to determine other relevant dimensions, but these did not all match the details from the excel spreadsheet. More consistent measurements of all design dimensions provided in one concise document could make the process smoother. Moreover, tank testing consisted of testing multiple ballasts at different locations on the bodies. It was a challenge to determine which ballast was most appropriate to model in WEC-Sim. The TSR should make sure to decide on a consistent model configuration (ballast value) at the onset of the project to provide to the facility, which would help avoid repeated work in developing the BEM runs and WEC-Sim model.
- More accurate and a greater number of sensing equipment should be used in the tank testing.
    - The sensing equipment used in the tank testing included wave gauges, a 6 DOF IMU on the main body, a load sensor on the mooring line, a pressure gauge on the PTO, a measured water output of the PTO, and an encoder measuring the rotation of the top hinge on the main body. Unfortunately, the results from the wave gauges did not match each other, so it is unclear how reliable those measurements are. The IMU on the main body was helpful, but it would have been advantageous to also have IMU data on the front float to better understand the relative motion. The mooring and PTO data were both useful as well but could be impacted by a number of factors in the testing. The encoder located at the hinge was most useful because it provided a time domain measurement of the hinge position which could be compared directly to WEC-Sim, and it correlates directly to the piston displacement. The encoder was not recording during free decay tests though which limited the ability for the WEC-Sim team to validate a free decay model. It would have also been valuable to have a sensor measuring the piston displacement for refence. Another factor that impacted the validation of the WEC-Sim model was potential differences between the draft and rotation values in the tank testing and WEC-Sim model. To mitigate this, markers (lines, rulers, etc.) can be placed on the bodies so that the draft and rotation at any given time is easily identifiable from pictures.

Overall, the general scope of the test plan was followed, and all tasks were completed, but the timeline was slightly changed. The facility initially created a model with body bodies having zero rotation. Due to changes in the design information (ballast value and placement), the team had to redo the BEM runs for new rotated conditions. Because of the fine meshes needed, this prolonged the model setup. The tuning of the model also took longer than expected. BEM had to be rerun multiple times to achieve a model that matched the results from tank testing. Despite these deviations from the test plan timeline, the project objectives were able to be completed.

8 CONCLUSIONS AND RECOMMENDATIONS

The overall objective of this project was to develop a WEC-Sim model for the Waveberg WEC and validate it using tank test data from a previous TEAMER award at Stevens Institute of Technology. The WEC-Sim facility successfully developed the WEC-Sim model and tuned the results primarily according to the data from an encoder located at the top hinge of the main body. The results from the tuning process indicated that the WEC-Sim model matched the results from the tank testing relatively well in terms of both value and trends (for hinge data) which achieved the overall goal of the project. Additional metrics included the response of the main body in heave and pitch, which differed more significantly between the WEC-Sim model and the tank test data, but this is likely due to differences in measurement location and differences in the shape of the body (tank testing model likely had a convex shape based on pictures). A power matrix for the 4 psi case demonstrated that the power is largest for a 1 second wave with the largest wave height while the capture width is maximized at lower wave heights. For the 32 psi case (which corresponds to full-scale design), the overall power is much larger, but still concentrated around a wave period of 1-1.2 seconds, while the capture width is then maximized at the largest wave heights.

The Waveberg design is still being developed and is planning to test at larger scales in the future. It is recommended that the Waveberg team complete a comprehensive design parameter study to improve the overall design using numerical modeling before completing additional tank testing. This can be done for a full-scale model and can include changes in the body shapes, arm length, set pressure, ballast, draft values, piston friction, mooring, etc. This study may use the WEC-Sim model developed here but may also leverage additional tools such as WecOptTool. Such a study can identify areas of improvement, parameters to minimize/maximize, and prioritize the design parameters for the Waveberg team. Then, once the detailed parameter study has been completed, a larger-scale tank testing can be completed to verify the performance of the improved WEC design. In this future tank testing, the design should be characterized using free decay tests, more encompassing (and properly calibrated) sensors, and RAO tests with and without PTO attached. It is recommended to explore any design iterations only after the baseline physical model has been tested and response measured in a wide variety of conditions.

9 REFERENCES

10 ACKNOWLEDGEMENTS

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and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

11 Appendix

Appendix 1: WEC-Sim vs. Tank Comparisons

The following plots show the BEMIO results from the original model. These are before the tuning process was completed to match the hinge angle response from the WEC-Sim model to the wave tank results.

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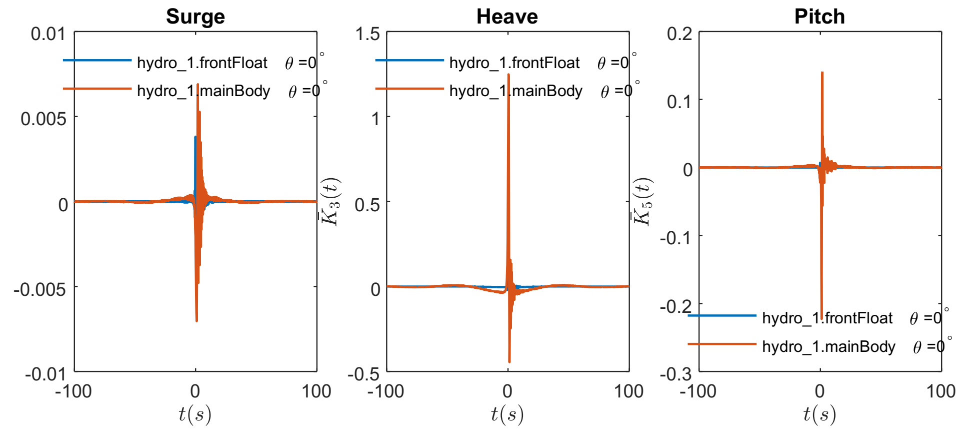
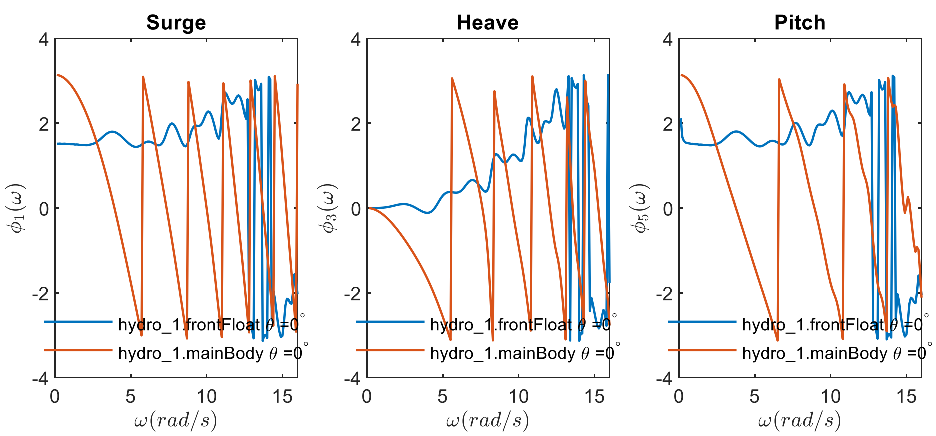
Normalized Excitation Impulse Response Functions: $\bar{K}_i(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{X_i(\omega,\theta)e^{i\omega t}}{\rho g} d\omega$

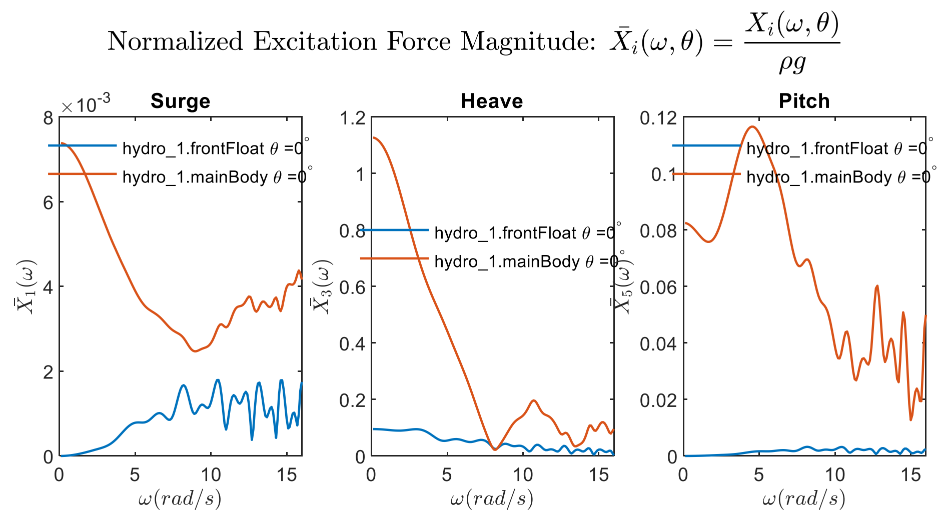


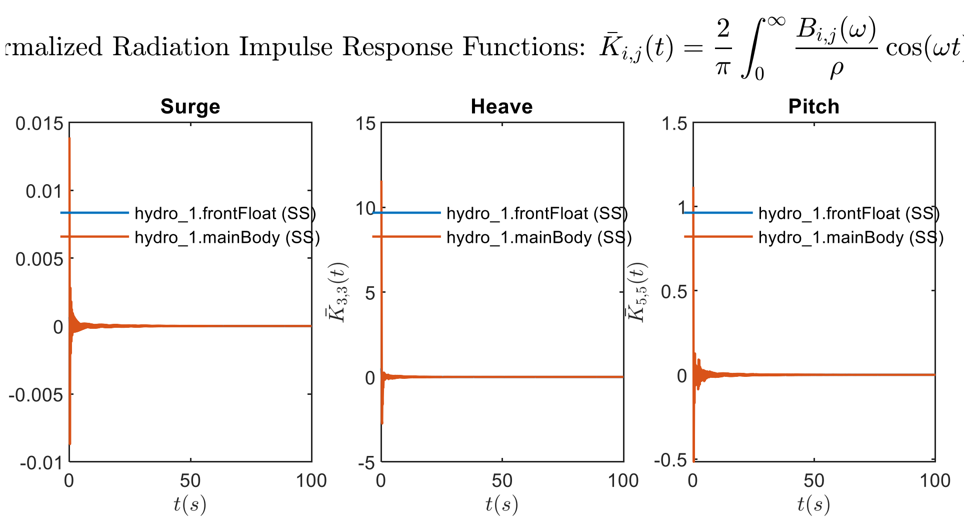
Notes:

- The IRF should tend towards zero within the specified timeframe. If it does not, attempt to correct this by adjusting the ω and t range and/or step size used in the IRF calculation.
- Only the IRFs for the first wave heading, surge, heave, and pitch DOFs are plotted here. If another wave heading or DOF is significant to the system, that IRF should also be plotted and verified before proceeding.

Excitation Force Phase: $\phi_i(\omega,\theta)$





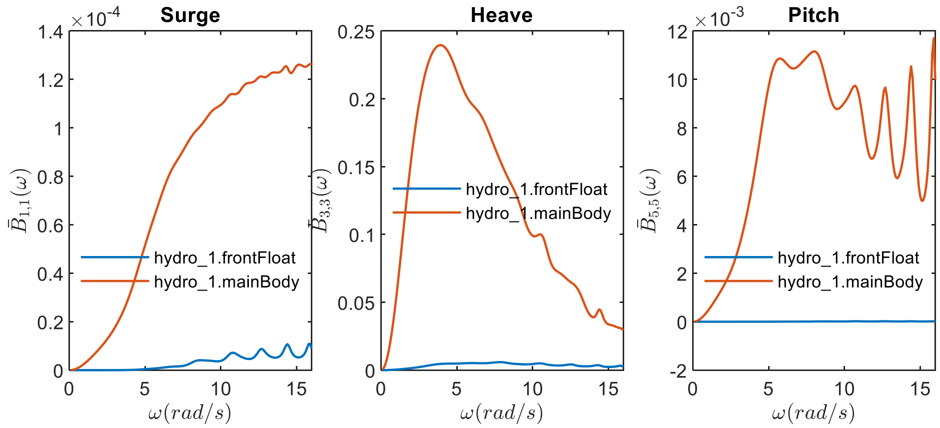


Notes:

- The IRF should tend towards zero within the specified timeframe. If it does not, attempt to correct this by adjusting the ω and t range and/or step size used in the IRF calculation.
- Only the IRFs for the surge, heave, and pitch DOFs are plotted here. If another DOF is significant to the system, that IRF should also be plotted and verified before proceeding.

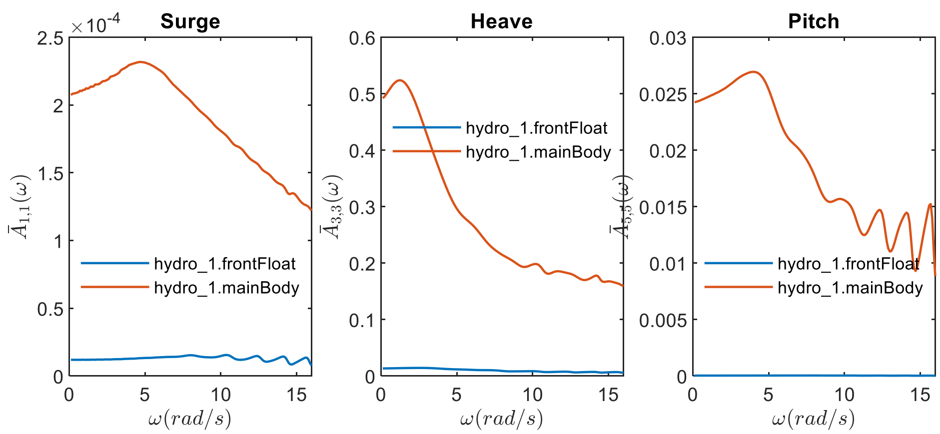
TEAMER
Testing & Expertise for Marine Energy

Normalized Radiation Damping: $\bar{B}_{i,j}(\omega) = \dfrac{B_{i,j}(\omega)}{\rho\omega}$



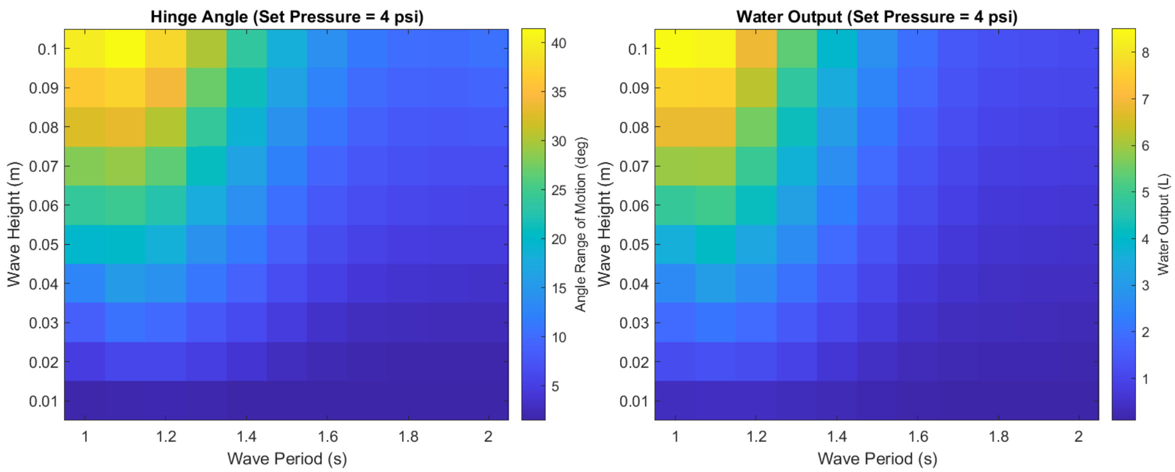
Notes:
• $\bar{B}_{i,j}(\omega)$ should tend towards zero within the specified ω range.
• Only $\bar{B}_{i,j}(\omega)$ for the surge, heave, and pitch DOFs are plotted here. If another DOF is significant to the system that $\bar{B}_{i,j}(\omega)$ should also be plotted and verified before proceeding.

Normalized Added Mass: $\bar{A}_{i,j}(\omega) = \dfrac{A_{i,j}(\omega)}{\rho}$

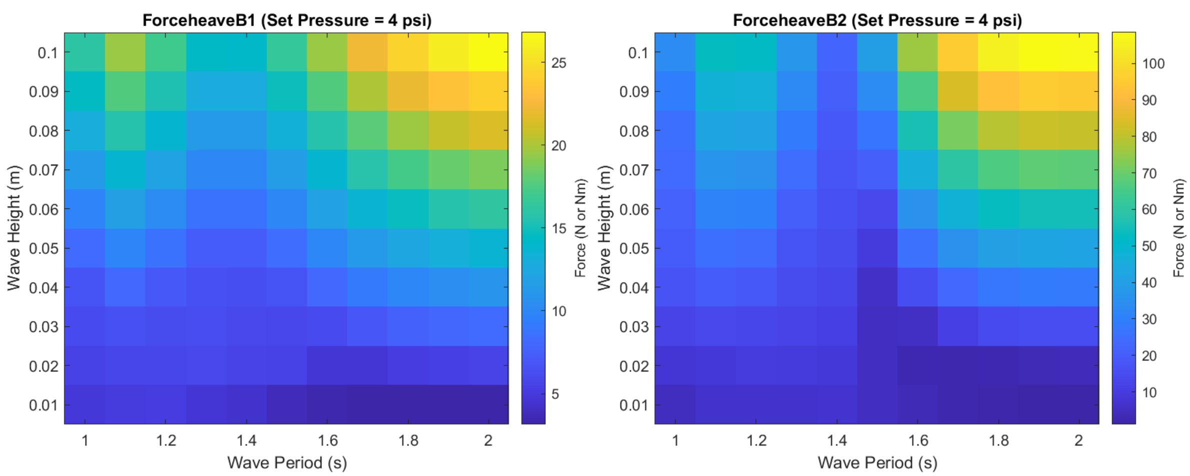


Notes:
• $\bar{A}_{i,j}(\omega)$ should tend towards a constant, A_∞, within the specified ω range.
• Only $\bar{A}_{i,j}(\omega)$ for the surge, heave, and pitch DOFs are plotted here. If another DOF is significant to the system, that $\bar{A}_{i,j}(\omega)$ should also be plotted and verified before proceeding.

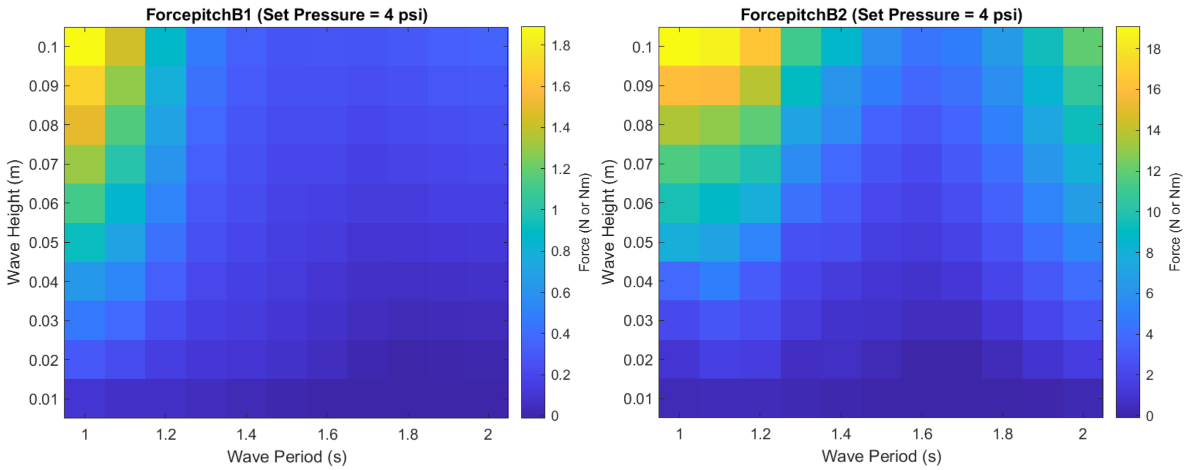
The following plots show additional results from the 4 psi and 32 psi multiple conditions runs in the range of wave conditions.



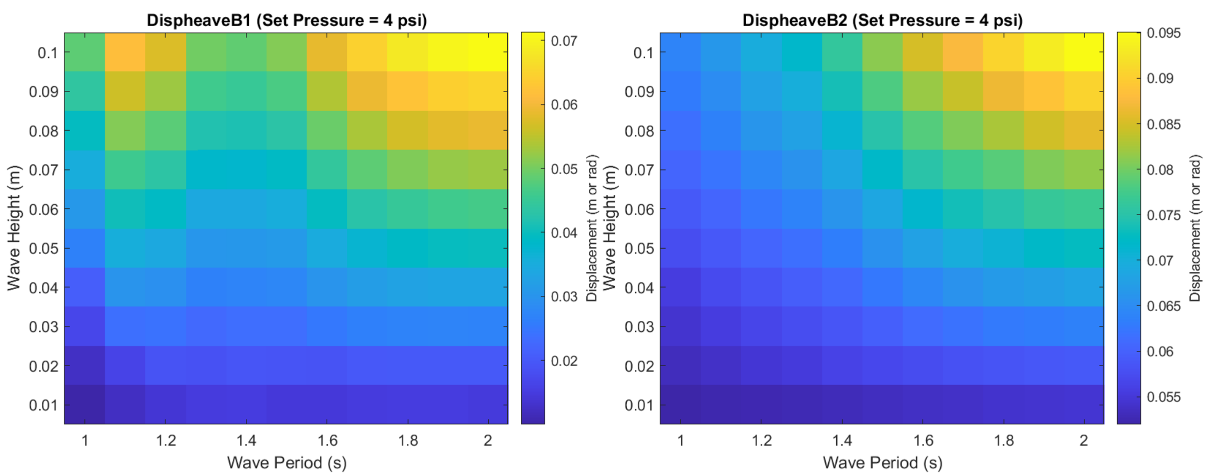
Range of hinge angle motion and calculated water output across the range of wave conditions for the 4 psi case.



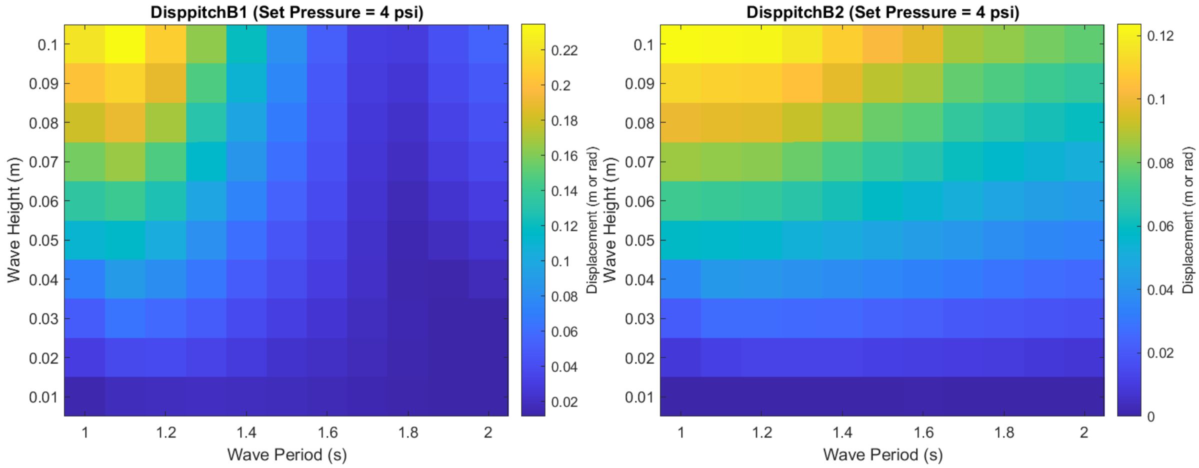
Total heave force on body 1 (front float) and body 2 (main body) across the range of wave conditions for the 4 psi case.



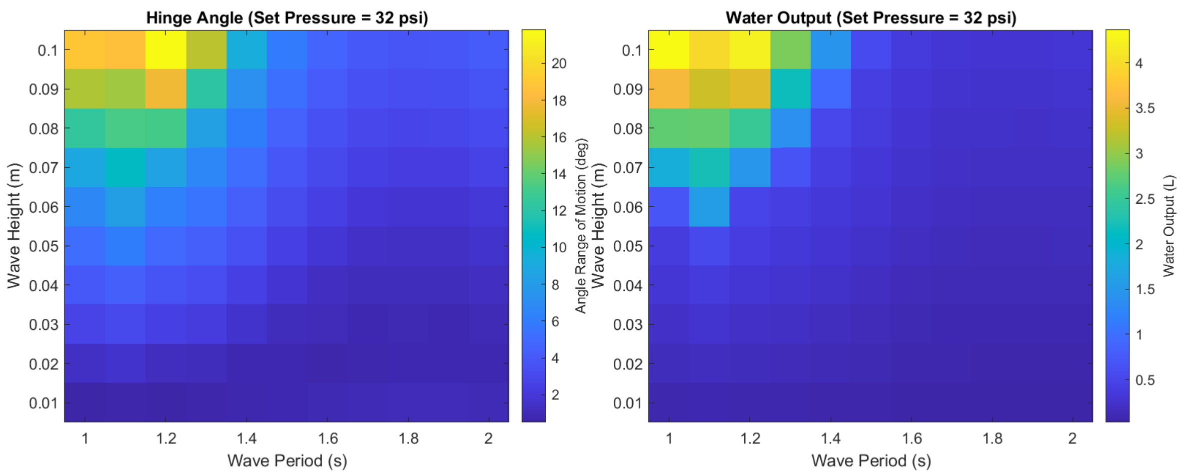
Total pitch force on body 1 (front float) and body 2 (main body) across the range of wave conditions for the 4 psi case.



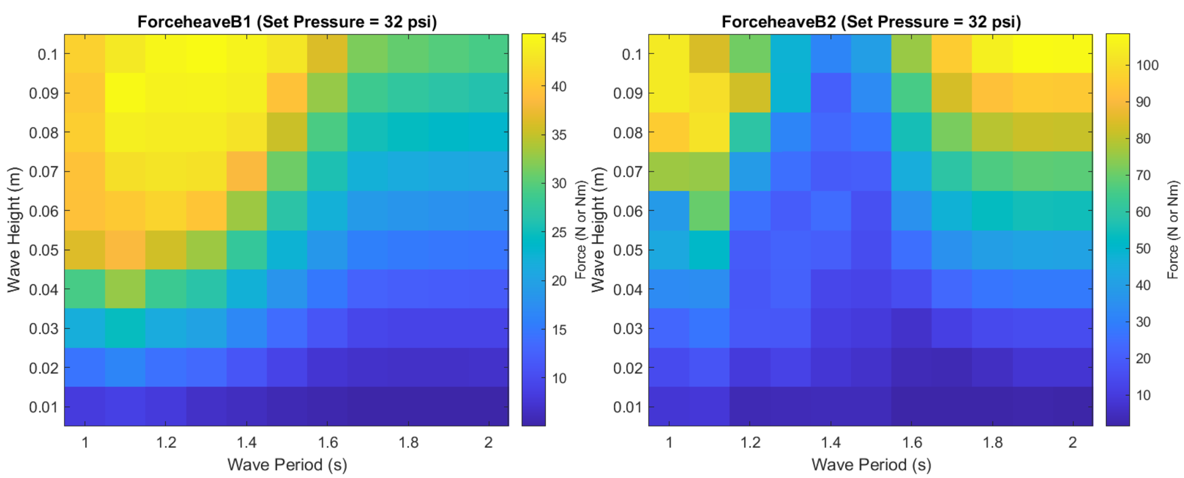
Total heave displacement for body 1 (front float) and body 2 (main body) across the range of wave conditions for the 4 psi case.



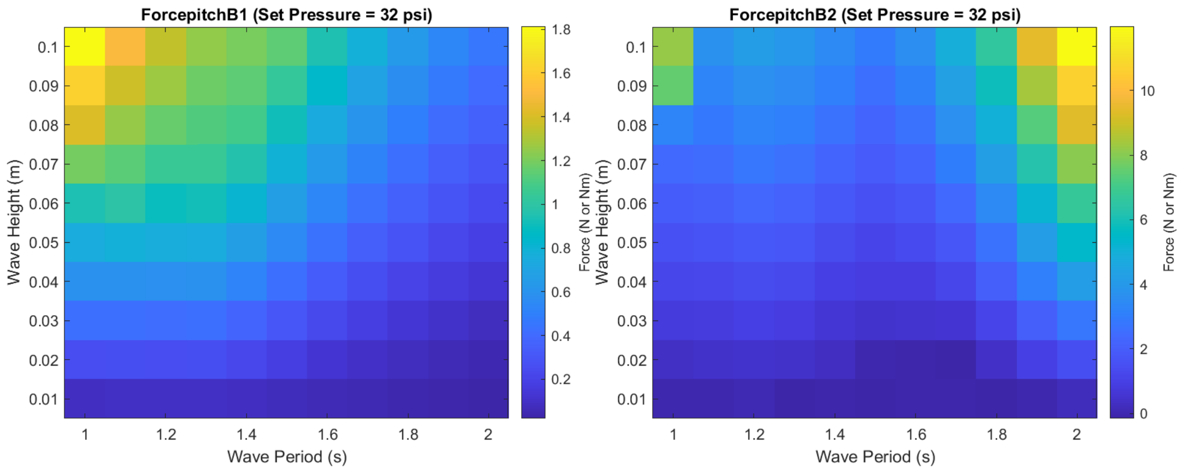
Total pitch displacement for body 1 (front float) and body 2 (main body) across the range of wave conditions for the 4 psi case.



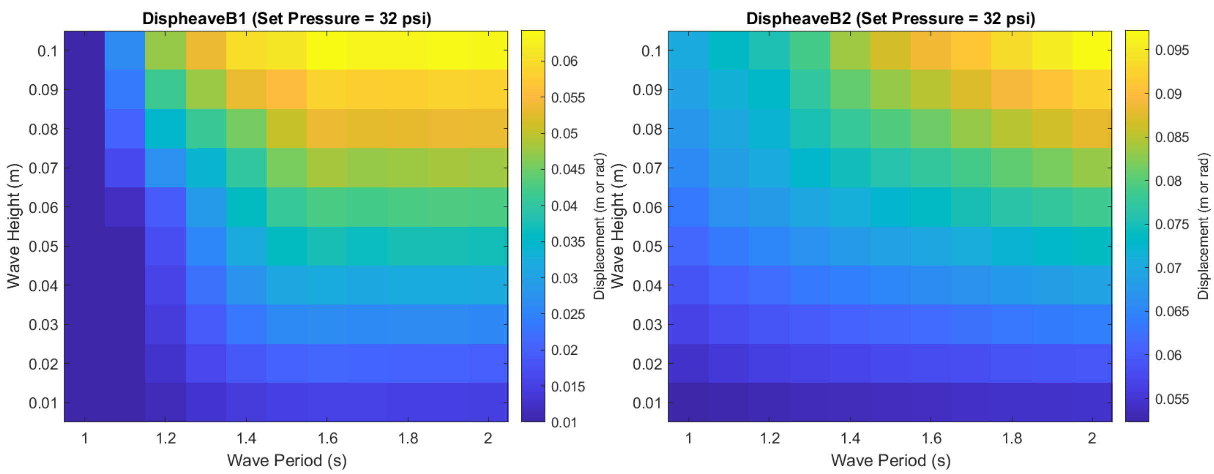
Range of hinge angle motion and calculated water output across the range of wave conditions for the 32 psi case.



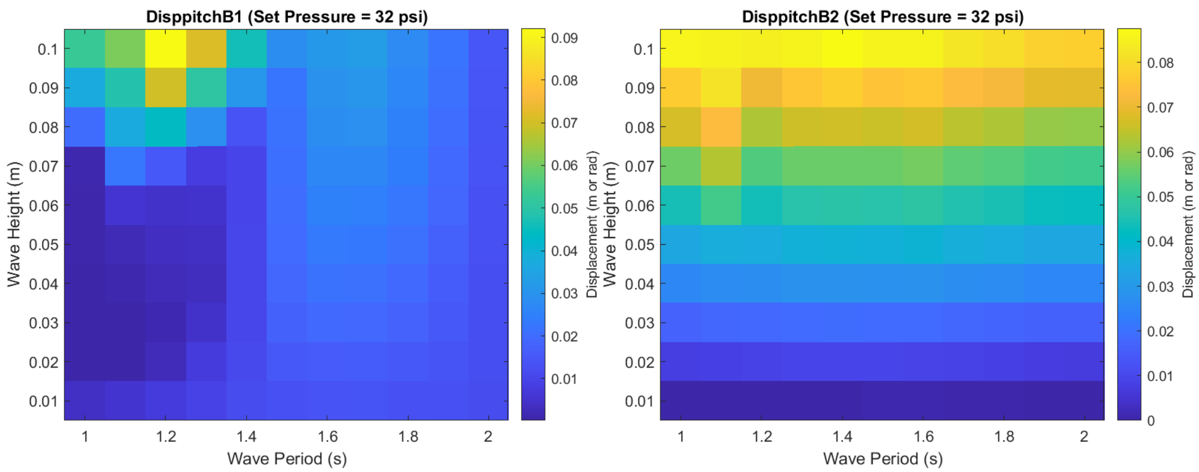
Total heave force on body 1 (front float) and body 2 (main body) across the range of wave conditions for the 32 psi case.



Total pitch force on body 1 (front float) and body 2 (main body) across the range of wave conditions for the 32 psi case.

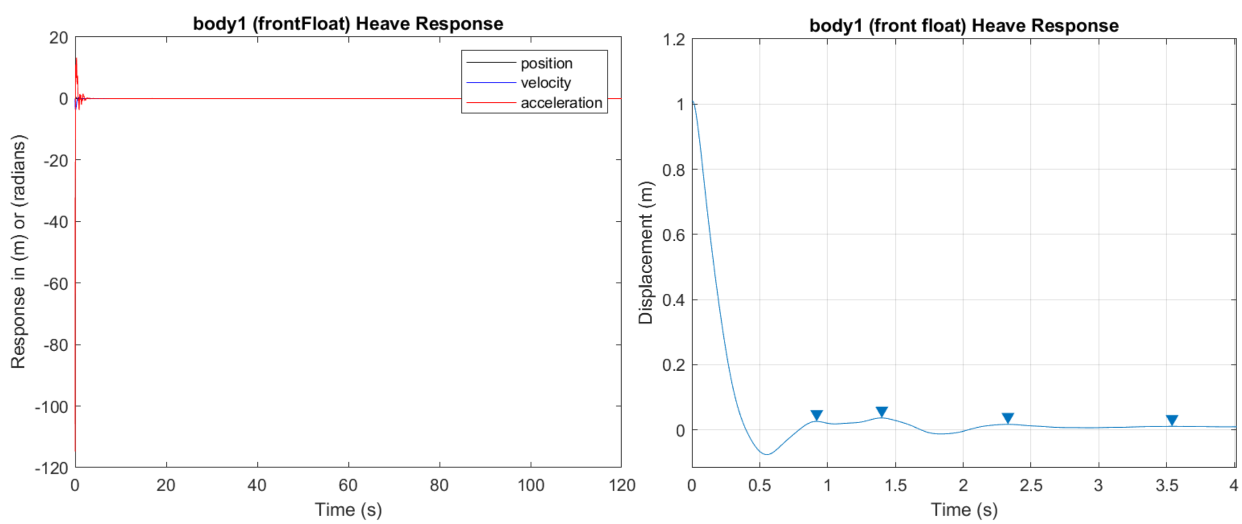


Total heave displacement for body 1 (front float) and body 2 (main body) across the range of wave conditions for the 32 psi case.

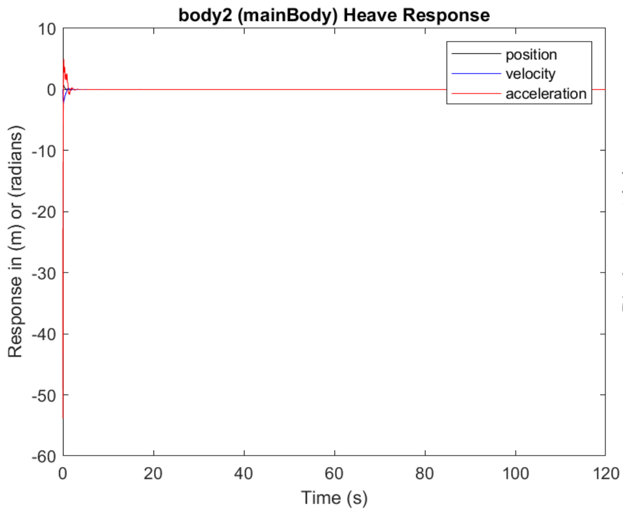


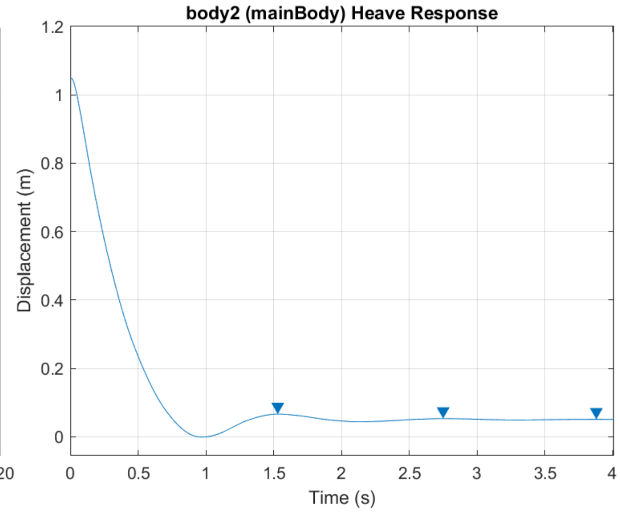
Total pitch displacement on body 1 (front float) and body 2 (main body) across the range of wave conditions for the 32 psi case.

Free decay results for the final tuned WEC-Sim model

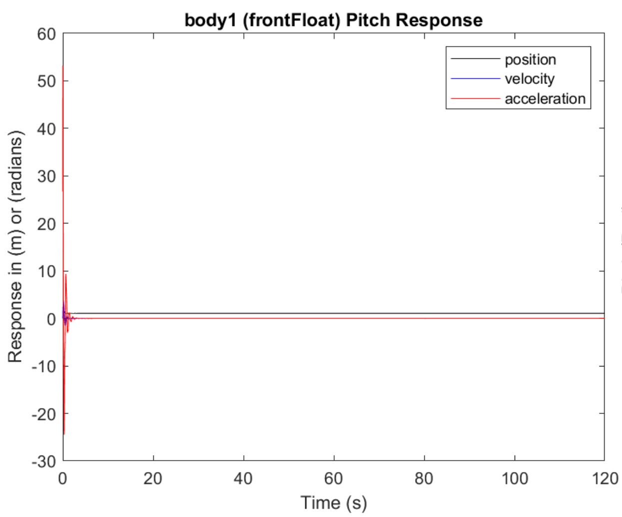


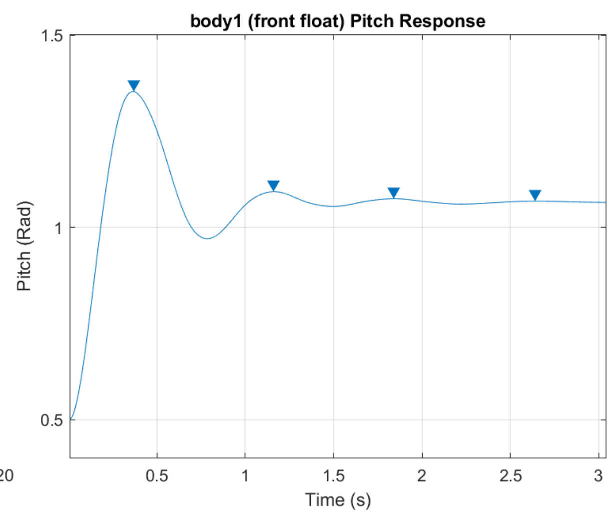
(3.54/4 = 0.8850 s)



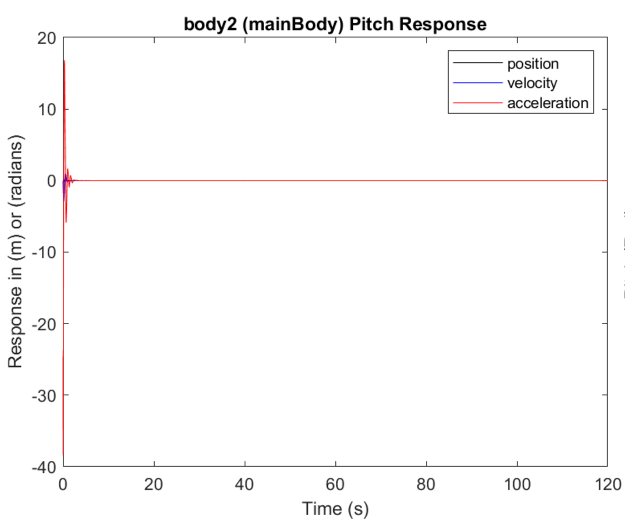


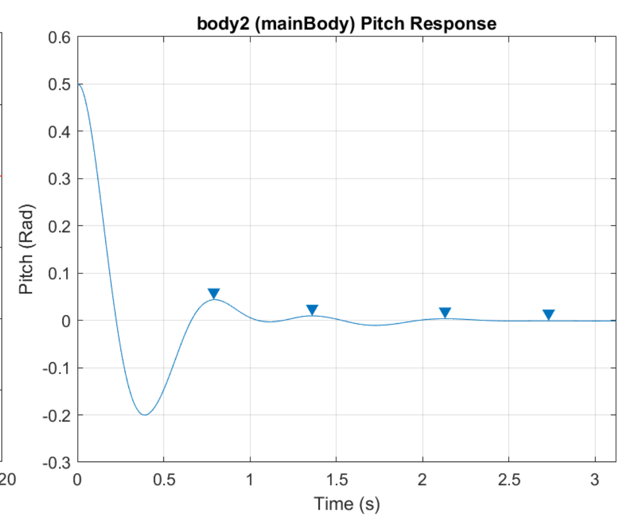
(3.88 / 3 = 1.2933 s)





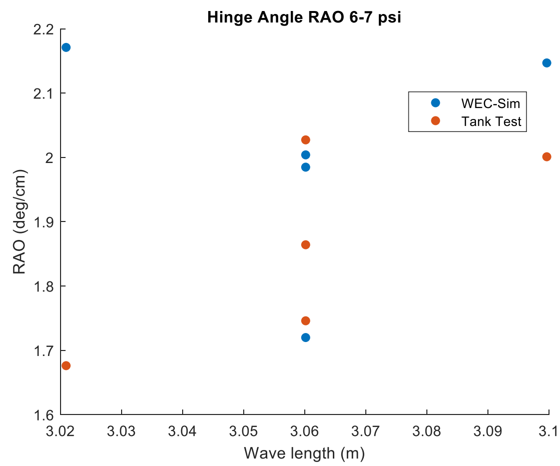
(2.64 / 4 = 0.66 s)





(2.73 / 4 = 0.6825 s)

Another set of test cases that were run in WEC-Sim are the 6-7 psi cases from the tank testing. These performed very well in the tank testing, and it was desirable to compare those results to the WEC-Sim model. Encoder data was only available for some of these runs (runs 64, 122, 123, 216, and 222), so the results for the hinge angle are shown below for those specific runs. Overall, the results from the tuned WEC-Sim model match the results from most of these runs relatively well. The one significant difference is for the lowest wavelength case (run 222) in which the WEC-Sim result overpredicts the hinge angle.



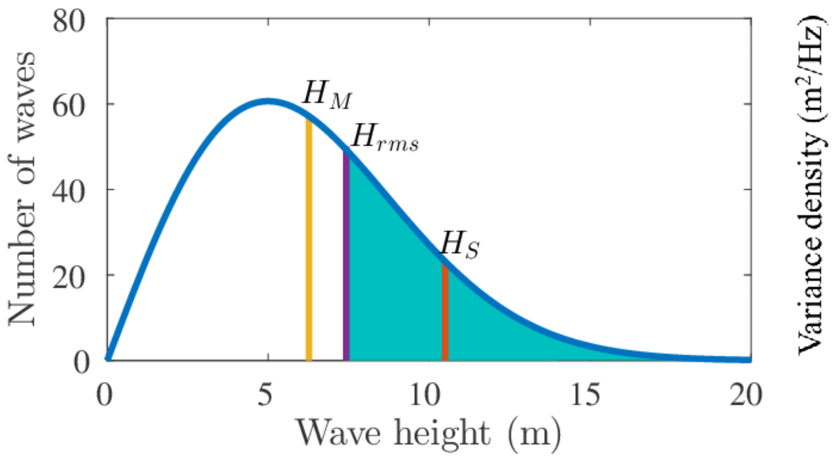
APPENDIX 2: WAVE PARAMETERS AND DEFINITIONS

Wave Height parameters:

Several statistical measures of the wave height are widely used. The RMS wave height, which is defined as square root of the average of the squares of all wave heights, is related to Hs, significant wave height, and Hm, the average wave height, by:

Hs = 1.350 Hrms and H1, the average wave height = 0.90 Hrms, so that Hs = 1.50 H1.[1]

The graph shows a Rayleigh distribution of wave height with types indicated.[2]



Different characteristic wave periods can be derived from the wave spectrum: the significant wave period T_{01}, the mean wave period T_{02} and the mean energy period $T_E \equiv T_{m-1,0}$. They are given by the expressions

$$T_{01} = \frac{\int_0^\infty E(f)df}{\int_0^\infty E(f)fdf}, \quad T_{02} = \sqrt{\frac{\int_0^\infty E(f)df}{\int_0^\infty E(f)f^2df}}, \quad T_E \equiv T_{m-1,0} = \frac{\int_0^\infty E(f)f^{-1}df}{\int_0^\infty E(f)df} . \qquad (B4)$$

The peak frequency $f_p = T_p^{-1}$ is related to the mean energy period T_E. Fitting the Pierson-Moskowitz distribution (B2) to field data yields $T_E/T_p \approx 0.85$; fitting the JONSWAP distribution (B3) yields $T_E/T_p \approx 0.9$. The ratio T_E/T_p can also be derived directly from field data. An analysis of hindcasted wave data for the US Atlantic and Pacific coasts [10] yielded an overall value $T_E/T_p = 0.81 - 0.85$. Considering separately wind wave-dominated data and swell-dominated data, the resulting values were $T_E/T_p = 0.85 - 0.88$ for wind waves and $T_E/T_p = 0.93–0.97$ for swell waves.

[3]

Wave period

Here we chose Te (energy period) = 0.95 Tp as the Waveberg will use swell waves almost exclusively. The various definitions of wave period are not straightforward. "Comparison was made between the energy flux obtained under the spectral diagrams and energy flux obtained using various wave periods and heights. Study shows that if the total energy flux is desired, then the most appropriate values to be used are the root mean square wave height and period corresponding to that wave height. Use of significant wave height, along with zero up-crossing period gives higher values."

References

1. Dean RG, Dalrymple RA. Water wave mechanics for engineers and scientists. Singapore ; Teaneck, NJ: World Scientific; 1991.

2. Bergeijk VM van. Modelling of sand transport in the surf zone [Internet] [Master Thesis]. 2017 [cited 2022 Nov 2]. Available from: https://studenttheses.uu.nl/handle/20.500.12932/27705

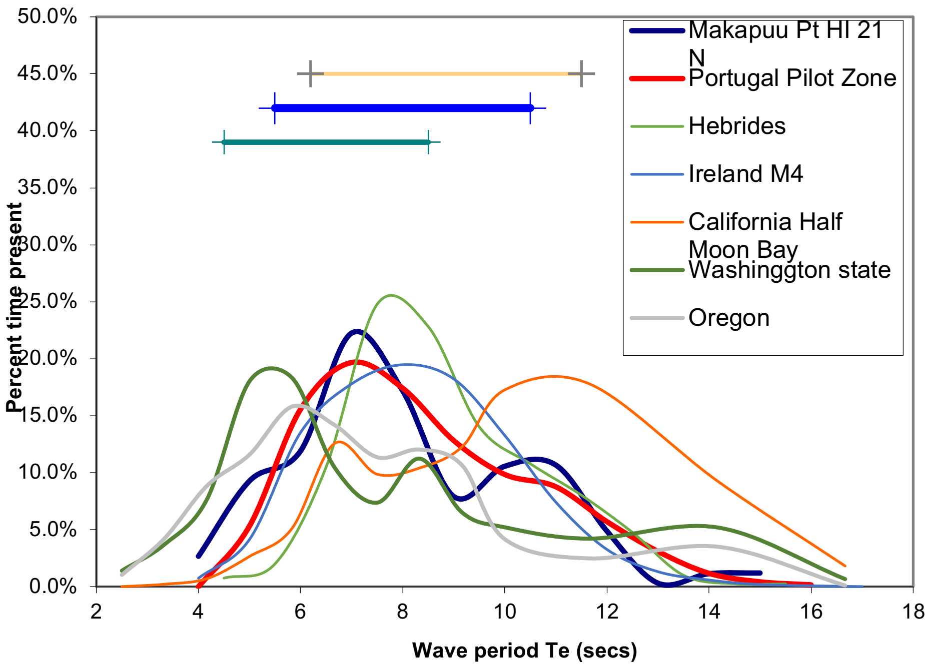
3. Ahn S. Modeling mean relation between peak period and energy period of ocean surface wave systems. Ocean Engineering. 2021;228:108937.

Appendix 3: Wave characteristics world-wide

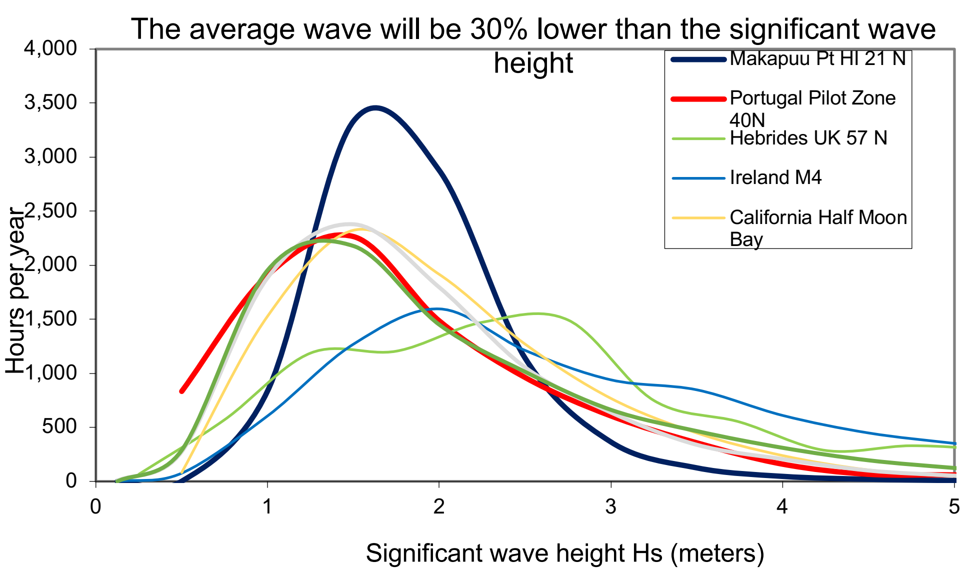
The most common wave in the world has a Period of 6 - 7 secs, Height (H_s) of 1.5 meters, Wavelength 76 meters and celerity (crest speed) of 11 m/sec. At the model scale of 1:25, this wave translates into average period of 1.4 secs, H of 0.04 m for regular waves in the tank, wavelength of 3.3 m and celerity of 2.2 m/sec. I use H_m = 0.04 m because average wave height = 2/3 Hs. The celerity diminishes with depth; I fitted a negative exponential to this data and the velocity 10 mm below the surface should be ~90% of the peak. Froude scaling is used for model testing.

We analyzed scatter diagrams for a number of locations suggested for wave energy. The hours per year for each cell were summed by period (Tp) (typically derived from zero-crossing measurements) and wave height (Hs). The periods were converted to Te (energy period) as the swell is the main source of wave energy. The bars at the top indicate the range of wave periods where the Waveberg performs well; the length of the devices will be adjusted to the distribution at the location.

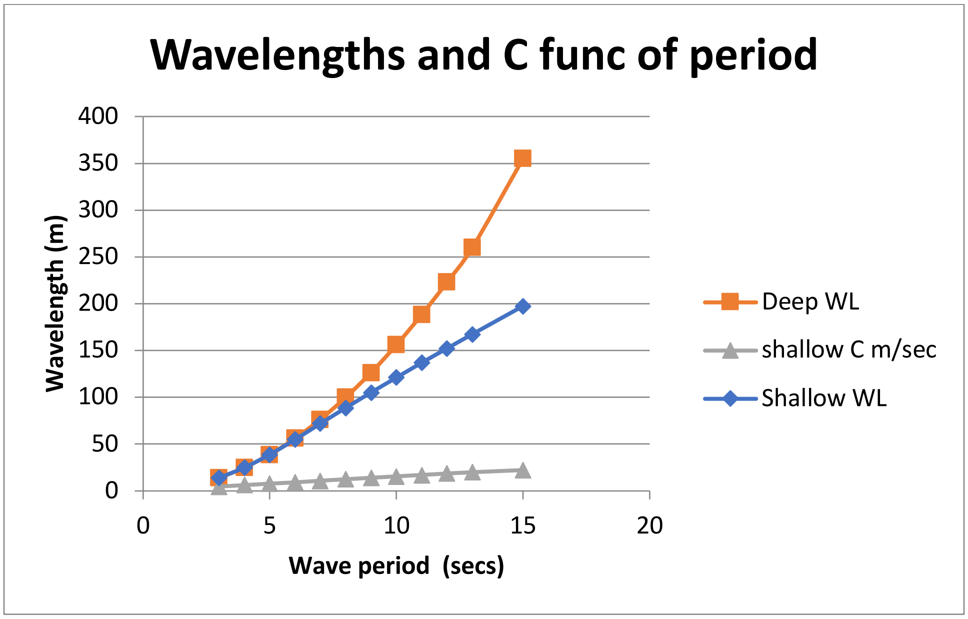
Wave period frequency distribution



Wave height frequency distribution



In shallow water, the wave slows and the wavelength shortens, while the period remains the same. This graph shows the effect for 20 m water depth. The Waveberg is designed for near-shore deployment.



The 7 sec common wave shortens by 5.8% at 20 m depth and the celerity is reduced by the same amount. At model scale 1:25, the 7 sec wave has a wavelength of 3.1 m and celerity of 2.07 m/sec.