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Experimental Testing of a Floating Oscillating Surge Wave Energy Converter

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ABSTRACT

In order to generate a public data set that can be used to validate Wave Energy Converter (WEC) numerical codes, such as WEC-Sim, Sandia National Laboratories led an experimental testing campaign of a 1:33 scale Floating Oscillating Surge Wave Energy Converter (FOSWEC) in the Directional Wave Basin at Oregon State University's Hinsdale Wave Research Laboratory. Testing was performed in two phases; Phase 1 testing was completed in November - December 2015, and Phase 2 testing was completed in May - June 2016. This experimental testing report details the selection and design of a FOSWEC, experimental setup and tests, and overview of the resulting dataset from Phase 1 and Phase 2 testing.

ACKNOWLEDGMENTS

The authors would like to acknowledge everyone who contributed in experimental testing of a Floating Oscillating Surge Wave Energy Converter (FOSWEC), team members listed in Figure 0-1. The Sandia and NREL multi-lab team generated the FOSWEC design concept and developed the experimental test plan. The FOSWEC was designed and fabricated by Andrews-Cooper, and the motion constraint was designed and fabricated by +D. Wave tank testing was performed in the Directional Wave Basin at Oregon State University's Hinsdale Wave Research Laboratory. The authors would like to give special thanks to: Chris Kelley and Chris Simmons from Sandia National Laboratories; Ratanak So from Oregon State University; Yi-Hsiang Yu, Michael Lawson, Nathan Tom and Jennifer Van Rij from the National Renewable Energy Laboratory; Sean Moran, Peter van Tamelen, and Blake Walker from Andrews-Cooper; and Enrique Gardeta from +D.

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Figure 0-1. FOSWEC testing team members

Experimental testing of a FOSWEC, as well as development and maintenance of the WEC-Sim code is funded by the U.S. Department of Energy's Water Power Technologies Office. WEC-Sim code development is a collaboration between the NREL and Sandia; Sandia led the FOSWEC experimental testing. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. The National Renewable Energy Laboratory is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC. under contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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EXECUTIVE SUMMARY

Experimental testing of a 1:33 scale Floating Oscillating Surge Wave Energy Converter (FOSWEC) was completed in the Directional Wave Basin at Oregon State University's Hinsdale Wave Research Laboratory. Testing was performed in two phases; Phase 1 testing was completed in November - December 2015, and Phase 2 testing was completed in May - June 2016. This experimental testing report details the selection and design of a FOSWEC, experimental setup and tests completed, and overview of resulting Phase 1 and Phase 2 data sets. The primary objective of the experimental testing is to generate a publicly available data set that can be used to validate Wave Energy Converter (WEC) numerical codes, such as WEC-Sim [6]. The secondary objective is to provide data and lessons learned relevant to extreme conditions (i.e. WEC loads and response), and other areas of interest identified by the wave energy industry (i.e. innovative measurement techniques).

The device tested is a FOSWEC consisting of a floating platform with two (fore and aft) oscillating flaps connected to an above-water power-take off. The FOSWEC was designed to be tested in four configurations (Config 1-Config 4), each with different allowable degrees of freedom. The device and wave basin were instrumented to characterize loads and motions of the flaps, platform, and power-take off components, as well as the incident wave field. Phase 1 testing included calibration of the wave fields, dry mass/inertia measurement, static offset, and free decay tests. Between the phases of testing, the device, instrumentation, and test plan were modified based on lessons learned from Phase 1 testing. Phase 2 included wave excitation, forced oscillation, and wave response tests for regular and irregular waves with varying device configurations to examine device response with degrees of freedom. This report is intended to accompany the Phase 1 and Phase 2 data sets which are publicly available on the Marine and Hydrokinetic Data Repository (MHKDR), and data processing scripts which are publicly available on the FOSWEC GitHub repository [2, 8].

TERMINOLOGY

Term	Definition
Arm	Motion constraint (between the FOSWEC and the basin floor)
BSpace	Phase 2 real-time control interface
COG	Center of Gravity
Config 1	Flap 1 pitch
Config 2	Flap 1 pitch; Flap 2 pitch
Config 3	Flap 1 pitch; Flap 2 pitch; Platform heave
Config 4	Flap 1 pitch; Flap 2 pitch; Platform heave, pitch and surge
DAQ	Data Acquisition System
DOF	Degree of Freedom
dSpace	Phase 1 real-time control interface
DWB	Directional Wave Basin
E_f	Energy per crest length (W/m)
FOSWEC	Floating Oscillating Surge Wave Energy Converter
FS	full scale
h	Water depth (m)
H	Wave height (m)
H_s	Significant wave height (m)
H_{m0}	Significant wave height (m), $H_{m0} = 4\sqrt{m_0}$
Heave	Translation in +Z
HWRL	Hinsdale Wave Research Laboratory (at OSU)
IRR	Irregular Waves
L	Wavelength (m)
MHKDR	Marine and Hydrokinetic Data Repository
MOI	Moment of Inertia (I_{xx}, I_{yy}, and I_{zz})
NREL	National Renewable Energy Laboratory
OSU	Oregon State University
p2p	peak-to-peak
PhaseSpace	Optical motion tracking system
Pitch	Rotation about Y-axis, θ
pmat	pressure mat
PMEC	Pacific Marine Energy Center
PTO	Power Take-Off
REG	Regular Waves
Sandia	Sandia National Laboratories
SS	Sea State
Surge	Translation in +X
SWL	Still Water Line
T	Wave period (s)
T_e	Energy period (s)
T_p	Peak period (s)
WEC	Wave Energy Converter
WEC-Sim	Wave Energy Converter Simulator
WESRF	Wallace Energy Systems & Renewables Facility (at OSU)

1. INTRODUCTION

Experimental testing of a 1:33 scale Floating Oscillating Surge Wave Energy Converter (FOSWEC) was completed in the Directional Wave Basin at Oregon State University's Hinsdale Wave Research Laboratory. Testing was performed in two phases; Phase 1 testing was completed in November - December 2015, and Phase 2 testing was completed in May - June 2016. This experimental testing report details the selection and design of a FOSWEC, experimental setup and tests completed, and overview of resulting Phase 1 and Phase 2 data sets. The primary objective of the experimental testing is to generate a publicly available data set that can be used to validate Wave Energy Converter (WEC) numerical codes, such as WEC-Sim. WEC-Sim is an open source multi-body code that solves wave energy converter (WEC) dynamics and performance when subject to operational and extreme waves, jointly developed by Sandia National Laboratories (Sandia) and the National Renewable Energy Laboratory (NREL), for more information refer to the WEC-Sim website [7]. The secondary objective is to provide data and lessons learned relevant to extreme conditions (i.e. WEC loads and response), and other areas of interest identified by the wave energy industry (i.e. innovative measurement techniques).

The device tested is a FOSWEC consisting of a floating platform with two (fore and aft) oscillating flaps connected to an above-water power-take off. The FOSWEC was designed to be configured into four configurations (Config 1-Config 4), each with different allowable degrees of freedom. The device and wave basin were instrumented to characterize loads and motions of the flaps, platform, and power-take off components, as well as the incident wave field. Phase 1 testing included calibration of the wave fields, dry mass/inertia measurement, static offset, and free decay tests. Between the phases of testing, the device, instrumentation, and test plan were modified based on lessons learned from Phase 1 testing. Phase 2 included wave excitation, forced oscillation, and wave response tests for regular and irregular waves with varying device configurations to examine device response with degrees of freedom. This report is intended to accompany the Phase 1 and Phase 2 dataset which is publicly available on the Marine and Hydrokinetic Data Repository (MHKDR), and data processing scripts which are publicly available on the FOSWEC GitHub repository [2, 8].

1.1. OBJECTIVES

Based on guidance from the Water Power Technologies Office at the U.S. Department of Energy, primary and secondary test objectives were defined.

Primary Objective: The primary objective of the experimental testing is to generate a publicly available data set that can be used to validate Wave Energy Converter (WEC) numerical codes, such as WEC-Sim. Since this data set will be publicly available, the device tested must be of sufficient complexity that the resulting data will be useful for codes of different fidelities, and account for different physical phenomena. All of the data collected for this objective is gathered with both a main and a backup sensor, thus ensuring that all primary measurements have redundancy.

Secondary Objective: The secondary objective is to provide data and lessons learned relevant to extreme conditions, and other areas of interest identified by the wave energy industry. The extreme conditions data of interest is focused on device response and WEC loads characterization. The area of interest identified by interviews with the WEC industry is innovative measurement techniques (i.e. sensors).

1.2. EXPERIMENTS

FOSWEC experimental testing was performed in two phases, namely Phase 1 and Phase 2. A description of each experiment and its corresponding objective is listed in Table 1-1. For details about the experiments performed in Phase 1 and Phase 2, refer to Section 5 and Section 7 respectively.

Phase 1: The goal of Phase 1 is to characterize the incident wave environment, perform baseline system identification tests, and complete at least 1 trial of each of the planned experiments. The Phase 1 tests generally progressed from the most simple (i.e. wave characterization and decay tests), to the most complex (i.e. forced oscillation) in a manner intended to characterize the FOSWEC, test the experimental setup, and stress the system to identify issues upfront. This approach gave the team valuable experience with changing configurations, capturing data, and provided data characterizing of the wave environment and the FOSWEC. Second, it allowed the experimental testing team to develop, debug, and refine the test procedures. Finally, this approach stressed the model so that issues could be identified upfront, and resolved prior to Phase 2 testing.

Phase 2: The goal of Phase 2 testing is to complete the breadth of planned tests in full, learning from the shakeout tests completed in Phase 1. The Phase 2 tests generally progressed to from the simplest (i.e. wave excitation) to the most complex (i.e. forced oscillation and Config 4 wave tests). Prior to Phase 2 testing, the lessons learned from Phase 1 testing were used to make changes to the FOSWEC and Arm designs, instrumentation, and PTO drivetrain. These revisions are outlined in Section 6. *The full validation data set was generated upon completion of the Phase 2 testing.*

Dry Tests Swing test using pendulum theory for each rigid body

Objective Determine FOSWEC center of gravity, mass, and moment of inertia

---

Wave Calibration Run REG/IRR wave cases without FOSWEC in the basin

Objective Calibrate wavemaker and verify incident wave conditions

---

Free Decay Offset and release FOSWEC from initial displacements for each DOF

Objective Determine FOSWEC natural periods, stiffness, and damping

---

Wave Excitation Hold FOSWEC and measure wave excitation loads in each DOF

Objective Determine wave excitation on FOSWEC

Forced Oscillation Drive the FOSWEC periodically with a fixed amplitude (no waves)

Objective Determine FOSWEC's added mass and radiation damping coefficients

---

Regular Waves Run REG waves for Config 1 - Config 4

Objective Characterize FOSWEC response to REG waves (i.e. motion, power, loads)

Irregular Waves Run IRR waves for Config 1 - Config 4

Objective Characterize FOSWEC response to IRR waves (i.e. motion, power, loads)

Table 1-1. Overview of Phase 1 and Phase 2 Experiments

1.3. TEAM

The testing team consists of 15 people, across 5 different institutions. The experimental testing campaign was led be Kelley Ruehl at Sandia National Laboratories. The wave tank testing was performed in the Directional Wave Basin at Oregon State University's Hinsdale Wave Research Laboratory, directed by Pedro Lomonaco. The FOSWEC design and fabrication was led by Sean Moran at Andrews Cooper. Enrique Gardeta from +D led the motion constrain design and fabrication. Yi-Hsiang Yu led the WEC-Sim code development and supported FOSWEC testing for the National Renewable Energy Laboratory. A full list of all of the testing team members is shown in Figure 0-1, along with a picture of the group before Phase 1 testing in Figure 1-1.

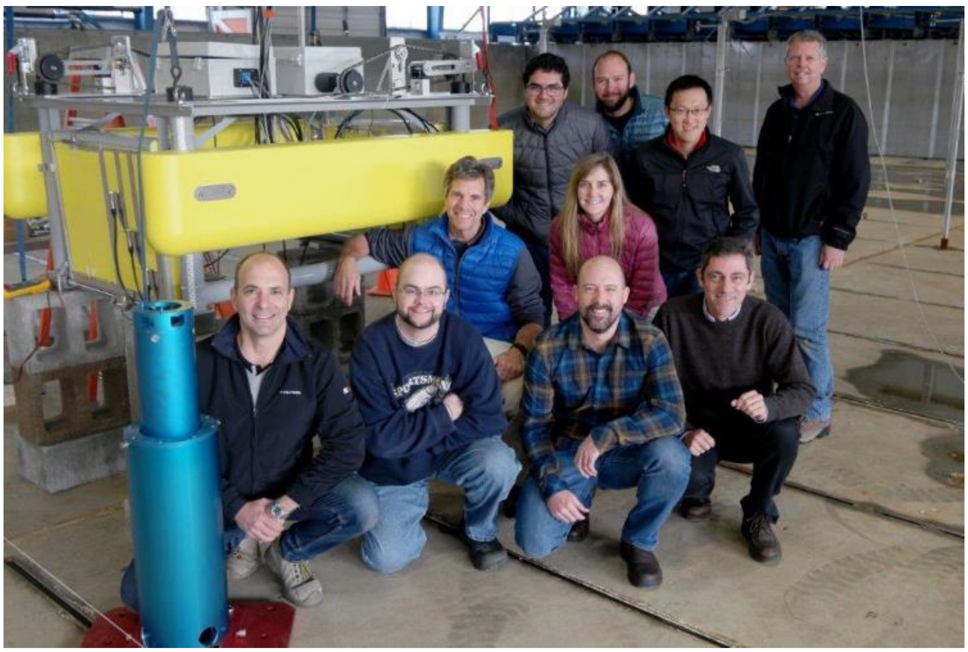

Figure 1-1. Delivery of the FOSWEC to Hinsdale Wave Research Laboratory, *front row*: Enrique Gardeta (+D), Asher Simmons (OSU), Sean Moran (AC), Pedro Lomonaco (OSU), *middle row* Peter van Tamalen (AC), Kelley Ruehl (Sandia), *back row* Carlos Michelen (Sandia), Yi-Hsiang Yu (NREL), Bret Bosma (OSU), Blake Walker (AC)

2. FACILITY

Oregon State University operates the Hinsdale Wave Research Laboratory (HWRL) [3]. This facility is one of the largest coastal and ocean hydraulic laboratories in North America. The Directional Wave Basin is equipped with a high-performance, piston-type, multi-directional wave maker [1]. Additionally, HWRL, Wallace Energy Systems & Renewables Facility (WESRF), and the Pacific Marine Energy Center (PMEC) have collaborated on the development of processes for high-precision tank testing [5, 4]. This collaboration was directly focused on enabling the development and testing of WECs. The team engaged with the HWRL staff, PMEC and WESRF during the device design phase, pulling on the combined expertise of these organizations.

The FOSWEC scale-model experiments were conducted in the Directional Wave Basin (DWB), one of the wave tank facilities located at HWRL. There are several basic features of the DWB that are integral to the FOSWEC experiments. First, the wave machine is made of 30 actuators, and 29 paddles which move in piston-type motion, allowing the tank can produce regular, irregular, multi-direction and user-defined waves. Secondly, supporting infrastructure of the DWB includes a crane, an instrument carriage that spans the basin, and built-in struts for securing models.

HWRL also has an inventory of instrumentation to measure free surface, velocity, pressure, stress, turbidity, and depth. There are nine types of pressure or strain instruments, three types of velocity instruments, and three types of wave gages available to the experimental testing team. Additionally, HWRL has two types of modular data acquisition (DAQ) systems and five types of video recording available. This minimized the number of instruments purchased for testing of the FOSWEC. Data sheets for HWRL's DWB and instrumentation capabilities can be found on the following pages, and accessed from their website [3].

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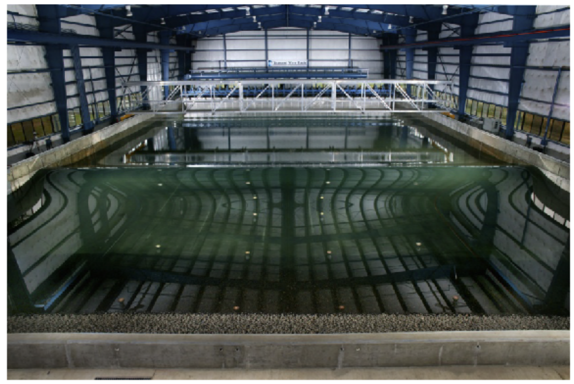
Directional Wave Basin

Previously known as the Tsunami Wave Basin, was designed to understand the fundamental nature of tsunami inundation, tsunami-structure impact, harbor resonance and to improve the numerical tools for tsunami mitigation.

In addition to tsunami research, the facility is particularly suited for general testing of coastal infrastructures, nearshore processes research, wave hydrodynamics, floating structures and renewable energy devices.

The wave machine is a unique powerful snake-type system made of 29 boards with up to 2.1 m long stroke. It has been designed to generate short- and long-period multidirectional high quality waves.



Wave Basin Dimensions

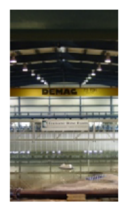
• Length:	48.8 m	160 ft
• Width:	26.5 m	87 ft
• Max depth:	1.37 m	4.5 ft
• Freeboard:	0.6 m	2.0 ft

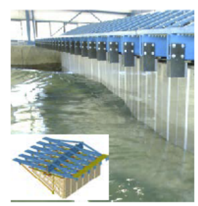
Wavemaker

• Type:	Piston-type, Electric motor
• Waveboards:	29 boards, 2.0 m (6.6 ft) high
• Wave types:	Regular, Irregular, Tsunami, Multidirectional, User defined
• Period range:	0.5 to 10 seconds
• Max. Wave:	0.75 m (2.5 ft) in 1.37 m (4.5 ft) depth
• Max. Stroke:	2.1 m (6.9 ft)
• Max. Velocity:	2.0 m/s (6.6 ft/s)

Supporting infrastructure

- 7.5 T capacity bridge crane
- Instrumentation carriage, spans 26.5 m
- Unistrut installed in floor and sides to secure models
- Two access ramps, 14 ft width (4.2 m)
- Steady flow currents installed on project-by-project basis





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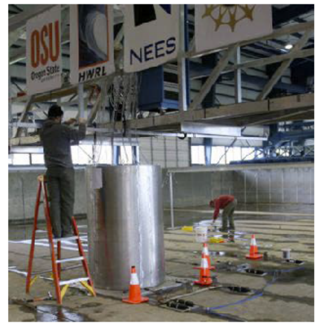
O. H. HINSDALE

WAVE RESEARCH LABORATORY

OREGON STATE UNIVERSITY

Instrumentation

The HWRL has a large inventory of conventional and state-of-the art instrumentation to measure free surface, velocity, pressure, stress, turbidity, and depth. Data can be made available in near-real time via the web.



Free Surface

- Surface-piercing resistance-type paired-wire wave gages
  - 7 8ch signal conditioners (ImTech)
  - 6 self-calibrating wave gage mounts for LWF
  - 8 self-calibrating wave gage mounts for DWB
  - 13 fixed wave gage mounts for LWF
  - 19 fixed wave gage mounts for TWB
  - 18 cantielver gage mounts
  - 26 runup gage mounts
- 9 Acoustic depth gages (0.2-2m)

Velocity

- 17 3-D acoustic-Doppler velocimeter (Nortek Vectrino)
- 4 2-D acoustic-Doppler velocimeter probe heads
- 3D Stereo Particle Image Velocimeter system (LaVision)

Pressure/Strain

- 15 pore pressure transducer, 5 psig (Druck PDCR81)
- 15 pressure transducers, 15 psig (Druck PDCR830)
- 4 10ch, 1 4ch signal conditioners (Vishay 2100)
- 4 50Kip, 3 20Kip pancake load cell (DeltaMetrics)
- 2 10Kip, 6 2Kip rod end load cell (DeltaMetrics)

Turbidity

- 16 optical backscatter sensor (D&A Instr., OBS-3)

Bathymetry

- 2 32 component ultrasonic ranging system (SeaTek)
- 4 laser range finder 0.2-200 m (Dimetix DLS-A30)
- LIDAR survey through subcontract arrangement

Data Acquisition System

3 modular PXI architecture DAQ systems, each with

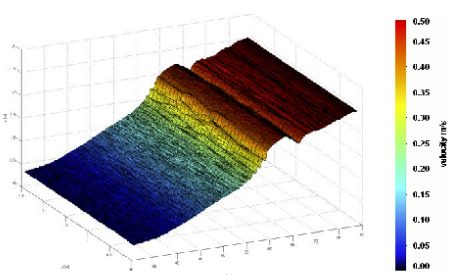
- Built-in signal conditioning and anti-aliasing
- 64 channel, 16-bit analog acquisition
- Digital pulse generation, external device synchronization
- Up to16 channel RS-232 / serial communication
- DAQs can be synched to provide 192 analog 48 digital ch

2 additional modular PXI architecture DAQ system with

- Up to16 channel RS-232 / serial communication

Video

- PhaseSpace Motion Capture system (8 cameras)
- 6 PTZ HD 1080p cameras
- 2 submersible HD 720p underwater cameras and lights
- 6 PIX SSD-based HD video recording systems
- 6 PTZ web cameras (Axis)
- Waterproof (GoPro) and handheld (Sony) HD cameras
- ARRI stage lights at up to 2000W power



Acoustic profiler for sediment transport

Pressure Druck PDCR830

DeltaMetrics Load Cell

ADV 3D probehead

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2.1. SCALE

Appropriate scaling was determined by assuming a full-scale water depth, h_{fs} = 45 m, and incorporating the following wavemaker limitations: deepest water depth, h_{max} = 1.37 (m); shortest wave period, T_{min} = 0.8 (s); and smallest wave height, H_{min} = 1-2 (cm). An analysis of the DWB provided by the HWRL staff based on the desired waves with wave height (H) ranging from 0.5 m to 4.5 (m) and period (T) ranging of 5 s to 20 (s) resulted in the Froude scaling of 1:33. The results of the analysis are shown in Figure 2-1. In this plot, the triangles are wavemaking capabilities assuming a 1:33 scale factor for the desired wave heights and periods. The x-axis is normalized by the wavelength (L). The majority of these wave cases fall within the linear region and intermediate water depth.

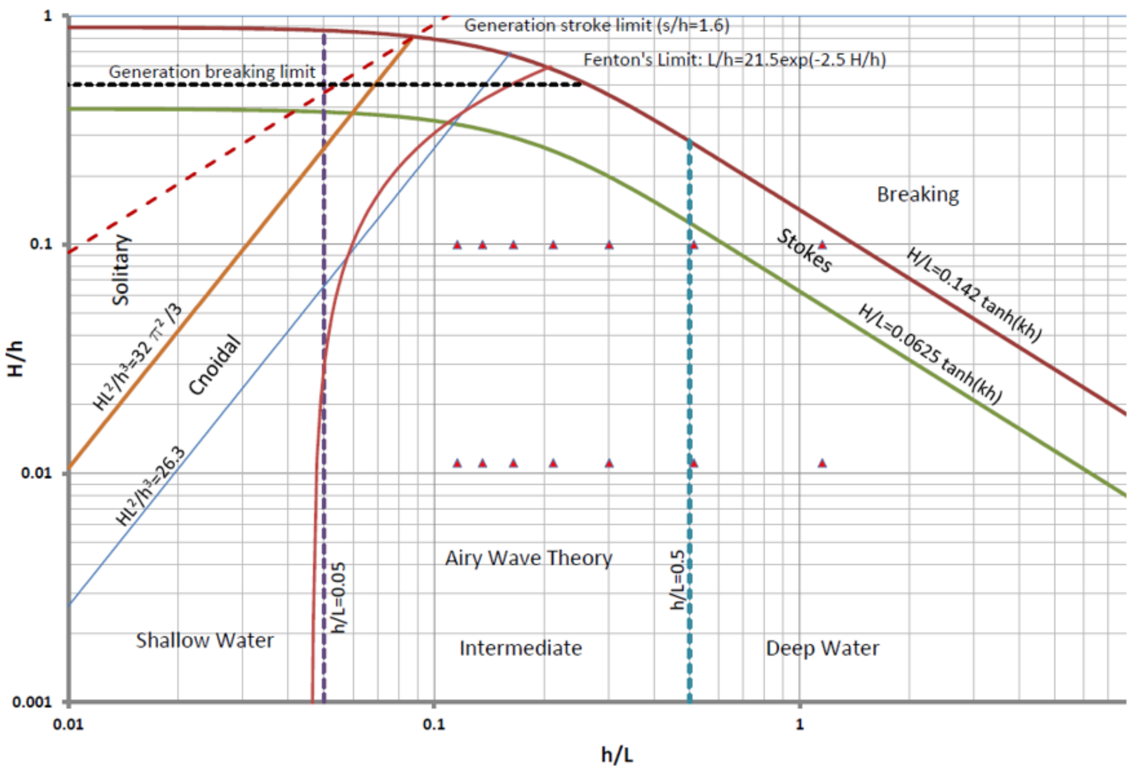


Figure 2-1. HWRL DWB 1:33 Scaling Analysis

3. FOSWEC

In order to determine the device archetype for the WEC-Sim experimental testing campaign, the WEC-Sim team used the Pugh Method, also known as the decision matrix method. This method was chosen because of the large number of variables to be evaluated, and the importance of producing a quality publicly available data set. The experimental testing campaign has two objectives: a primary objective to generate a validation data set based on WEC performance data, and a secondary objective to characterize WEC loads. In the following sections, the method the WEC-Sim team used to select a WEC archetype is described.

3.1. DESIGN CRITERIA

The device selection process was broken into two categories: Validation Ability and Testability. Validation Ability is weighted higher (67%) than the Testability (33%) because the primary objective of the experimental testing is to validate the modeling capabilities of codes such as WEC-Sim. Each of the two categories were broken into five decision criteria. The total weighting for each category sums to 100%, distributed among the criteria according to relative importance, determined as the average of each individual team member's weighting preference. Each WEC archetype was then rated according to its ability to meet the Validation Ability and Testability criteria.

3.1.1. Validation Ability

The criteria for the ability of the code to be validated by the WEC archetype are listed below. Each of these criteria are described and weighted according to their relative importance, as shown in Figure 3-1. The criteria were then rated for each WEC archetype on a 0-2 scale, according to the archetype's ability to validate the WEC-Sim code.

WEC-Sim Modeling: Can WEC-Sim model the WEC (i.e., dominant degrees of freedom and operating principles)?

DOF Testing: Does the device allow for coupled degrees of motion (i.e., surge/pitch) to be tested?

Wave Directionality: Can the effects of wave directionality be tested?

Body-to-body Hydrodynamic Interaction: Can body-to-body hydrodynamic interaction be tested?

Nonlinear Hydrostatics and Hydrodynamics: Can non-linear hydrodynamic and hydrostatic effects be tested?

Validation Ability						
Title	*WEC-Sim Modeling*	*DOF Testing*	*Wave Directionality*	*Body-to-Body Interaction*	*Nonlinear hydrostatics & hydrodynamics*	***Validation Ability Total***
Description	Can WEC-Sim model the WEC (ie. dominant degrees-of-freedom and operating principles)?	Does the device allow for coupled degrees of motion (i.e. surge/pitch) to be tested?	Can the effects of wave directionality be tested?	Can body-to-body hydrodynamic interaction be tested?	Can non-linear hydrodynamic and hydrostatic effects be tested?	
Ratings	0 = Device allows minimal or no testing of this component 1 = Device allows satisfactory testing of this component 2 = Device allows comprehensive testing of this component					
Weights	23%	23%	13%	20%	21%	67%

Figure 3-1. Overview of Validation Ability Criteria, Ratings and Weights

3.1.2. Testability

The criteria related to the ability of the WEC archetype to be tested are listed below. Each of these criteria are described and weighted according to their relative importance, as shown in Figure 3-2. The criteria were then rated for each WEC archetype on a 0-2 scale, according to the archetype's testability.

Modularity of Testing: Can the device be tested as individual bodies and restrict varying modes of motion?

Performance Instrumentation: Will the device facilitate the addition of performance instrumentation (i.e. motion tracking)?

Ease of Deployment: Will the device be easy to set up and breakdown (i.e., change headings and make modifications)?

Ease of Construction: Will the device be easy to design and fabricate?

Loads Instrumentation: Will the device facilitate the addition of loads instrumentation (i.e., pressure/slam panels)?

Testability						
Title	*Modularity of Testing*	*Performance Instrumentation*	*Ease of Deployment*	*Ease of Construction*	*Loads Instrumentation*	*Testability Total*
Description	Can the device be tested as individual bodies and restrict varying modes of motion?	Will the device be easy to add performance instrumentation (i.e. motion tracking)?	Will the device be easy to set up and breakdown (i.e. changing headings and make modifications)?	Will the device be easy to design and fabricate?	Will the device be easy to add loads instrumentation (ie. pressure/slam panels)?	
Ratings	0 = Substantial design and construction 1 = Moderate design and construction 2 = Minimal design and construction					
Weights	21%	24%	22%	15%	18%	33%

Figure 3-2. Overview of Testability Criteria, Ratings and Weights

3.2. DEVICE SELECTION

After comparing 12 different WEC archetypes through the device selection process described in the previous section, the device archetype chosen was a Floating Oscillating Surge WEC (FOSWEC). The overall score for the floating FOSWEC was the highest, with a rating of 1.88 out of 2.0, as shown in Figure 3-3.

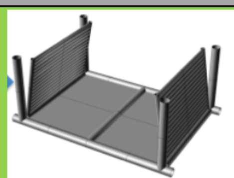
Wave Energy Converter					
Example Image		Archetype	Industry Example	Operating DOF	PTO Type
		Floating oscillating surge device	Langlee 	3: Surge, heave, pitch	Rotational
Validation Ability					
WEC-Sim Modeling	*DOF Testing*	*Wave Directionality*	*Body-to-Body Interaction*	*Nonlinear hydrostatics & hydrodynamics*	***Validation Ability Total***
2	2	2	2	2	2
Testability					
Modularity of Testing	*Performance Instrumentation*	*Ease of Deployment*	*Ease of Construction*	*Loads Instrumentation*	***Testability Total***
2	2	1	1	2	1.63
Weighted Total					**1.88**

Figure 3-3. FOSWEC Overall Score

A rendering of the FOSWEC hydrodynamic design is shown in Figure 3-4, and the global coordinate system is defined in Figure 3-5. The architecture lends itself well to modular construction and component testing, as explained in the following section. The model size was determined using Froude scaling, and was driven by the wave facility capabilities described in Section 2. A scale factor of 1:33 was applied to the FOSWEC model. The resulting dimensions are shown in Figures 5-2 and 7-2. Table 3-1 lists the DOF and the corresponding expected maximum FOSWEC excursions from its undisturbed position.

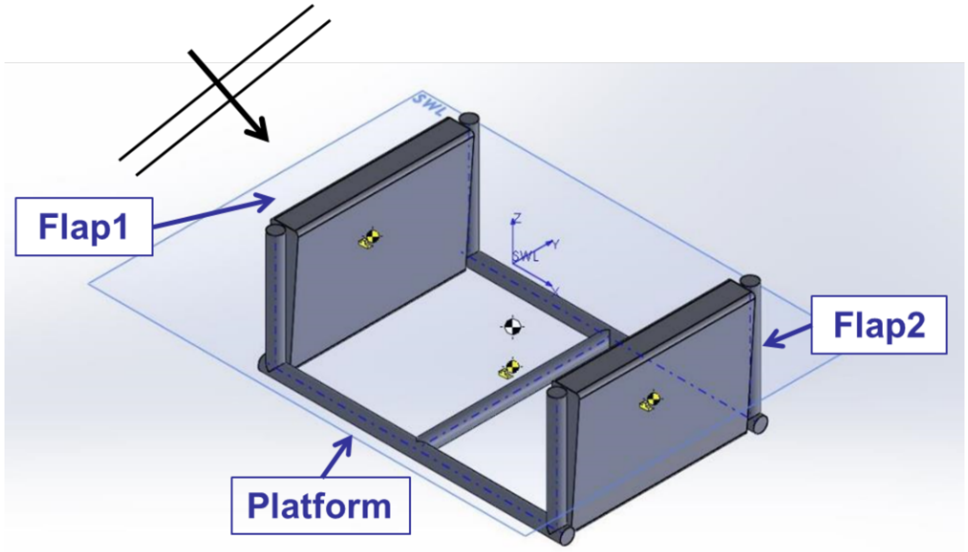


Figure 3-4. FOSWEC hydrodynamic design concept

FOSWEC	DOF	Max Motion
Flap	Pitch (RY)	+/- 25°
Platform	Heave (Z)	+/- 20 cm
	Pitch (RY)	+/- 20°
	Surge (X)	+/- 24 cm

Table 3-1. 1:33 scale FOSWEC maximum motions

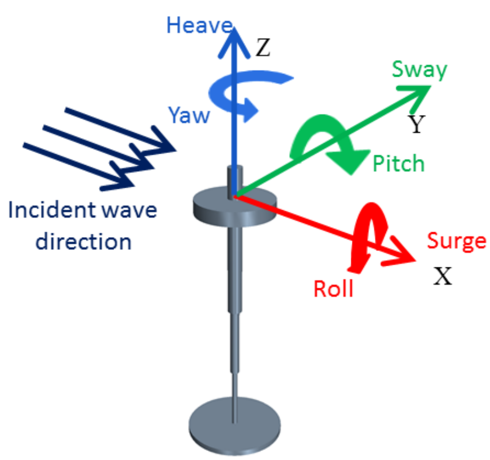


Figure 3-5. Global coordinate system, defining 6 DOF

Modularity The testability of an archetype in a modular fashion was identified as an important criteria by the WEC-Sim team. The FOSWEC is a highly modular device whose dynamics can be tested with increasing complexity. This allows the difference in performance of one configuration to be directly compared to a second configuration both in the tank experimentally, and in numerical simulations. Tested configurations, a subset of the possible FOSWEC configurations, is shown in Table 3-2. This is made possible by fixing and freeing each rigid body degree of freedom. Degrees of freedom not listed (i.e., platform roll) are constrained, as described in the following section.

FOSWEC	DOF	Config 1	Config 2	Config 3	Config 4
Flap 1	Pitch (RY)	Free	Free	Free	Free
Flap 2	Pitch (RY)	Locked	Free	Free	Free
Platform	Heave (Z)	Locked	Locked	Free	Free
	Pitch (RY)	Locked	Locked	Locked	Free
	Surge (X)	Locked	Locked	Locked	Free

Table 3-2. FOSWEC Configurations (Config 1 - Config 4)

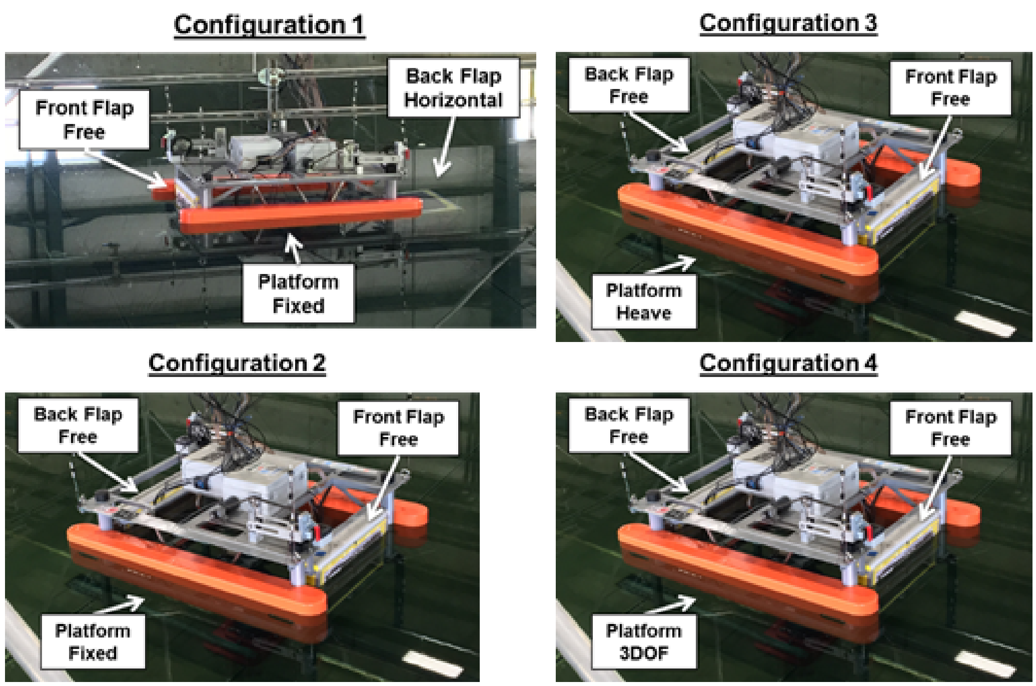


Figure 3-6. FOSWEC configurations (Config 1 - Config 4)

Arm Since the primary objective of this experimental test campaign is to generate a validation data set for hydrodynamic codes such as WEC-Sim, a traditional mooring system was not implemented. Instead, the FOSWEC was designed for the platform to move in three degrees of freedom: heave, pitch, and surge. A motion constraint system (called the Arm) was designed, allowing for independent control over heave, pitch, and surge degrees of freedom. This has the additional benefit of allowing for direct measurement of the load between the platform and the arm. A conceptualization of the arm's attachment to the FOSWEC is displayed in Figure 3-7.

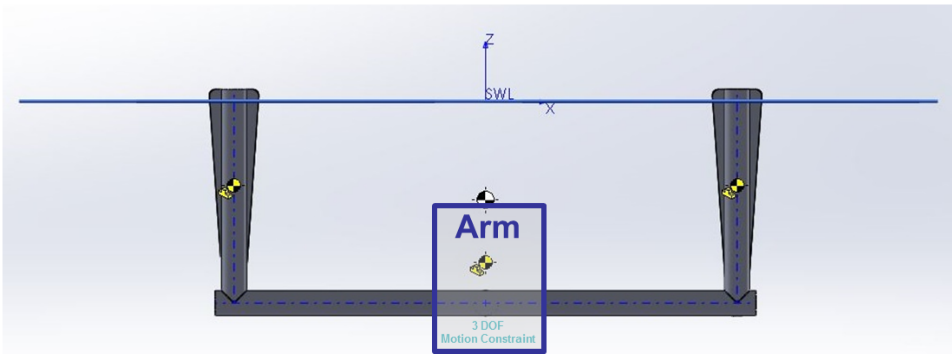


Figure 3-7. Concept of the motion constraint (Arm)

3.3. DESIGN AND FABRICATION

The design and fabrication of the FOSWEC device, and design and fabrication of the motion constraint were subcontracted to organizations for design and fabrication according to the specifications provided by the experimental testing team.

3.3.1. FOSWEC

Based on the level of complexity associated with the FOSWEC design, along with the model size and the need for on-site support, the experimental testing team hired Andrews-Cooper, a local engineering firm from Corvallis, Oregon, to design, fabricate, and support the FOSWEC model. The FOSWEC design and fabrication contact was managed by Sandia National Laboratories, an effort led by Kelley Ruehl. Andrews-Cooper was responsible for the following efforts: designing and fabricating the FOSWEC according to specifications; integrating instrumentation provided by Sandia and OSU into design; interfacing with the motion constraint (Arm) designed by +D; testing, troubleshooting, and repairing the FOSWEC design; modifying the FOSWEC according to Phase 1 findings.

3.3.2. Motion Constraint

The motion constraint (arm) was designed and fabricated by +D, a Spanish engineering firm with a history of designing and fabricating custom solutions. The arm design and fabrication contract was managed by OSU, with the effort led by Pedro Lomonaco. +D was responsible for: designing and fabricating the Arm according to specifications; constraining FOSWEC platform to heave, pitch, and surge motion; providing linear restoring stiffness in heave, pitch, and surge; modifying the arm according to Phase 1 findings.

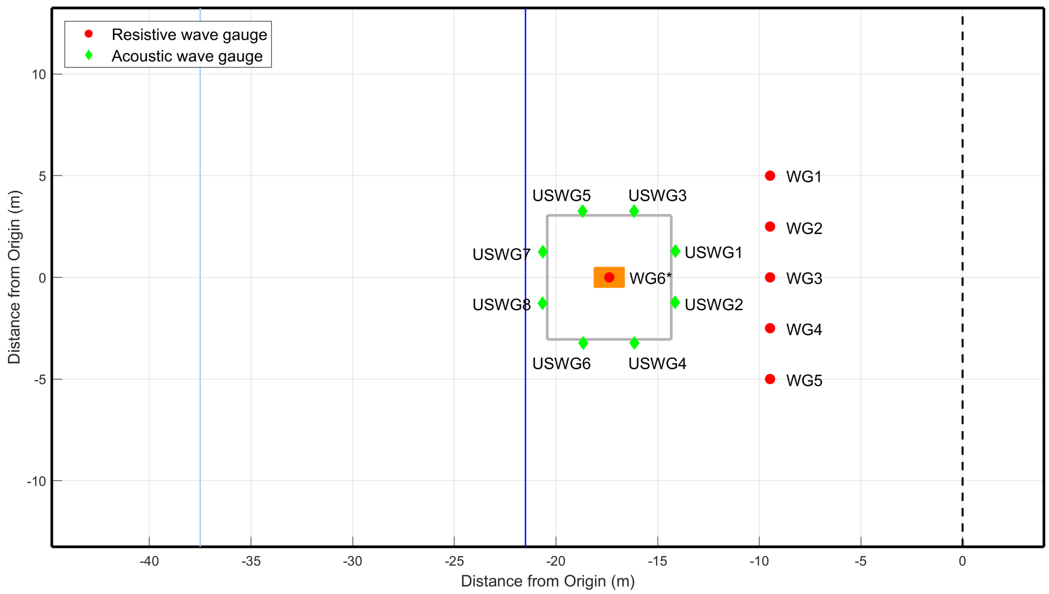


Figure 3-8. The layout of the DWB during testing, showing the location of the wave gauges, test frame (gray) and the FOSWEC device (orange rectangle). Note that wave gauge 6 (WG6) was only in place for wave calibration tests, when the FOSWEC device was not in the basin. The origin is the middle of the wave maker, indicated by the dashed line. The initiation of the beach (dark blue) and the SWL (light blue) are also indicated.

3.4. INSTRUMENTATION

Instrumentation of the FOSWEC and wave basin was categorized as either Primary or Secondary. The Primary Instrumentation set provides the data required by the Primary Objectives, and the Secondary Instrumentation targets the Secondary Objectives; Refer to Section 1 on test objectives. The specifications of the individual instruments are found in Appendix B.

3.4.1. Primary Instrumentation

Wave Elevation The wave surface elevation data is captured by wave probes provided by HWRL. There were seven resistive probes, which measure the resistance along an electrical path that includes the water in the basin. The resistance between the wires changes with water level. Five of these instruments were installed in the DWB and calibrated by the HWRL team. The remaining two were installed on the FOSWEC flaps by the ET team, and calibrated by HWRL staff. The wave surface elevation data surrounding the deployed FOSWEC is also tracked by nine acoustic wave probes (Figure 3-8). These devices bounce sound off the surface of the water and record the echo return time. These devices were provided and managed by the HWRL team.

WEC Motion WEC motion includes the motion of the entire platform as well as the motion of each flap. Flap motion relative to the platform is recorded by the two rotational encoders mounted on the end of the axles about which each flap rotates. The platform motion is measured by a PhaseSpace system, two tape-potentiometers placed between the FOSWEC platform and the Arm, and an inclinometer mounted on the FOSWEC platform. PhaseSpace is a motion tracking system using a set of cameras placed to target antennae attached to the four upper corners of the FOSWEC platform. The antennae emit light from different LEDs with known spacing that is recorded by the camera array. The visual data is then processed using standard video processing techniques, creating a full description of the platform motion. Additionally, two tape-potentiometers and an inclinometer resolve platform motion. The inclinometer is attached to the interior of the FOSWEC above the floats. It is aligned such that its axis is aligned with the FOSWEC pitch axis. One potentiometer is attached vertically to the platform and the Arm to measure heave, and the other is attached horizontally to the platform and the Arm to measure surge.

Power Take-off (PTO) The PTO designed for the FOSWEC has three modes of operation. In the generating mode, the motor controls the damping placed on the FOSWEC flaps as a linear ratio of speed to torque. This damping is determined by the PTO Damping Optimization experiment and utilized during the regular and irregular wave tests. The motoring mode drives the flaps and is used for the forced oscillation tests. Finally, the positioning mode is used to hold the flap at a specified position, and is used for the wave excitation tests.

The mechanical power captured by the FOSWEC is transferred from the flap axle to the Maxon motor located in the waterproof PTO box, as depicted in the photo montage found in Figure 3-9. The flap axle is instrumented with a 6-DOF load cell at the interface between the flap and the axle, in addition to the rotary encoders. The end of the axle is attached to a chain which transfers the mechanical power vertically from below water (bottom of the FOSWEC) to above water (top of the FOSWEC). On the top of the FOSWEC, a second chain is used to transfer the mechanical power horizontally from the edge of the device to the PTO box. The gearing ratio is selected as 1:1, 1:2 or 1:4 to maintain torque values within the measurement range of the instrumentation.

At the top-center of the FOSWEC, the horizontal chain turns an axle that passes through a torque fuse, a torque transducer, and a combined planetary gear-motor-quadrature encoder component. The torque fuse is a failsafe that interrupts the torque path when the torque exceeds a programmable level, protecting the expensive torque transducer from overload. The torque transducer is a FUTEK device with a built-in signal amplifier. The Maxon-assembled component containing the planetary gear box, motor, and encoder converts the mechanical energy to electrical, and allows FOSWEC control via a driver board and software utilities.

The motor driver voltage is monitored, and the total current as well as the constant-load current are measured by two Hall-effect sensors. By subtracting these current values, the current in the motor can be determined, and the electrical power calculated by multiplication with the driver voltage.

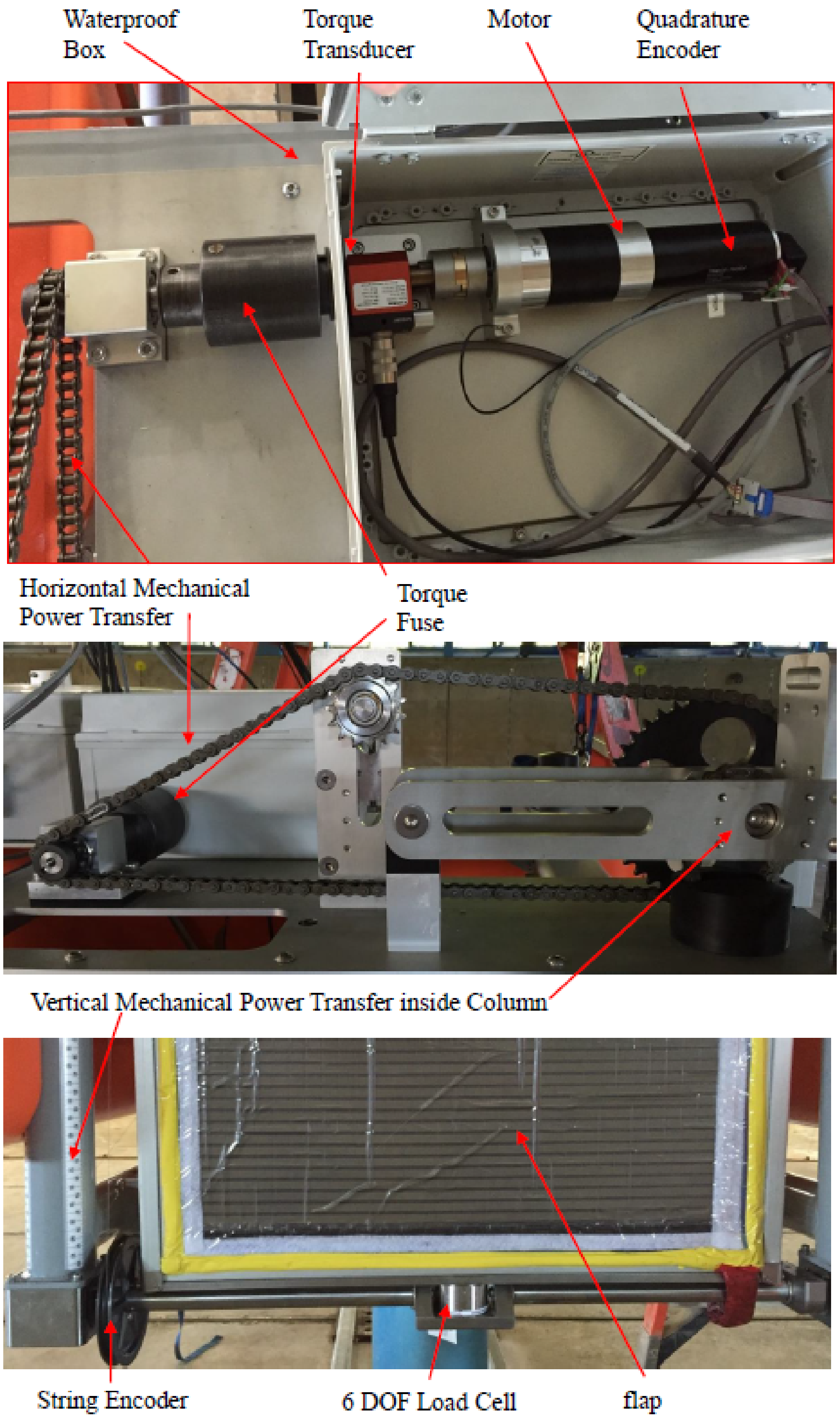


Figure 3-9. Plan and Elevation View of HWRL-Provided Instruments

3.4.2. Secondary Instrumentation

Constraint Forces Forces and moments at particular points on the FOSWEC platform were measured as part of the secondary objective- load characterization. The loads at end of the axle where the flaps meet the platform were instrumented with the aforementioned load cells. The loads located between the constraint arm and the platform itself were recorded by an ATI submersible Omega 160 6-DOF load cell.

Pressure Each flap had redundant pressure instrumentation. One flap side had two (stern) or three (bow) Druck miniature point pressure sensors. The sensors were provided by the HWRL team. An experimental pressure mat was placed on the outward-facing sides of each flap. The sensor is considered experimental as it is available from a sole vendor at high cost and has not been verified in this application. The mat has a 612 mm x 431 mm sensing area containing a 32 x 32 array of sensors. The pressure mats are read by a proprietary software and generate a real-time map of relative pressure distributions. This data is potentially highly useful for secondary test objectives. Figure 3-10 shows the installation of the pressure mat on the FOSWEC.

Figure 3-10. Installed Pressure Mat (Phase 1)

3.4.3. Data Acquisition System (DAQ)

With the exception of the PhaseSpace data and the pressure mat data, all data is recorded by the HWRL main Data Acquisition System (DAQ). The system is a National Instruments 6323 device that has 16-bit resolution per channel. All channels are configured to be $\pm$ 5 V analog, sampled at a rate of 0.02 s for Phase 1 testing (and 0.01 s for Phase 2), and synchronized to trigger simultaneously with the wavemaker. The DAQ system was setup and operated by the HWRL staff.

As shown in the cabling diagrams, some of the instrumentation, such as the Maxon rotary encoder, did not output data in a format compatible with the DAQ. Refer to Figure C-1 and Figure C-2 for the FOSWEC cabling diagram used for Phase 1 and Phase 2 testing respectively. These instruments were instead routed to a dSpace interface board. The data was reconfigured within dSpace to produce the $\pm$ 5 V signal needed by the DAQ. The use of the dSpace system also enabled virtual, real-time instrumentation of data along the PTO. Figure 3-11 shows the tracking screen developed by the OSU/HWRL team members. This approach provides the team with accurate feedback regarding the experiment, enabling issue identification and rapid debugging. The dSpace system was provided by the OSU WESRF group for Phase 1 testing, but was not available for Phase 2 testing. For Phase 2 testing, the team used an alternative system referred to as Bspace, details of the Bspace system are described in Section 6.

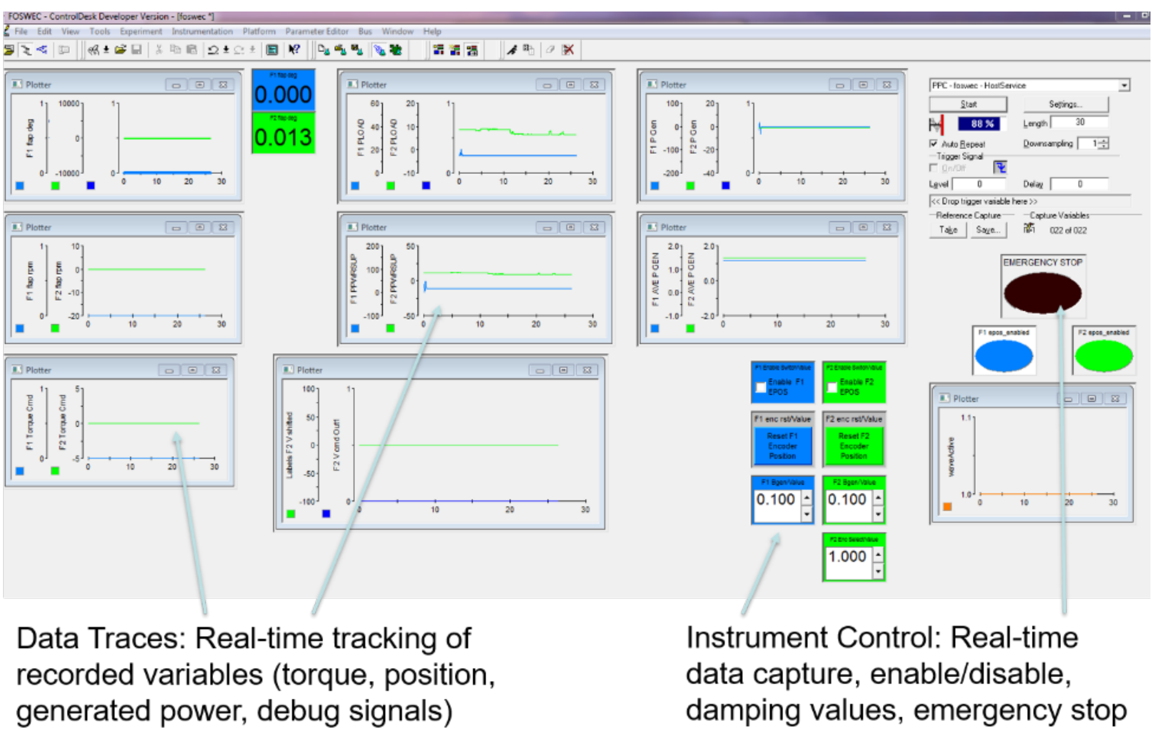


Figure 3-11. Real-Time Data Visualization

4. WAVES

This section provides an overview of the waves that were run in Phase 1 and Phase 2 of WEC-Sim testing. Wave calibration is performed prior to Phase 1 testing to ensure that the desired wave cases can be reliably and repeatably produced at the location of the FOSWEC device. Wave gauges described in the preceding section are placed in their permanent locations and an additional wave gauge is placed at the nominal location of the FOSWEC. A pressure gauge placed near the wave machine provides a reference water level reading. Finally, paddle 15 (center paddle) of the wave machine reports position and surface elevation. A selection of irregular and regular waves were produced, and the wave field was resolved in time at the locations of each wave gauge.

4.1. REGULAR WAVES

Regular waves are single frequency, single amplitude waves and are not representative of actual sea states, but are useful for device characterization. Twenty five regular wave cases were selected for calibration in the DWB. Out of the 25 cases tried, 23 were successfully calibrated within $\pm 5\%$ of the target H (20 within $\pm 2\%$) and $\pm 0.1\%$ of the target T. Table 4-1 defines the calibrated waves by nominal values of wave height H_0, wave period T_0, and the corresponding energy-per-crest length E_{f0}. Actual values observed in the DWB are tabulated as H, T, and E_f, respectively. The ratio between observed and nominal values (e.g., T/T_0) are also reported in Table 4-1. Figure 4-1 shows a graphical comparison between targeted waves (red triangles), and observed (black squares). A matrix of the 1:33 Froude scale calibrated waves is shown in Table 4-2, and a matrix of their full scale values is shown in Table 4-3. The $T = 3.31$ (s) and $H = 0.015$ (m) ($T = 19$ (s) and $H = 0.5$ (m) at full scale) wave was unstable in the DWB due to cross-seiche, and $T = 0.87$ (s) and $H = 0.136$ (m) ($T = 5$ (s) and $H = 4.5$ (m) at full scale) wave was unstable due to wave steepness and exceeded the wave machine acceleration limits; these waves were not used in the wave tank tests. The regular waves listed in Table 4-2 were selected for testing of the FOSWEC, where the black cells refer to uncalibrated waves.

Trial	T (s)	H (m)	E_f (W/m)	T_o (s)	H_o (m)	$E_{f,o}$ (W/m)	H_o/H (-)	T_o/T (-)	$E_{f,o}/E_f$ (-)
1	0.87	0.015	0.19	0.87	0.015	0.19	1.00	1.00	1.00
2	0.87	0.045	1.72	0.87	0.044	1.64	1.00	0.97	0.95
3	1.22	0.015	0.27	1.22	0.015	0.27	1.00	0.99	0.98
4	1.22	0.045	2.43	1.22	0.045	2.36	1.00	0.99	0.97
5	1.22	0.136	21.85	1.22	0.141	23.31	1.00	1.03	1.07
6	1.22	0.242	69.05	1.22	0.237	65.90	1.00	0.98	0.95
7	1.57	0.015	0.37	1.57	0.015	0.37	1.00	1.00	1.01
8	1.57	0.045	3.32	1.57	0.046	3.39	1.00	1.01	1.02
9	1.57	0.136	29.90	1.57	0.134	28.91	1.00	0.98	0.97
10	1.91	0.015	0.49	1.92	0.015	0.49	1.00	1.00	1.01
11	1.91	0.045	4.39	1.92	0.046	4.53	1.00	1.01	1.03
12	1.91	0.136	39.52	1.91	0.135	38.70	1.00	0.99	0.98
13	1.91	0.242	124.90	1.91	0.241	123.61	1.00	1.00	0.99
14	2.26	0.015	0.60	2.26	0.015	0.61	1.00	1.01	1.02
15	2.26	0.045	5.36	2.26	0.045	5.31	1.00	0.99	0.99
16	2.26	0.136	48.25	2.26	0.136	47.84	1.00	1.00	0.99
17	2.61	0.015	0.68	2.61	0.015	0.70	1.00	1.01	1.02
18	2.61	0.045	6.13	2.61	0.046	6.19	1.00	1.00	1.01
19	2.61	0.136	55.17	2.61	0.137	55.36	1.00	1.00	1.00
20	2.61	0.242	174.37	2.61	0.246	179.91	1.00	1.02	1.03
21	3.31	0.045	7.16	3.31	0.045	6.99	1.00	0.99	0.98
22	3.31	0.136	64.48	3.30	0.138	66.01	1.00	1.01	1.02
23	3.31	0.242	203.78	3.31	0.242	202.39	1.00	1.00	0.99

Table 4-1. Regular Wave Calibration Results

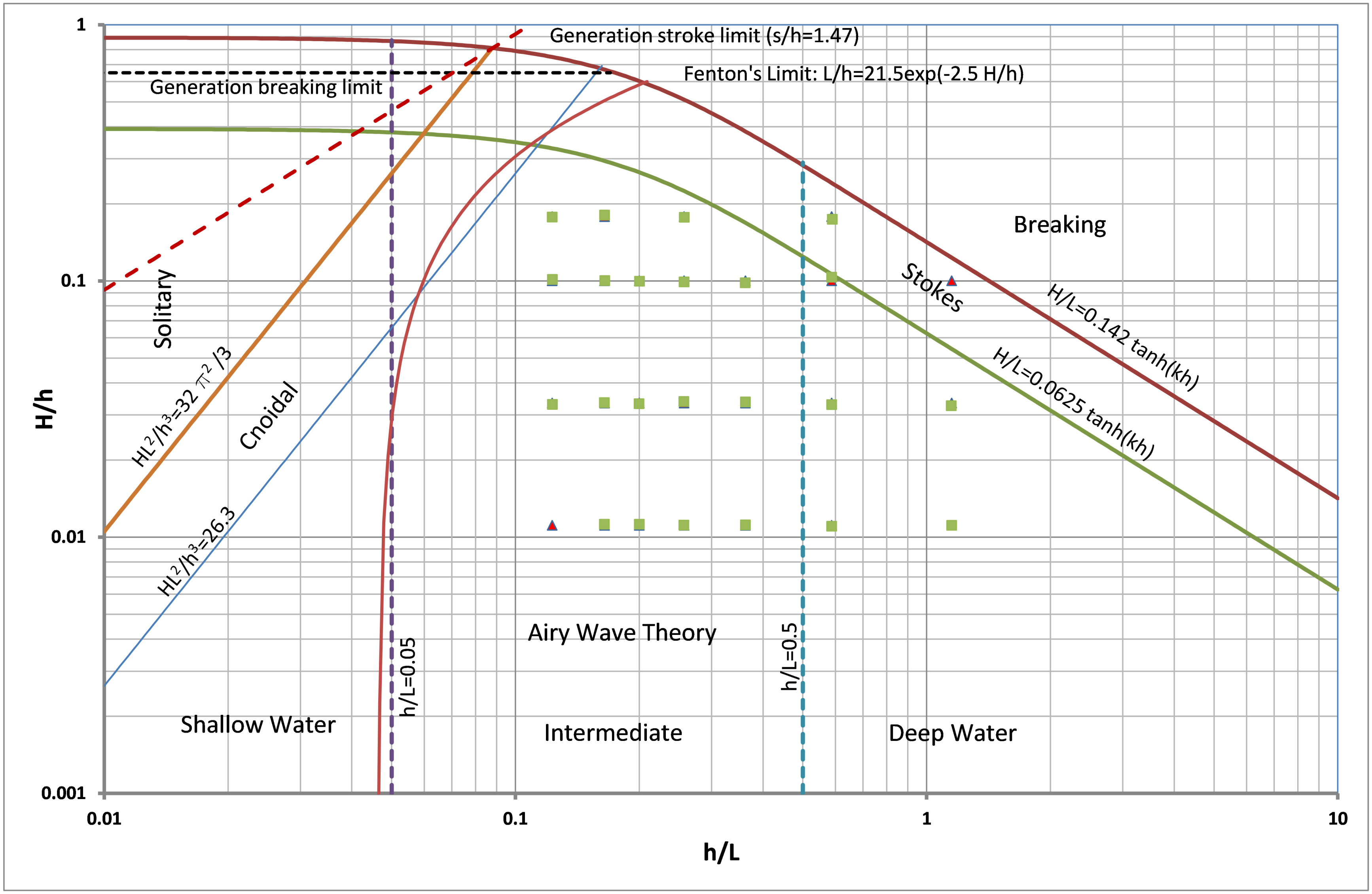


Figure 4-1. Regular Wave Calibration Results (red triangles are targeted, and green squares are observed)

H (m)							
0.242	■		■		■		
0.136	■						
0.045							
0.015							■
	0.87	1.22	1.57	1.91	2.26	2.61	3.31
	T (s)						

Table 4-2. Regular Waves at 1:33 Froude Scale

H (m)							
8.0	■		■		■		
4.5	■						
1.5							
0.5							■
	5.0	7.0	9.0	11.0	13.0	15.0	19.0
	T (s)						

Table 4-3. Regular Waves at Full Scale

4.2. IRREGULAR WAVES

Six sea states of irregular waves generated using a Pierson-Moskowitz Spectra were calibrated in the DWB. The target sea states at 1:33 Froude scale and their full scale equivalents are listed in Table 4-4. The target peak period (T_p) and significant wave height (H_{m0}) were calibrated for each of the six sea states. The calibration results are reported in Table 4-5, where observed peak period and significant wave height are denoted as $T_{p,o}$ and $H_{m0,o}$ respectively. Calibration results are shown in Figure 4-2, where orange circles are targeted, and black squares are average observed sea states, and in Figure 4-3, where colored dots are the individual wavetrains for each sea state.

Five of the six cases were successfully calibrated within $\pm 5\%$ of the target H_{m0}, and four of the six were calibrated within $\pm 5\%$ of the target T_p. Breaking waves were observed for the $T_p = 1.22$ (s) and $H_{m0} = 0.136$ (m) case, $T_{p,fs} = 7$ (s) and $H_{m0,fs} = 4.5$ (m) at full scale, indicating that the prescribed conditions were not feasible. However, the observed conditions are still useful for testing. For the targeted energy flux, five of the six cases are within $\pm 10\%$, four of six are within $\pm 5\%$.

Sea State	T_p (s)	H_{m0} (m)	$T_{p,fs}$ (s)	$H_{m0,fs}$ (m)
SS1	1.22	0.015	7.0	0.5
SS2	1.22	0.045	7.0	1.5
SS3	1.22	0.136	7.0	4.5
SS4	2.61	0.015	15.0	0.5
SS5	2.61	0.045	15.0	1.5
SS6	2.61	0.136	15.0	4.5

Table 4-4. Irregular Sea States at 1:33 Froude Scale and Full Scale

Trial	T_p (s)	H_{m0} (m)	T_e (s)	E_f (W/m)	$T_{p,o}$ (s)	$H_{m0,o}$ (m)	$T_{e,o}$ (s)	$E_{f,o}$ (W/m)	$\frac{T_{p,o}}{T_p}$ (-)	$\frac{H_{m0,o}}{H_{m0}}$ (-)	$\frac{T_{e,o}}{T_e}$ (-)	$\frac{E_{f,o}}{E_f}$ (-)
1	1.22	0.015	1.07	0.12	1.12	0.015	1.06	0.12	0.92	1.01	1.00	1.02
2	1.22	0.045	1.07	1.07	1.15	0.046	1.06	1.07	0.95	1.00	1.00	1.00
3	1.22	0.136	1.07	9.61	1.28	0.110	1.17	6.91	1.05	0.81	1.09	0.72
4	2.61	0.015	2.26	0.28	2.82	0.016	2.33	0.31	1.08	1.03	1.03	1.08
5	2.61	0.045	2.26	2.56	2.48	0.046	2.26	2.65	0.95	1.02	1.00	1.04
6	2.61	0.136	2.26	23.03	2.48	0.139	2.26	23.86	0.95	1.02	1.00	1.04

Table 4-5. Irregular Wave Calibration Results

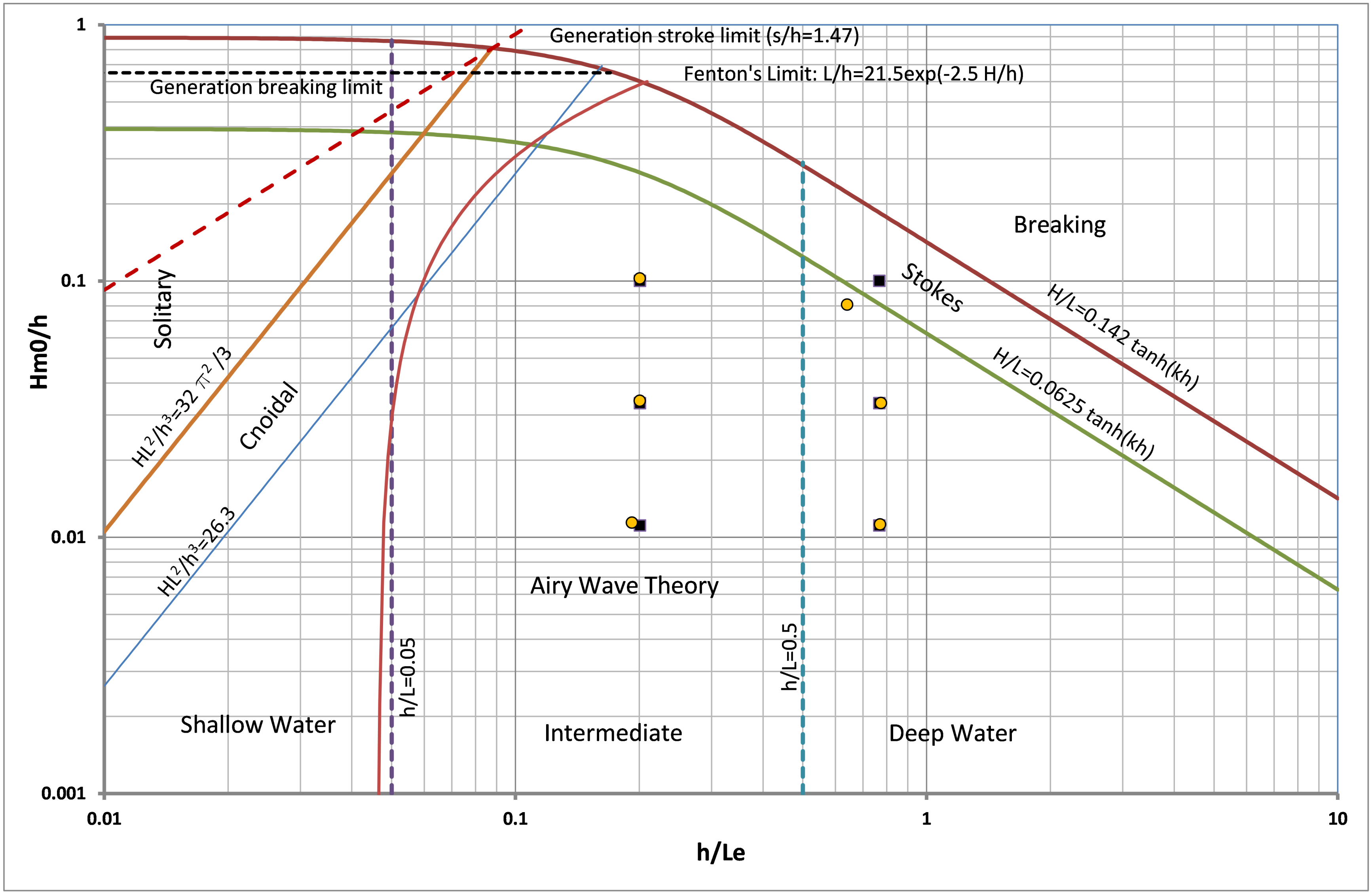


Figure 4-2. Irregular Wave Calibration Results, Averaged (orange circles are targeted, and black squares are average observed)

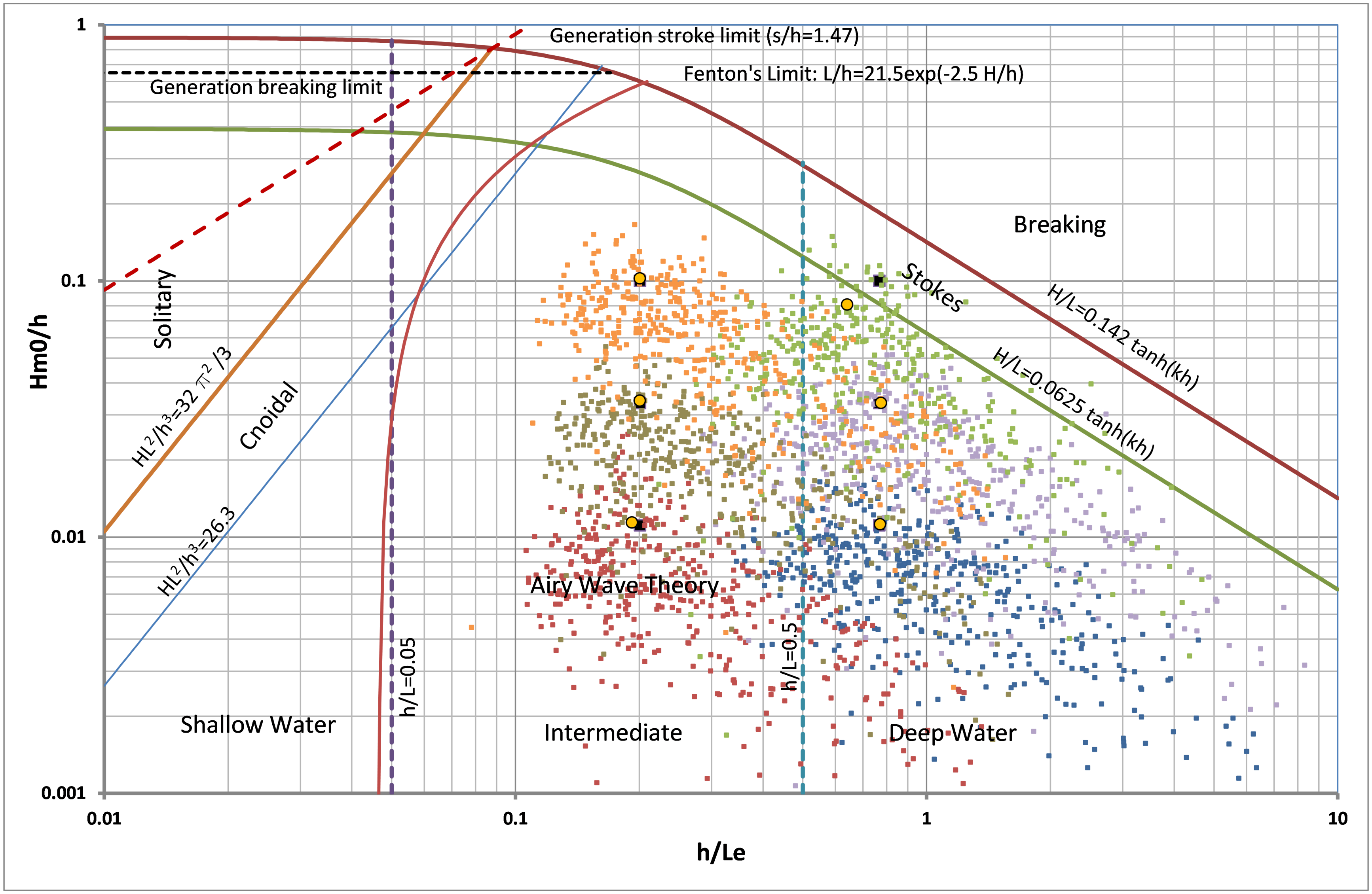


Figure 4-3. Irregular Wave Calibration Results, Detailed (orange circles are targeted, black squares are average observed, colored dots are the individual wavetrains for each sea state)

5. PHASE 1

This section provides a description of the FOSWEC and the motion constraint designs, an overview of the instrumentation, and details of the experiments performed in Phase 1 of FOSWEC testing. Phase 1 testing occurred in November and December of 2015. The goal of Phase 1 was to characterize the incident wave environment, perform baseline system identification tests, and complete at least 1 trial of each of the planned experiments. The experimental test plan for Phase 1 testing included both dry tests and wet tests, details of which are described in the following sections.

5.1. FOSWEC

Figure 5-1 shows a rendering of the Phase 1 FOSWEC with a selection of its instrumentation and design features identified. The *PhaseSpace Antenna* are rigidly mounted to the FOSWEC frame in order to provide data to the PhaseSpace motion tracking system. The *Waterproof PTO Box* contains the PTO instruments: torque transducer, geared motor, and position encoder. The *Buoyancy Blocks* provide buoyancy to the model. The *Pressure Mat* is an integrated array of pressure sensors that provide real-time differential pressure results across the face of the flap. The *Flap 6DOF Load Cell* is placed between the flap base and the axle, thus directly measuring loads on the flap. Finally, the *Rotary Encoder* measures the flap position. Figure 5-2 shows plane views of the FOSWEC model with the 1:33 scale (as built) dimensions. Figure 5-3 shows a photograph of the as built FOSWEC, as it is being installed in the basin.

A 1:4 gearing ratio was selected for the motor gears to transfer the mechanical power at the flap axle to the input of the PTO. Buoyancy blocks on the port and starboard of the device ensure positive buoyancy. The “Motor Gears” incorporate a 1:4 gear set along with transferring the mechanical power at the flap axle to the input of the Power Take Off (PTO). The flexibility provided by the gearing provides a way of tuning the torque instrument ranges to match the torque values being induced on the model by the applied waves.

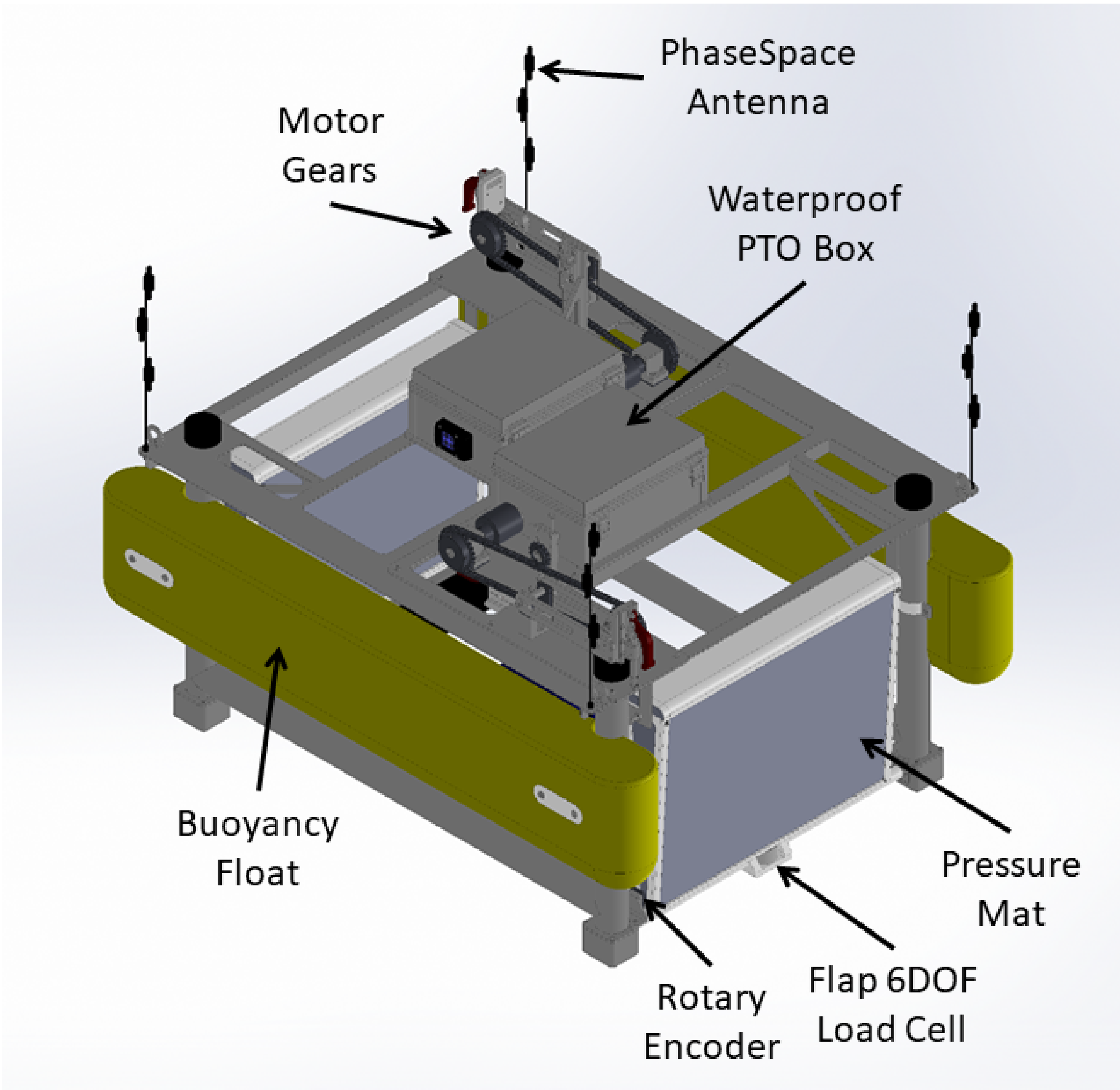


Figure 5-1. FOSWEC Mechanical Design Rendering (Phase 1)

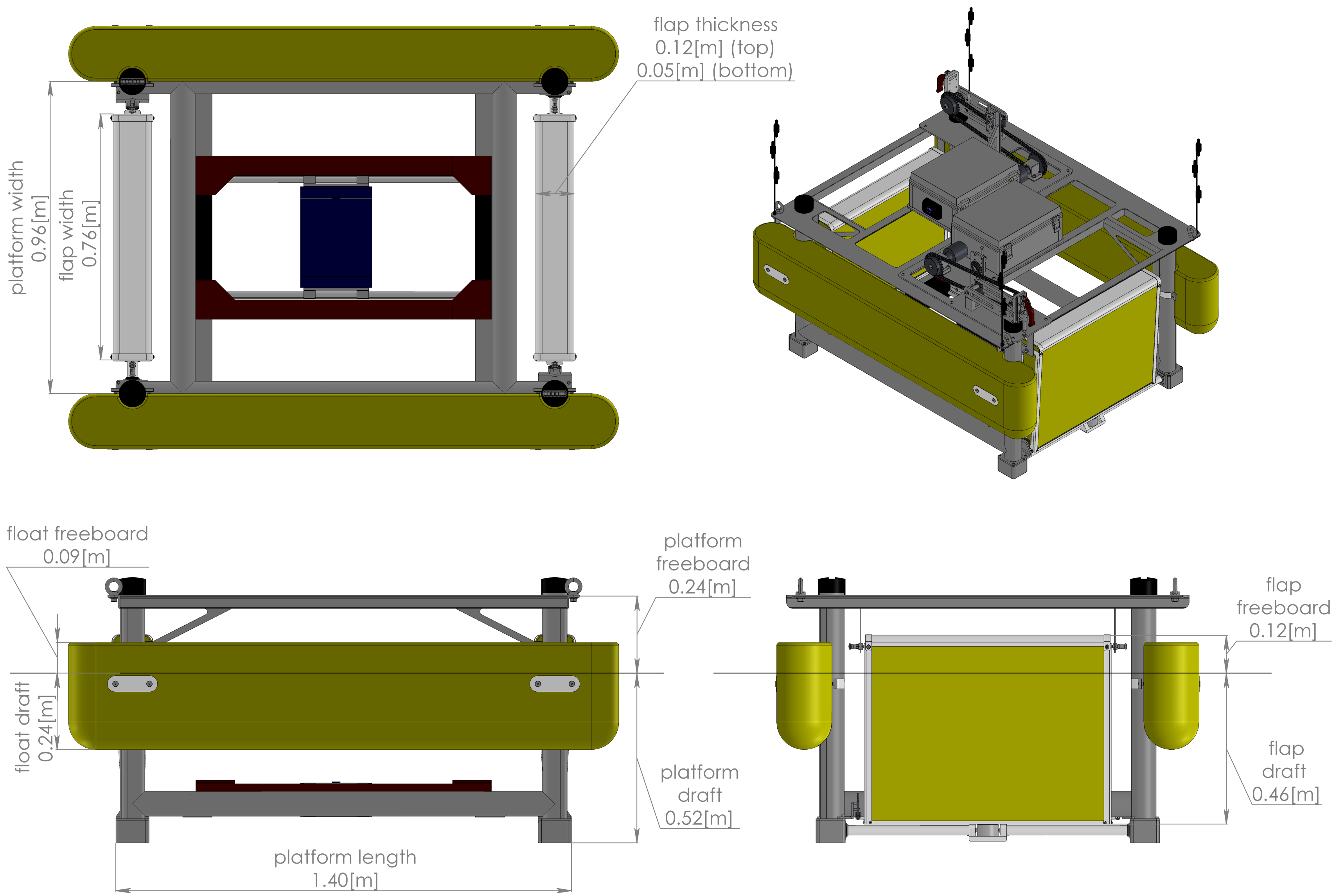


Figure 5-2. FOSWEC Mechanical Design Dimensions (Phase 1)

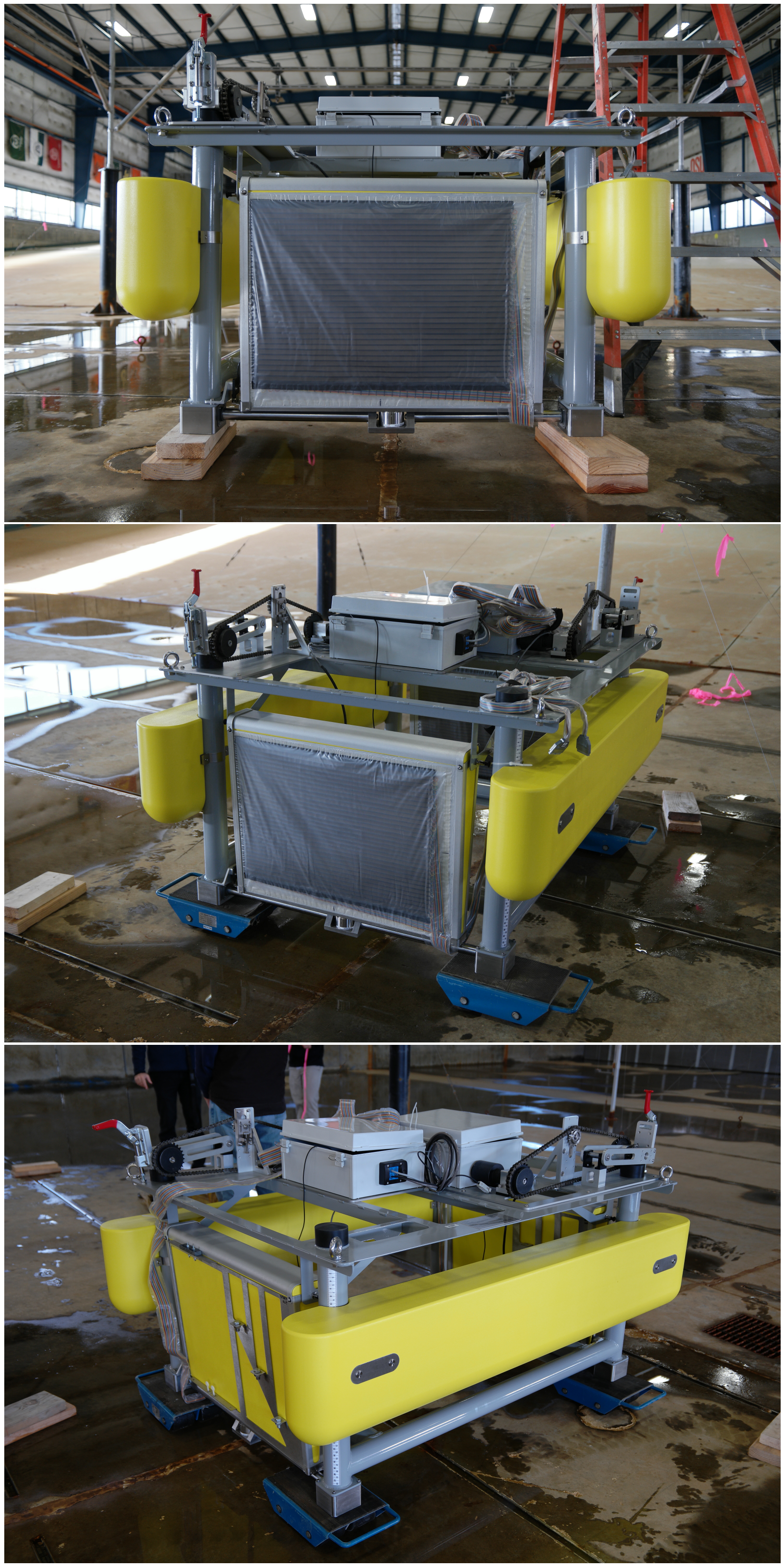


Figure 5-3. FOSWEC before installation (Phase 1)

5.2. ARM

A rendering of the Arm used in Phase 1 testing is shown in Figure 5-4. This rendering identifies the heave, pitch and surge constraint systems. Figure 5-5 shows a photograph of the Arm components, laid out as they are to be assembled. The telescoping heave constraint is encapsulated by blue tube to the right side of the image. The red platform at the bottom of the photo connects the Arm to the DWB floor. The ring at the top of the heave constraint stabilizes and protects the 6-DOF load cell, and provides the point of connection between the Arm and the FOSWEC, as shown in Figure 5-6. The bungee cord provides the surge restoring force, as shown in Figure 5-7. The smaller red components to the right of the picture connect the load cell (center blue circle) to the surge rails (black and aluminum) and provide the pitch constraint.

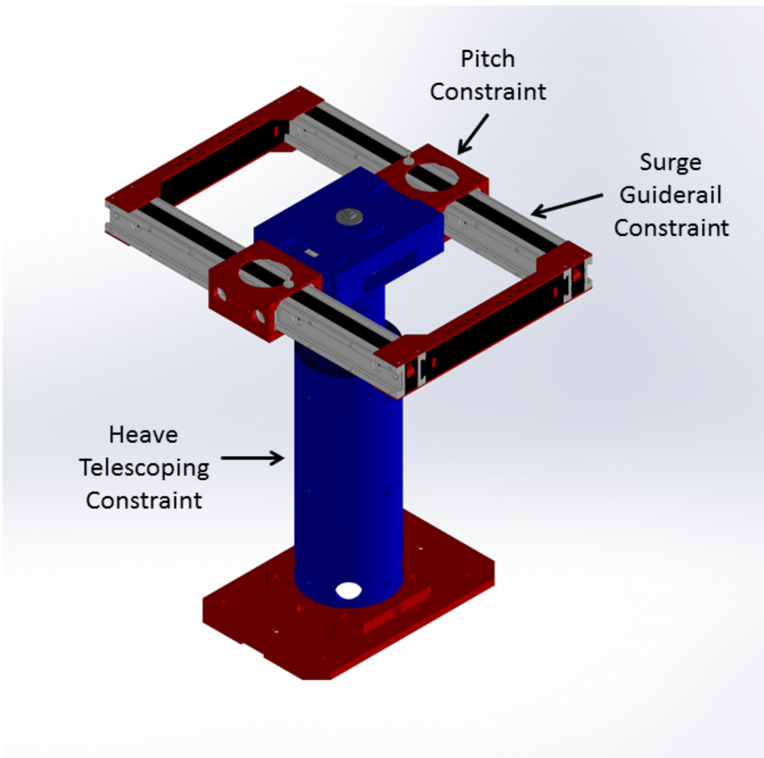


Figure 5-4. Arm Rendering (Phase 1)

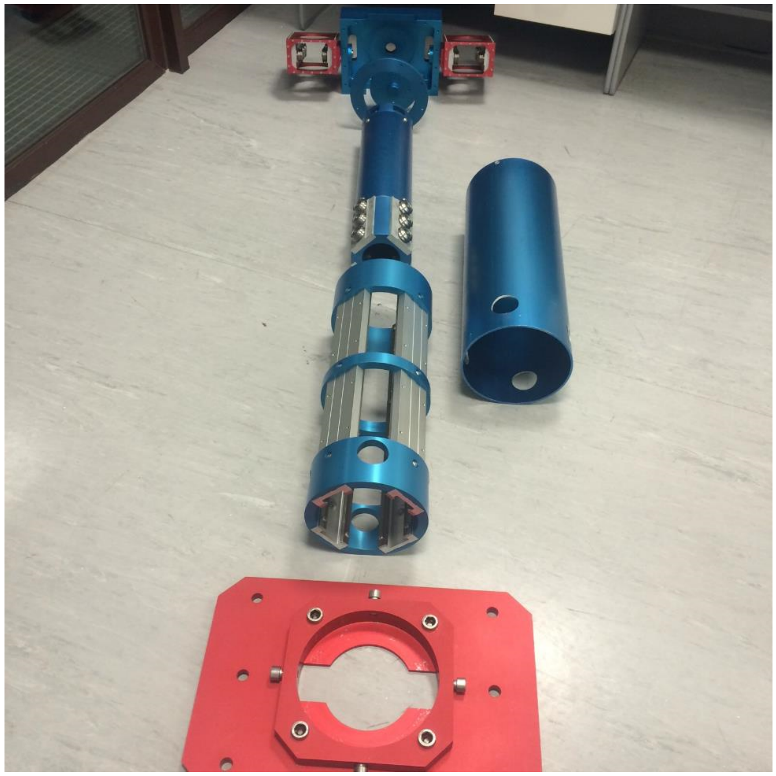


Figure 5-5. Layout of the Arm

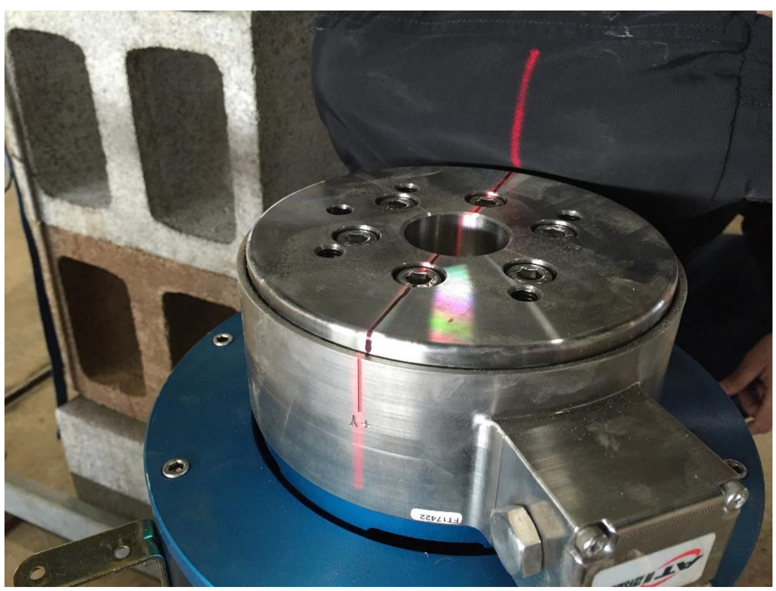


Figure 5-6. 6-DOF Load Cell between Arm and FOSWEC

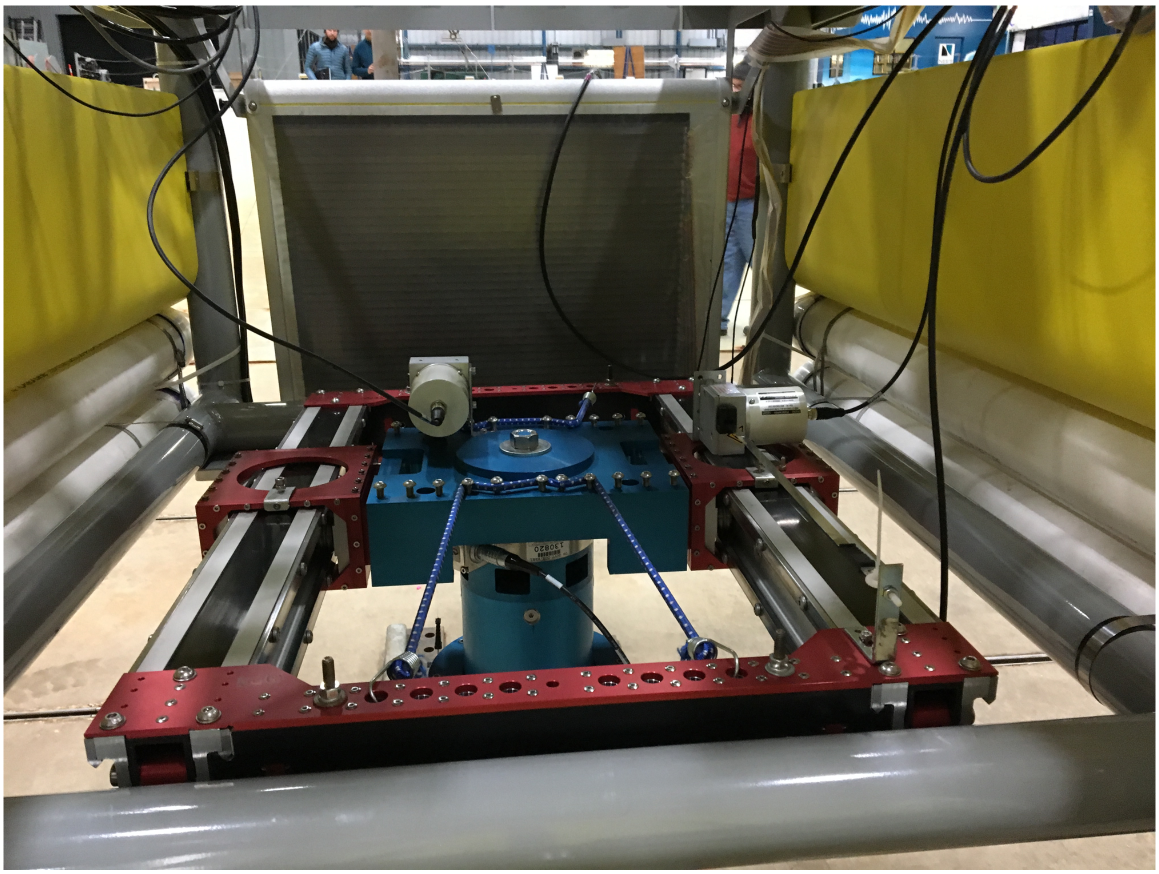


Figure 5-7. Interior view of Arm/FOSWEC Assembly

5.3. INSTRUMENTATION

The instrumentation used in Phase 1 testing is listed in Table 5-1.

Sensor	Manufacturer	Model Number	# of Sensors
Flap Encoder	Gil	Blade25	2
Pressure Mat	Tactilus	custom	2
Flap 6DOF Load Cell	ATI	9105-TW-MINI58-R-5-IP68	2
Arm 6DOF Load Cell	ATI	9105-TIF-OMEGA160-IP68	1
Pressure Sensors	Druck	PDCR830	5
PTO Motor	Maxon	ESPOS2	2
PTO Motor Encoder	Maxon	HEDL5540	2
PTO Torque Transducer	Futek	TRS300	2

Table 5-1. Phase 1 Instrumentation

5.4. EXPERIMENTS

A description of each experiment performed during FOSWEC Phase 1 testing is provided in the following sections. The list of experiments performed during Phase 1 testing and the name of their corresponding directory on the data repository are listed in Table 5-2. A description of the FOSWEC data structure on the data repository is provided in Section 8. Test logs for each experiment performed during Phase 1 testing are provided in Appendix D, and in the '/data/WECSIM/logs' directory of the FOSWEC data set on the data repository

Experiment	Directory
Dry Tests (Phase 1)	N/A
Heave Decay	HeaveDecay
Pitch Decay	PitchDecay
Surge Decay	SurgeDecay
Flap Decay (PTO Connected)	FlapDecay1
Initial Waves	N/A
Damping Optimization	N/A
Wave Excitation	N/A
Forced Oscillation	N/A

Table 5-2. Phase 1 Experiments

5.4.1. Dry Tests (Phase 1)

Dry tests are used to determine the mass, moment of inertia (MOI), and center of gravity (COG) for each FOSWEC body. The mass was measured using a scale or estimated from CAD models, with the measurement method denoted in Table 5-3. The COG for each FOSWEC body is reported in Table 5-4, along with the method of measurement. All measurements are from the still water line (SWL), with coordinate axis defined in Figures 5-8 and 5-9. The moments of intertia (I_{xx}, I_{yy}, and I_{zz}) for each of the FOSWEC bodies are reported in Table 5-5. For more information on how each of the tests were performed, refer to Appendix A.

Body	**Mass (kg)** *Method*	**Notes**
Flap 1	23.1 *Measured*	with pressure mat and sensors
Flap 2	23.2 *Measured*	with pressure mat and sensors
Platform	153.8 *Measured*	without flaps
FOSWEC	200.1 *Estimated*	Platform with flaps
FOSWEC	201.4 *Measured*	Platform with flaps
Arm	47.7 *Measured*	Surge constraint
Arm	23.8 *Measured*	Heave constraint, with load cell
Arm	73.3 *Estimated*	Heave/Surge constraint
FOSWEC & Arm	274.7 *Estimated*	Platform, flaps, and arm
FOSWEC & Arm	290.3 *Estimated*	Platform, flaps, arm, and buoyancy

Table 5-3. Phase 1 Mass Properties

Body	x_{cog} (m)	y_{cog} (m) *Method*	z_{cog} (m)	Notes
Flap 1	-0.65 *Scale*	0.011 *Scale*	-0.29 *Pendulum*	
Flap 2	0.65 *Scale*	0.011 *Scale*	-0.29 *Pendulum*	
Platform	-0.0009 *Scale*	-0.004 *Scale*	0.46 *Pendulum*	without flaps

Table 5-4. Phase 1 Center of Gravity (from SWL)

Body	I_{xx} (kgm^2)	I_{yy} (kgm^2)	I_{zz} (kgm^2)	Notes
Flap 1	1.42	1.19	1.99	
Flap 2	1.58	1.62	1.25	
Platform	37.88	29.63	N/A	without flaps
Platform	44.83	60.61	N/A	with Flaps

Table 5-5. Phase 1 Moment of Inertia (relative to COG)

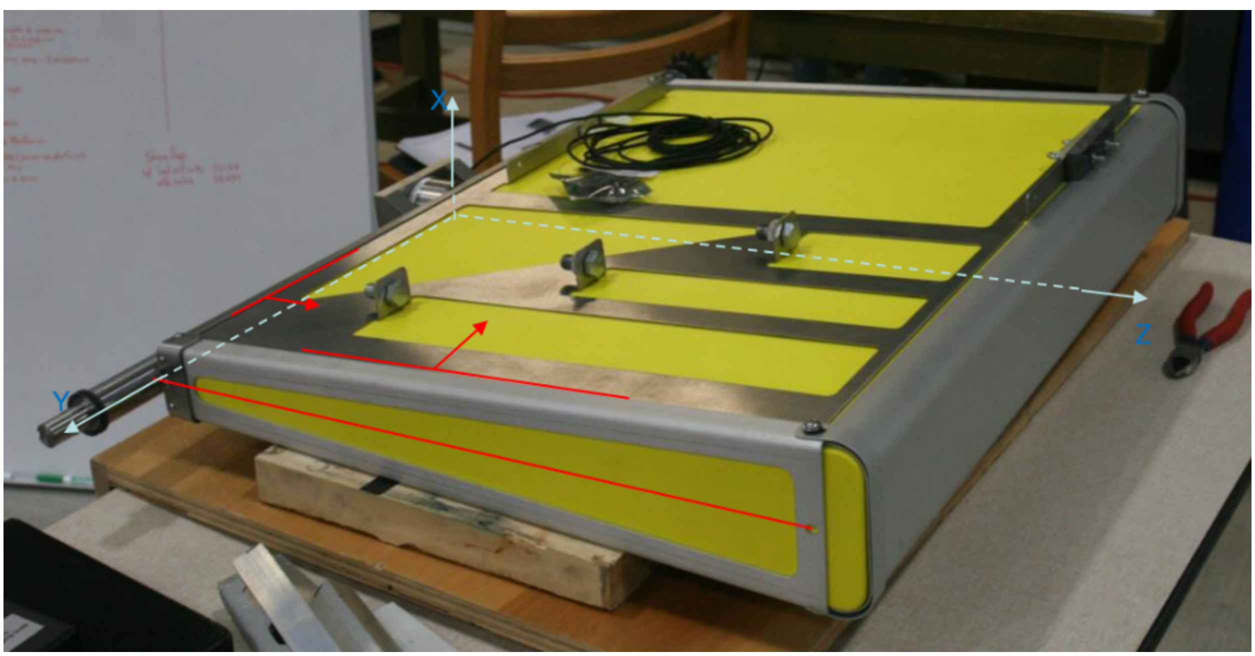


Figure 5-8. Reference Photo for Flap COG Calculation

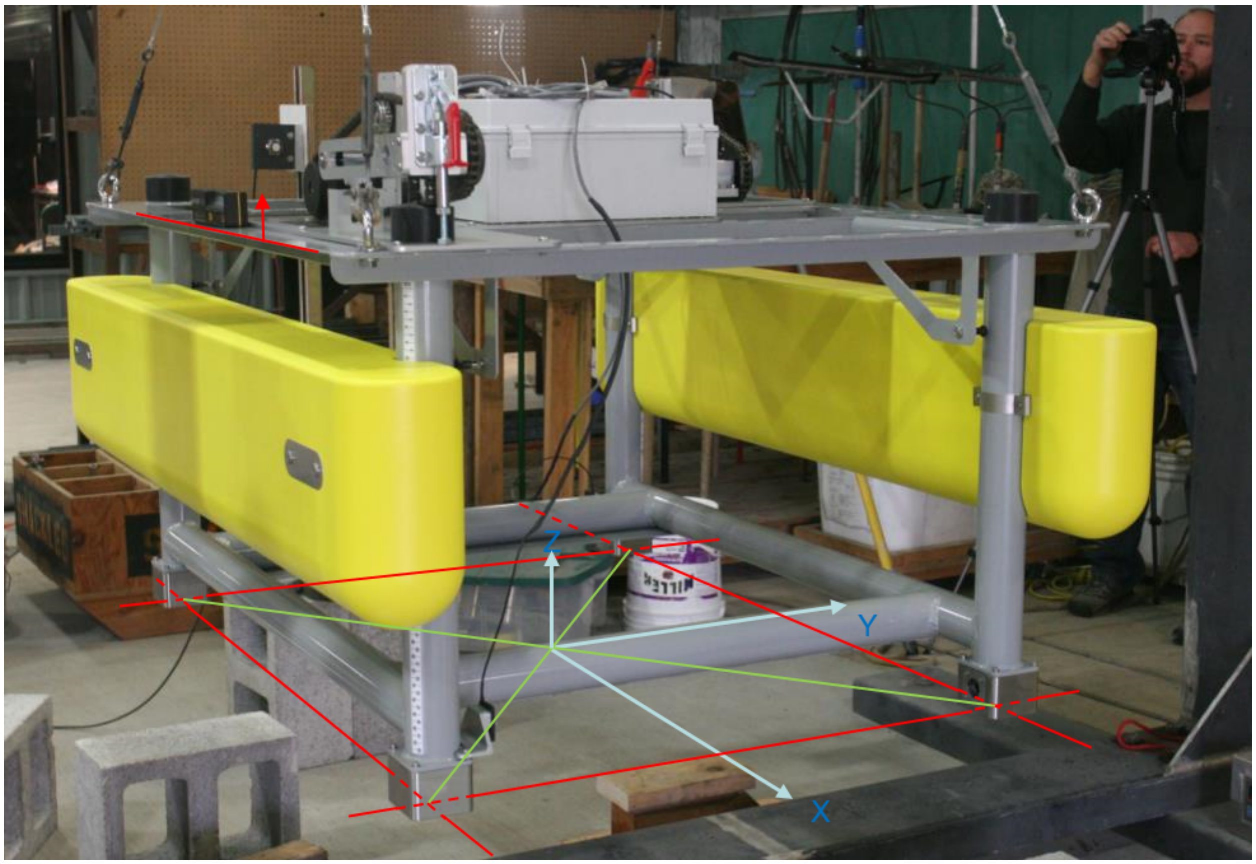


Figure 5-9. Reference Photo for Platform COG Calculation

5.4.2. Heave Decay

The heave decay and static offset tests are used to determine the natural frequency (ω_n), the damping value, and the restoring stiffness of the FOSWEC in heave. To perform the heave decay tests, the platform was unlocked in heave and locked in pitch and surge, the flaps were locked in their upright positions, and the overhead crane was connected to a load cell attached to the platform. A picture of the heave decay experimental setup is shown in Figure 5-10. The overhead crane was used to lift the FOSWEC to the desired vertical displacement (Δz), the load cell value was recorded while the surface of the tank stabilized, whereupon the cable connecting the load cell to the platform was cut. FOSWEC heave motion was recorded until device motion ceased, and wave gauges recorded the radiated wave surface elevation. For static offset tests, the heave hydrostatic force was measured for a range of vertical displacements (Δz), but the cable is not cut. Heave static offset tests are used to determine the relationship between heave displacement and the corresponding restoring force, i.e. hydrostatic stiffness. The heave decay and static offset test log is provided in Table D-1.

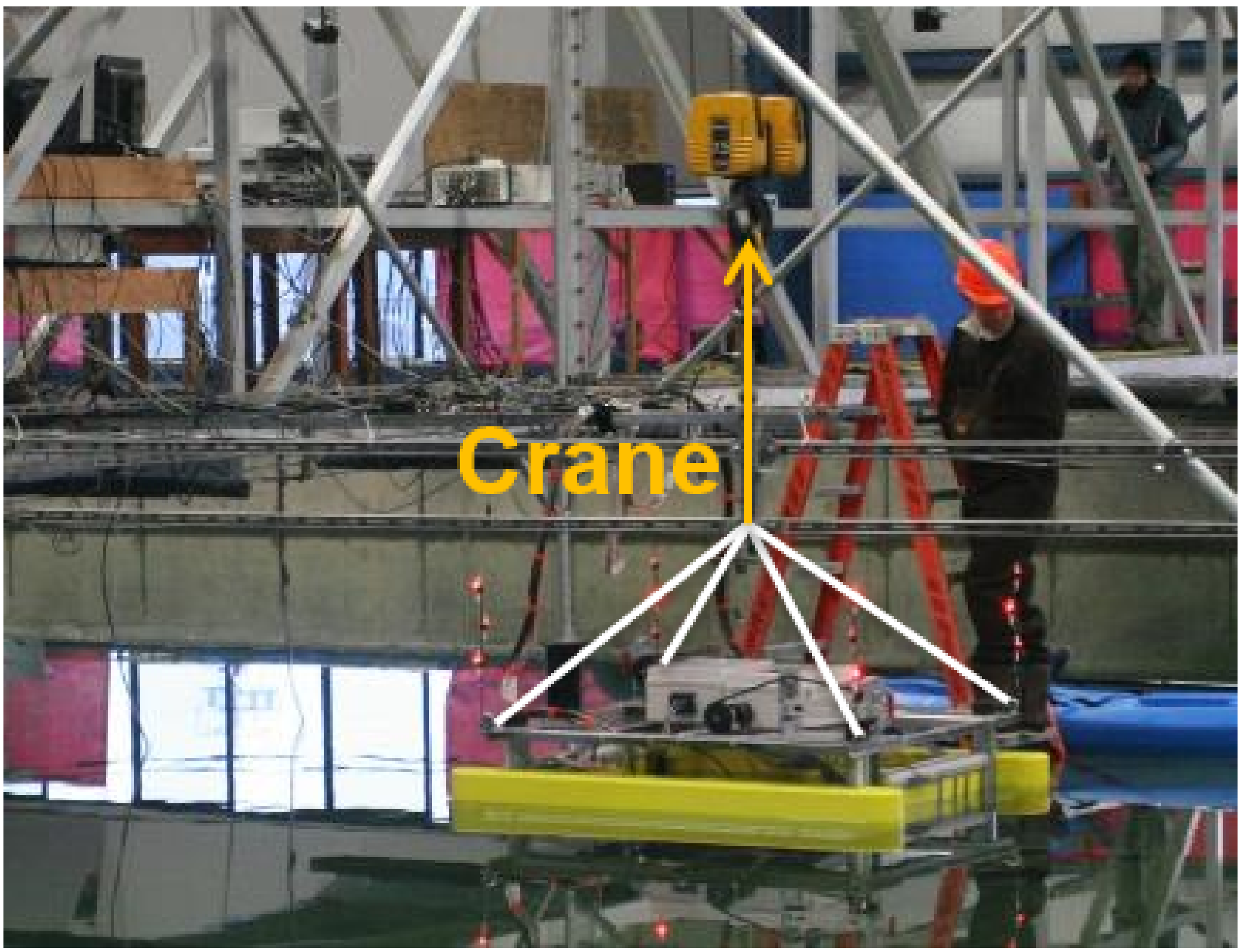


Figure 5-10. Heave Decay and Static Offset Setup

5.4.3. Pitch Decay

The pitch decay and static offset tests are used to determine the natural frequency (ω_n), the damping value, and the restoring stiffness of the FOSWEC in pitch. To perform the pitch decay tests, the platform was unlocked in pitch and locked in heave and surge, the flaps were locked in their upright positions, and the overhead crane was connected to a load cell attached to the platform. A picture of the pitch decay experimental setup is shown in Figure 5-11. The overhead crane was used to rotate the FOSWEC to the desired pitch displacement ($\Delta\theta$), the load cell value was recorded while the surface of the tank stabilized, whereupon the cable connecting the load cell to the platform was cut. For static offset tests, the pitch hydrostatic force was measured for a range of pitch displacements ($\Delta\theta$), but the cable is not cut. Pitch static offset tests are used to determine the relationship between pitch displacement and the corresponding restoring torque, i.e. hydrostatic stiffness. The pitch decay and static offset test log is provided in Table D-2.

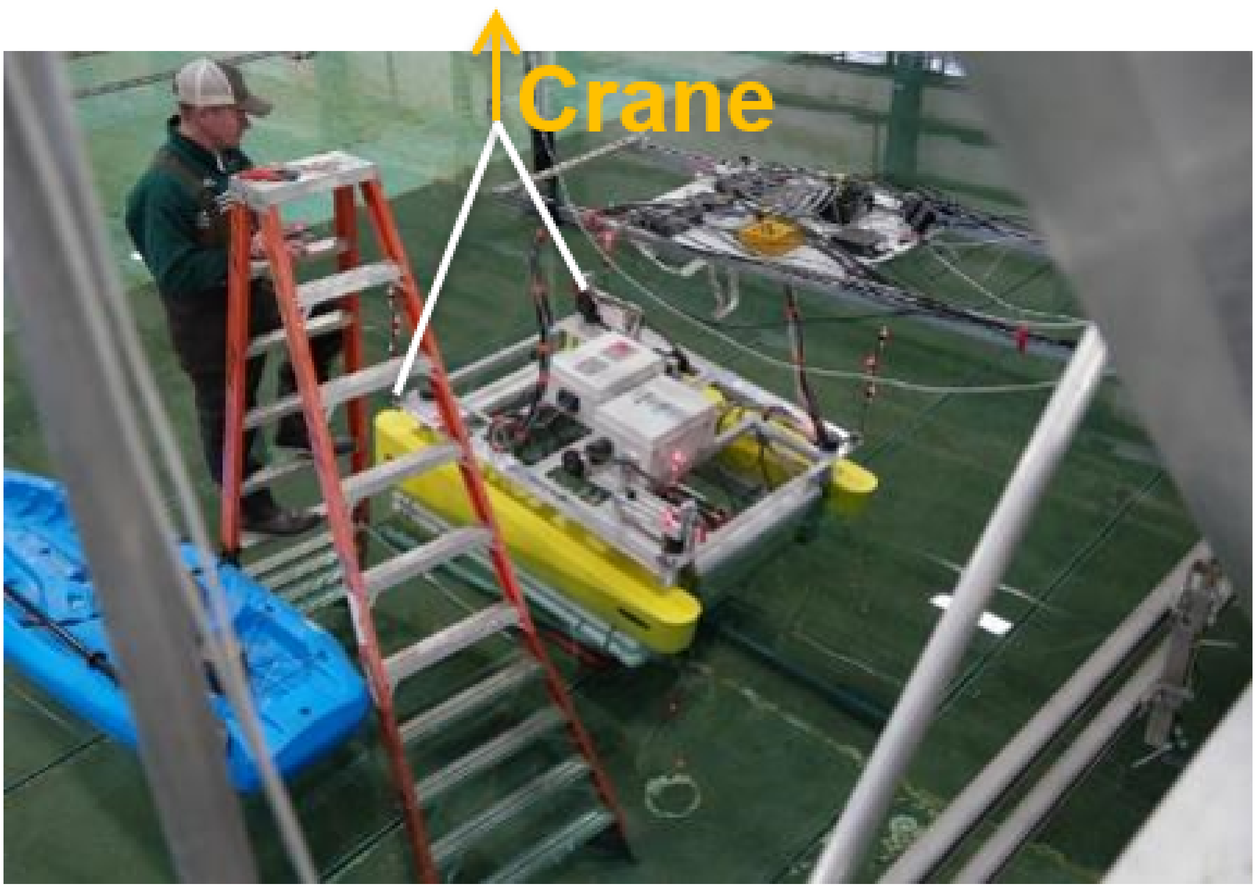


Figure 5-11. Pitch Decay and Static Offset Setup

5.4.4. Surge Decay

The surge decay and static offset tests are used to determine the natural frequency (ω_n), the damping value, and the restoring stiffness of the FOSWEC in surge. To perform the surge decay tests, the platform was unlocked in all DOF (pitch, heave and surge), the flaps were locked in their upright positions, and the overhead crane was connected to a load cell attached to the platform. The surge restoring force was provided by four blue bungee cords attached to the FOSWEC platform and the surge constraint, as shown in Figure 5-7. The bungees utilized for this test, pulley location, and the points at which they were connected were iterated during testing to prevent the surge displacement from also causing displacement in pitch. The crane cable was turned by a pulley so that a vertical displacement of the crane results in a horizontal displacement of the FOSWEC. The load cell was relocated to the section of cable between the pulley and the FOSWEC. A picture of the surge decay experimental setup is shown in Figure 5-12. The overhead crane was used to pull the FOSWEC to the desired surge displacement (Δx), the load cell value was recorded while the surface of the tank stabilized, whereupon the cable connecting the load cell to the platform was cut. For static offset tests, the surge hydrostatic force was measured for a range of surge displacements (Δx), but the cable is not cut. Surge static offset tests are used to determine the relationship between surge displacement and the corresponding restoring force, i.e. bungee stiffness. The surge decay and static offset test log is provided in Table D-3.

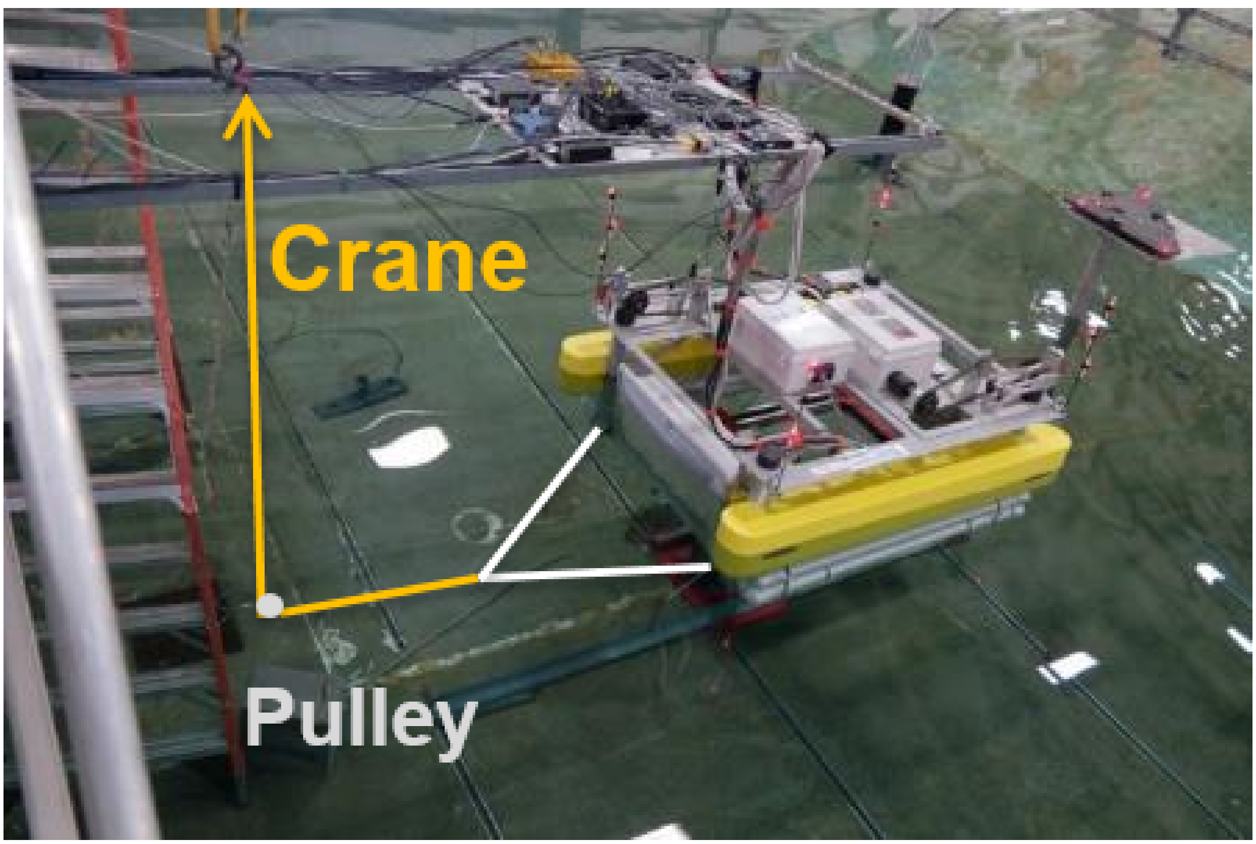


Figure 5-12. Surge Decay and Static Offset Setup

5.4.5. Flap Decay

The flap decay and static offset tests are used to determine the natural frequency (ω_n), the damping value, and the restoring stiffness of the flap in pitch. To perform the flap decay tests, the front flap was unlocked, the back flap was locked in its upright position, the platform was locked in all DOF (pitch, heave and surge), and the overhead crane was connected to a load cell attached to the flap. The front flap's PTO was connected but turned off so no external motor damping was applied, however the mechanical drive train was connected which affected the flap's response (Note: the flap decay test was repeated in Phase 2 with the PTO disconnected). A picture of the flap decay experimental setup is shown in Figure 5-13, a setup similar to the one used for surge decay. The overhead crane was used to rotate the flap to the desired flap displacement ($\Delta\theta$), the load cell value was recorded while the surface of the tank stabilized, whereupon the cable connecting the load cell to the flap was cut. For static offset tests, the pitch hydrostatic force was measured for a range of flap displacements ($\Delta\theta$), but the cable is not cut. Flap static offset tests are used to determine the relationship between flap displacement and the corresponding restoring torque, i.e. hydrostatic stiffness. The flap decay and static offset test log is provided in Table D-4 for the PTO connected.

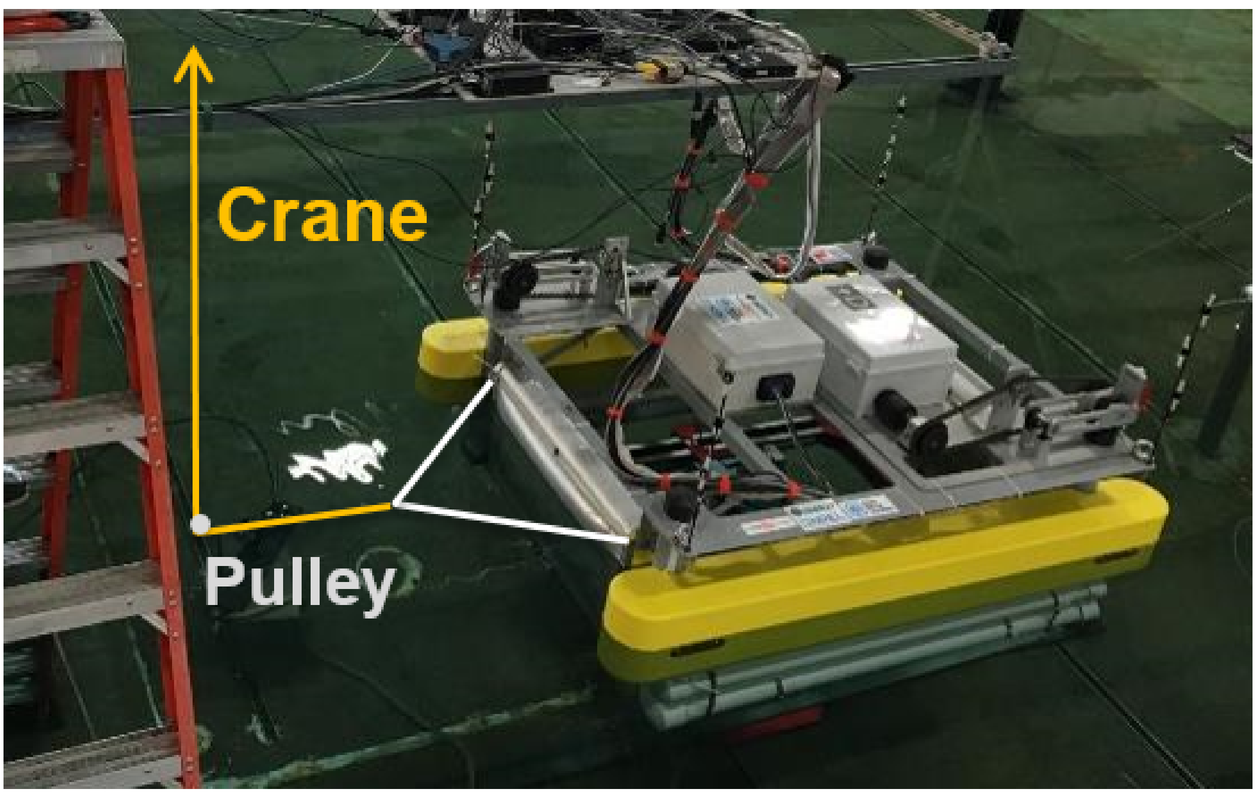


Figure 5-13. Flap Decay and Static Offset Setup

5.4.6. Initial Waves

Initial wave tests were performed to examine the FOSWEC's response a subset of the planned regular cases in order the stress and debug the system. All FOSWEC DOF were unlocked, the flaps were free to pitch, and the platform was free to move in heave, pitch and surge. For the initial wave tests, the flap PTOs did not apply additional damping to the system. Eight wave tests were completed, and none caused a failure of the FOSWEC, instrumentation or data logging software. The initial waves test log is provided in Table D-5. *Data from this test is not included in the MHKDR data set because it was intended purely for preliminary testing.*

5.4.7. Damping Optimization

Damping optimization tests were performed to determine an applied damping value that results in optimal power generation. For the damping optimization tests, the front flap was unlocked, the back flap was held in the horizontal position, and the platform is locked in all 3 DOFs. Regular waves were run to excite the model with the initial applied damping value set to 0.01 Nm/rpm. The damping value is increased by 0.01 Nm/rpm at set intervals, while the generated power was observed. This test illuminated several issues with the PTO drivetrain which were noted for the planned FOSWEC redesign between Phase 1 and Phase 2. First, there was unexpected slack in the PTO drivetrain. In addition, the motor control developed for this test relied on velocity information calculated from the motor encoder. However, the positions recorded by this encoder included the effects of backlash in both the power transfer mechanism and in the integrated motor gearbox, and were thus not representative of actual motor velocity, leading to issues with the PTO control. The issues were documented for the FOSWEC redesign, and the test was moved to Phase 2 (where it was completed). *Data from this test is not included in the MHKDR data set.*

5.4.8. Wave Excitation

Wave excitation tests were performed to determine the wave exciting loads on the FOSWEC with the flaps and platform motions locked (no DOF free). For the wave excitation tests, regular waves were run while the flaps were held in place by commanding the motor controller to hold the flaps in a vertical position (without mechanically locking them in place), and the platform was locked in place. This was done so that the wave exciting loads on the flap could be directly measured using the flap 6DOF load cells, and the loads on the platform measured using the arm 6DOF load cell. This test was not successfully completed in Phase 1 due to the aforementioned issues with the PTO drivetrain, which did not effectively hold the flaps in a vertical position and prevent flap motion. The issues were documented for the FOSWEC redesign, and the test was moved to Phase 2 (where it was completed). *Data from this test is not included in the MHKDR data set.*

5.4.9. Forced Oscillation

Forced oscillation tests were performed to determine the hydrodynamic added mass and damping as a function of oscillation frequency and amplitude. For the forced oscillation tests, both flaps are free to move and the FOSWEC platform was locked in all DOFs (heave, pitch and surge). The front flap was then driven with motor controller to produce sinusoidal flap motion with an amplitude of $\pm 5^\circ$ for a range of periods. This test was not successfully completed in Phase 1 due to several issues with the PTO drivetrain. The 5° displacement range was too small to overcome drivetrain backlash and produce a meaningful encoder signal. Also, the platform stabilizing the motor began to flex at a torque of about 30 Nm, 45 Nm before it was expected to experience problems. The issues were documented for the FOSWEC redesign, and the test was moved to Phase 2 (where it was completed). *Data from this test is not included in the MHKDR data set.*

5.5. CONCLUSIONS

The goal of Phase 1 was to characterize the wave environment, perform baseline system identification tests, and complete preliminary trials of each of the planned experiments. The Phase 1 tests generally progressed from the most simple (i.e. wave characterization and decay tests), to the most complex (i.e. forced oscillation) in a manner intended to characterize the FOSWEC, test the experimental setup, and stress the system to identify issues upfront. This approach gave the team valuable experience with changing configurations, capturing data, and provided data characterizing of the wave environment and the FOSWEC. Second, it allowed the experimental testing team to develop, debug, and refine the test procedures. Finally, this approach stressed the model so that issues could be identified upfront, and resolved prior to Phase 2 testing.

5.5.1. Lessons Learned

Upon completion of Phase 1 testing, the team had an initial data set, and documentation of issues and planned improvements related to the FOSWEC and Arm designs, instrumentation, and PTO drivetrain. During Phase 1 testing, temporary solutions were employed when they could be quickly implemented to minimize down-time, and permanent solutions were devised to be implemented between Phase 1 and Phase 2 testing. The problems encountered and proposed solutions are briefly summarized in Table 5-7, with detailed explanations and solutions described subsequently.

FOSWEC: Buoyancy

Issue The buoyancy blocks on the side of the FOSWEC provided insufficient buoyancy

Cause Hardware required to coupled Arm to FOSWEC added unplanned weight

Proposed Solution Add buoyant foam

FOSWEC: PTO Drivetrain

Issue Unreliable encoder signal and motor control

Cause Play in drivetrain components and deformation of mounting points

Proposed Solution Reinforce mounting points, adjust or repair drivetrain

Motion Constraint: Pitch Motion

Issue Difficult locking/unlocking of DOF at the Arm

Cause Location of lock/unlock mechanisms

Proposed Solution Extend interface points away from mechanism, add handles

Motion Constraint: Configuration

Issue Unwanted FOSWEC pitching motion

Cause Pitch constraint of the arm did not effectively restrain pitch DOF

Proposed Solution Redesign pitch constraint

Table 5-6. Phase 1: Issues, causes, and proposed solutions

Instrumentation: Inclinometer

Issue The platform inclinometer measurement saturated during high pitch accelerations

Cause Inclinometer mounted away from body center-of-inertia

Proposed Solution Relocate inclinometer

Instrumentation: Pressure Mats

Issue Pressure mat sensors non-functional

Cause Inadequate waterproofing

Proposed Solution Address with manufacturer or custom design waterproofing

Instrumentation: Flap Encoder

Issue Limited flap range of motion and encoder cannot be used for PTO control

Cause Flap encoder mounting and interface

Proposed Solution Modify encoder mounting and/or use a different encoder

Instrumentation: DAQ Sample Rate

Issue Interpolation steps necessary to process data

Cause Nominal wave periods are not integer multiples of DAQ sample rate, 0.02 (s)

Proposed Solution Adjust DAQ sample rate to 0.01 (s)

Instrumentation: Real-Time Interface

Issue Unavailable for Phase 2 testing

Cause On loan from OSU for Phase 1, needed for class during Phase 2

Proposed Solution Purchase real-time control interface

Table 5-7. Phase 1: Issues, causes, and proposed solutions

6. MODIFICATIONS

This section describes the modifications made between Phase 1 and Phase 2 testing.

6.1. FOSWEC

Buoyancy Early in Phase 1 the team discovered that the buoyancy floats were insufficient for the combined weight of the Arm and the FOSWEC. For Phase 1, this was addressed with the addition of air-filled PVC pipes attached to the bottom of the foam floats, shown in Figure 6-1. For Phase 2 testing the yellow floats and PVC pipes were replaced by a larger set of orange floats, shown in Figure 6-1.

PTO Drivetrain During the Phase 1 damping optimization and wave excitation tests it was noted that the motor was unable to drive the flaps or maintain flap position due to play in the drivetrain chain and flexing of the motor mounting platform. The Andrews-Cooper team enhanced the stability of the motor mount by adding a small I-beam under the screws which improved the rigidity of the motor mount.

Upon completion of Phase 1 testing the Andrews-Cooper team debugged the drivetrain and determined that the axle-gear at the lower end of the vertical chain was detached from the axle, and observed the top of the platform flexing during testing. Further examination showed that the axles, made of three components screwed together, had bent and deformed. Additionally, it was determined that the motor was no longer screwed to the integrated planetary gear, and was violently shifting at the end of each oscillation. The motor was returned to the manufacturer, where it was rebuilt, and returned for Phase 2 testing.

The flexing of the top of the platform was addressed by the addition of a set of structural supports added to the interior of the model, shown in Figure 6-2. The mount for the PTO system (torque transducer and integrated motor component) was stiffened by the addition of a 0.25” piece of plate metal mounted underneath the PTO box. The three components of the axle were welded together, addressing the axle flex issue. Finally, the keyway for the gear attached to the flap axle was stiffened so that it would no longer shake loose under stress. These modifications improved the PTO drivetrain performance, but were unable to entirely remove play from the drivetrain. To constrain the flap, Andrews-Cooper designed a mechanical locking mechanism that could be easily installed/removed to hold the flap in the vertical position, shown in Figure 6-3. The lock was mounted such that the forces observed by the flap load cell were unaffected, and thus could be used for the forced oscillation tests.

Figure 6-1. Phase 1, Additional buoyancy provided by PVC pipes (top); Phase 2, Additional buoyancy provided by new floats (bottom)

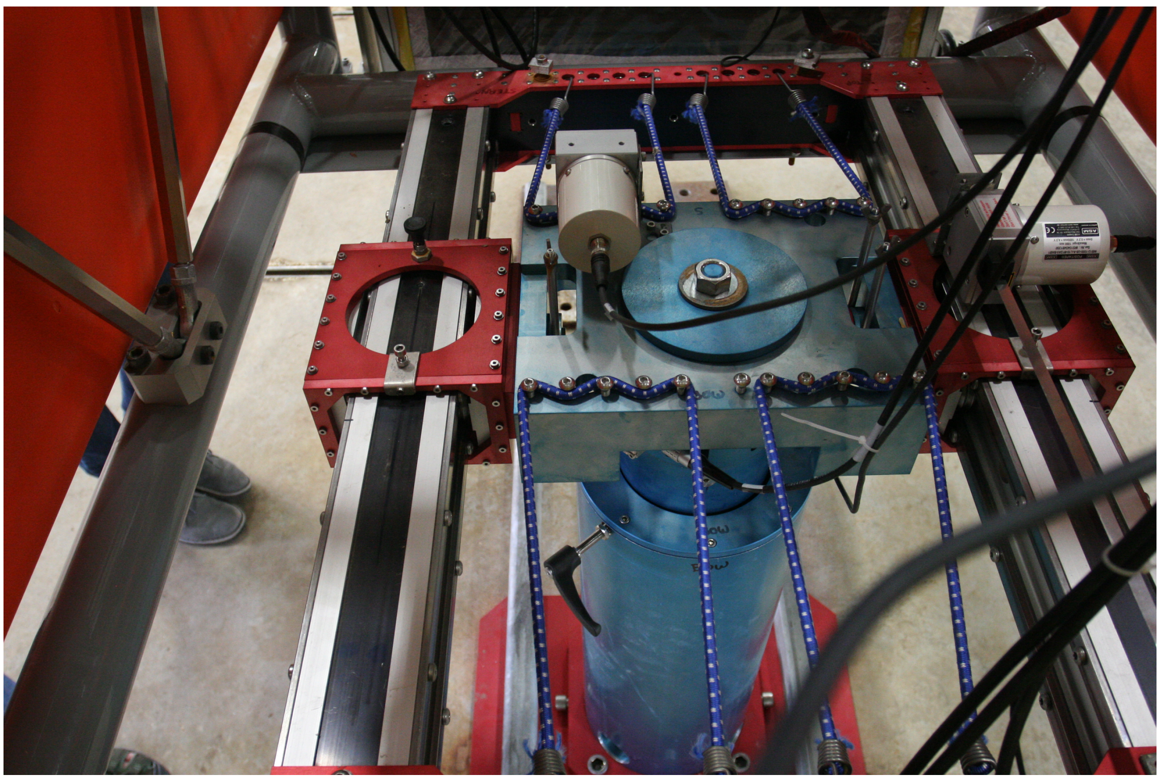


Figure 6-2. Platform Stabilizing Supports (diagonal bars on left side)

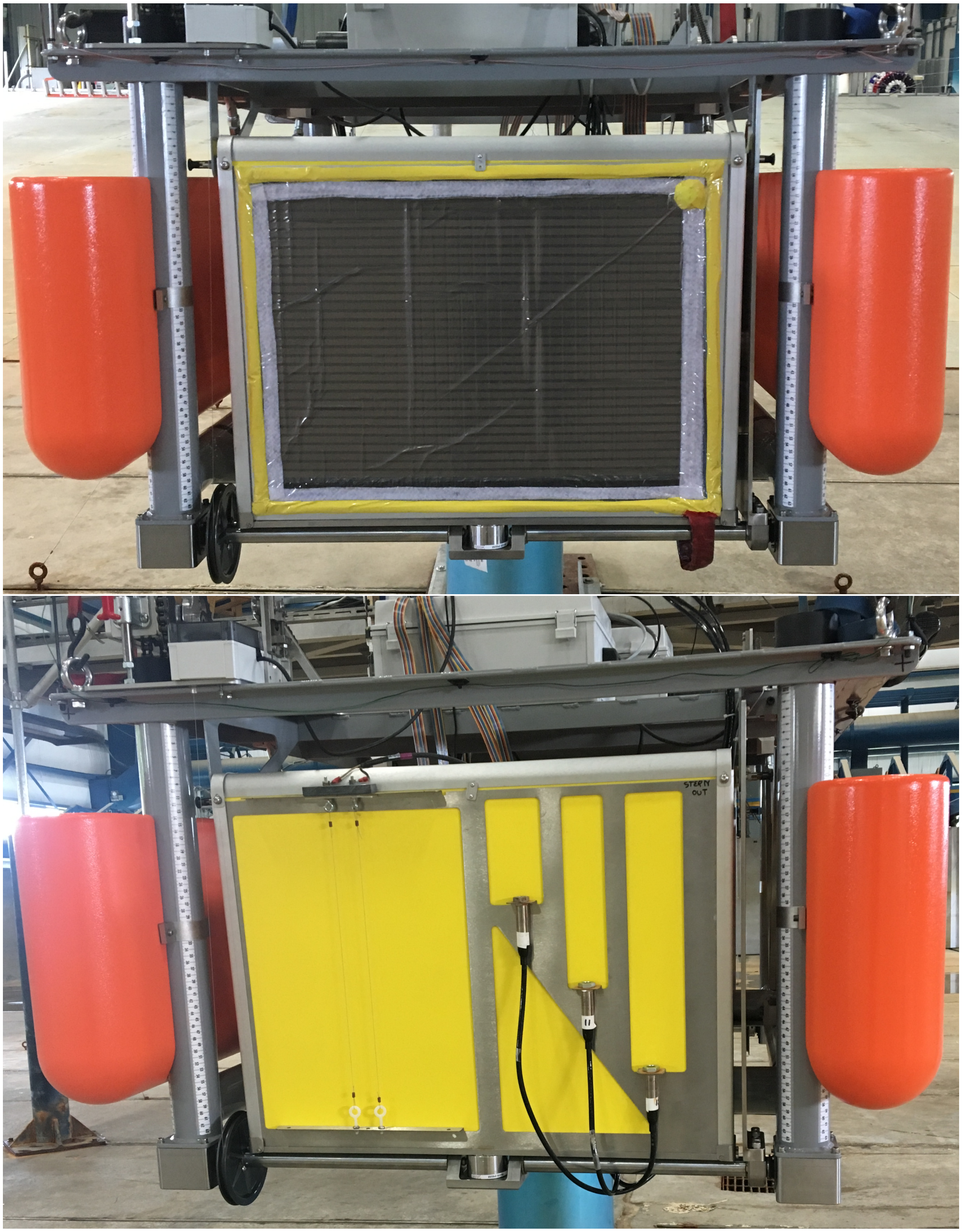


Figure 6-3. Flap Locking Mechanism (vertical bar on right side of flap) and Pressure Mat Waterproofing (top image)

6.2. MOTION CONSTRAINT

Pitch Motion The excessive play in the pitch DOF could not be addressed without a full re-design of the Arm, which was not pursued. Instead, the team deployed an external support system built from uni-strut, that supported each of the four feet of the FOSWEC. These supports were sized to prevent the FOSWEC from pitching without lifting it off of the constrain arm.

Configuration Locking/unlocking each Arm DOF could not be easily done from above water, and required tools, a process which delayed the reconfiguration of the FOSWEC between tests. This was addressed with a minor change to the Arm design where the locks that controlled the configuration were fitted with handles that could be reached from above the FOSWEC. The heave constraint mechanism is shown in Figure 6-4, while Figure 6-5 and Figure 6-6 show the pitch and surge constraint mechanisms respectively.

Figure 6-4. Heave Constraint Modification

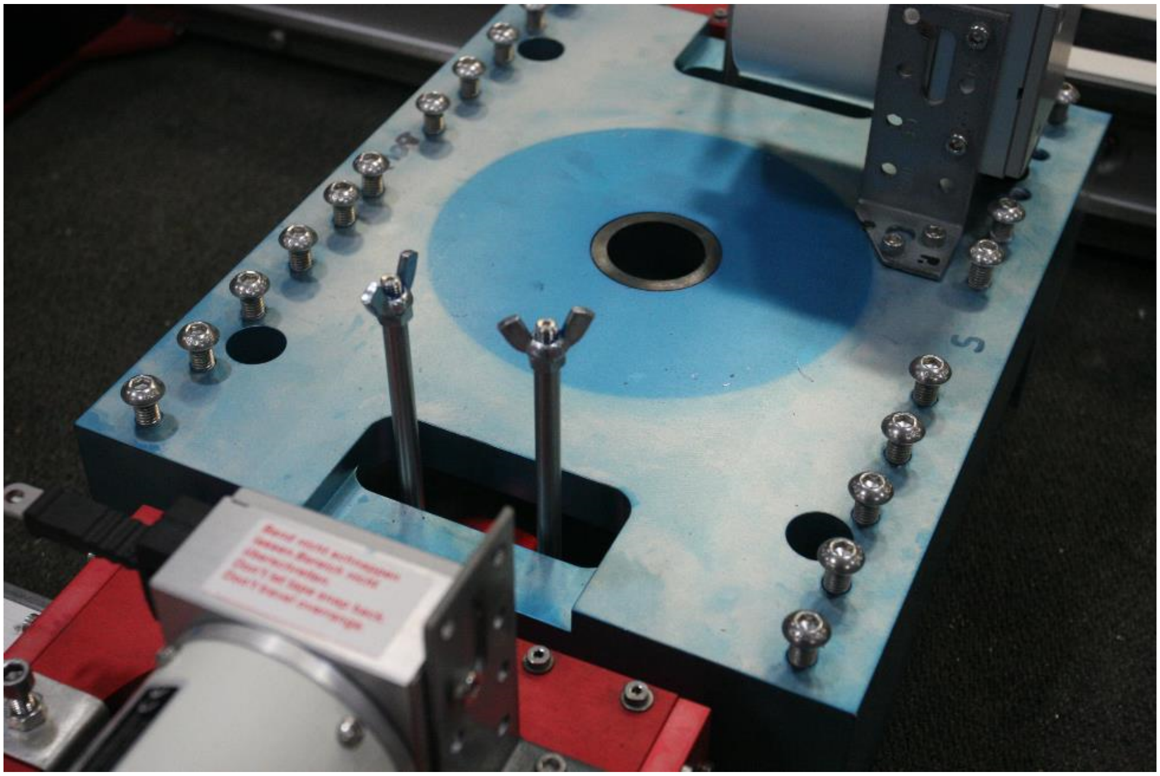


Figure 6-5. Pitch Constraint Modification

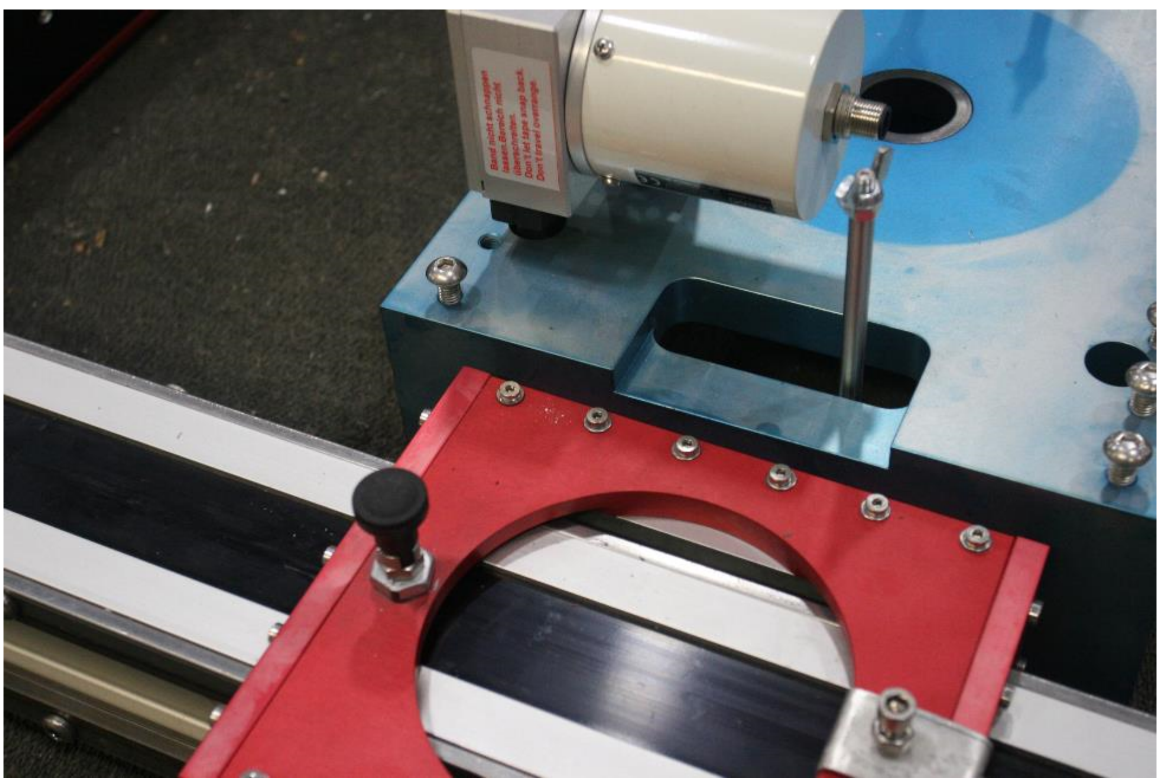


Figure 6-6. Surge Constraint Modification

6.3. INSTRUMENTATION

Inclinometer The FOSWEC inclinometer could not accurately measure the platform angle when the platform was moving above a certain acceleration. The instrument had been placed on the platform offset from the model center of inertia, inadvertently increasing the radial accelerations beyond the instrument capabilities. The instrument was relocated to a spot nearer to the center of inertia for the Phase 2 testing.

Pressure Mats The pressure mats did not accurately provide distributed pressure data, and although they were waterproofed by the manufacturer, water was observed inside the waterproofing. Additionally, the waterproofing was not vacuum sealed, so there was a large air bubble between the water and the pressure mat, resulting in inaccurate pressure measurements. While the air in the pressure mat waterproofing can be seen in Figure 5-3 while the FOSWEC is out of the water, it was exacerbated once the FOSWEC was submerged. The manufacturer provided limited support on these issues, so the pressures mats were sent to colleagues to NREL to be debugged and waterproofed with a vacuum seal. The Phase 2 pressure mat waterproofing is shown in the top of Figure 6-3.

Flap Encoder The Gill Blade rotary encoder mounting on the flap axle restricted flap motion; the specified 90° range was reduced to about 20°, and the encoder interface could not be used as a control input for the PTO. For the Phase 2 testing, the team purchased a pair of higher quality absolute rotary position sensors from IncOder. The sensor had two data type outputs, SSI and analog, which allowed signals to be simultaneously used for control and routed to the DAQ. While debugging the new instrumentation in water and developing the PTO controller, both sensors stopped working and were returned to the manufacturer. The manufacturer verified the failure and determined that either the waterproofing of the sensor failed or was never applied. However, the time-line for repairing and returning the sensors was incompatible with Phase 2 testing. Luckily another group at Sandia had two string encoders that were not currently being used. Andrews-Cooper developed a mounting system for the linear string encoders to measure the flap rotation, shown in Figure 6-7, and Phase 2 testing was able to continue on schedule. However, due to time constraints, the motion control system driving the motor (a speed-based proportional-integral (PI) controller with a secondary position PI controller) could not be accurately tuned, so the team resorted to open-loop control for Phase 2 testing.

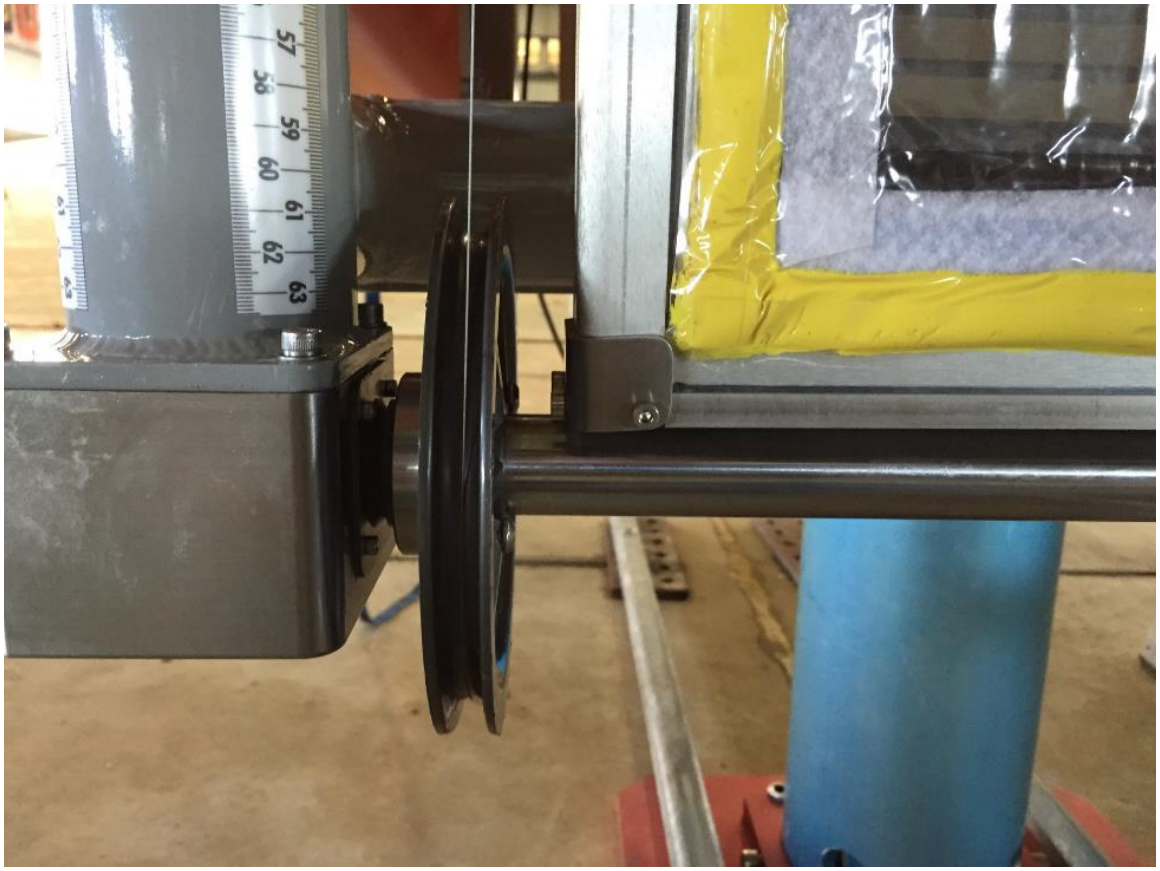


Figure 6-7. String Encoder for Flap

DAQ Sample Rate The nominal wave periods considered were not integer multiples of the DAQ sample rate of 0.02 (s). This complicated the data processing, introducing an undesired interpolation step. The sample rate was changed to 0.01 (s) for Phase 2 testing.

Real-Time Interface The Phase 1 real-time system was design using the dSpace platform, which was on loan from OSU WESRF. The system was not available for the Phase 2 testing, and thus was replaced by National Instruments interface to the Matlab real-time system (referred to as BSpace), which provided similar functionality.

7. PHASE 2

This section provides a description of the FOSWEC and the motion constraint designs, an overview of the instrumentation, and details of the experiments performed in Phase 2 of FOSWEC testing. Phase 2 testing occurred in May and June of 2016. The goal of Phase 2 testing was to complete the breadth of planned tests in full, learning from the shakeout tests completed in Phase 1. The experimental test plan for Phase 2 testing included both dry tests and wet tests, details of which are described in the following sections.

7.1. FOSWEC AND ARM

Figure 7-1 shows a rendering of the Phase 2 FOSWEC with a selection of its instrumentation and design features identified. Section 6 provided an overview of the differences between the Phase 1 and Phase 2 FOSWEC designs, notable in this rendering are the larger floats and new rotary encoders. Dimensions of the modified system are shown in Figure 7-2.

The Arm also underwent modifications based on the lessons learned from Phase 1 testing, details of which are provided in Section 6. Modifications made to the Arm were relatively minor, and primarily focused on easing the FOSWEC configuration changes (i.e. from Config 1 to Config 2, etc).

7.2. INSTRUMENTATION

The instrumentation used in Phase 2 testing is listed in Table 7-1.

Sensor	Manufacturer	Model Number	# of Sensors
Flap String Encoder	microEpsilon	WDS-1500-P60-CR-TTL	2
Pressure Mat	Tactilus	custom	2
Flap 6DOF Load Cell	ATI	9105-TW-MINI58-R-5-IP68	2
Arm 6DOF Load Cell	ATI	9105-TIF-OMEGA160-IP68	1
Pressure Sensors	Druck	PDCR830	5
PTO Motor	Maxon	ESPOS2	2
PTO Motor Encoder	Maxon	HEDL5540	2
PTO Torque Transducer	Futek	TRS300	2

Table 7-1. Phase 2 Instrumentation

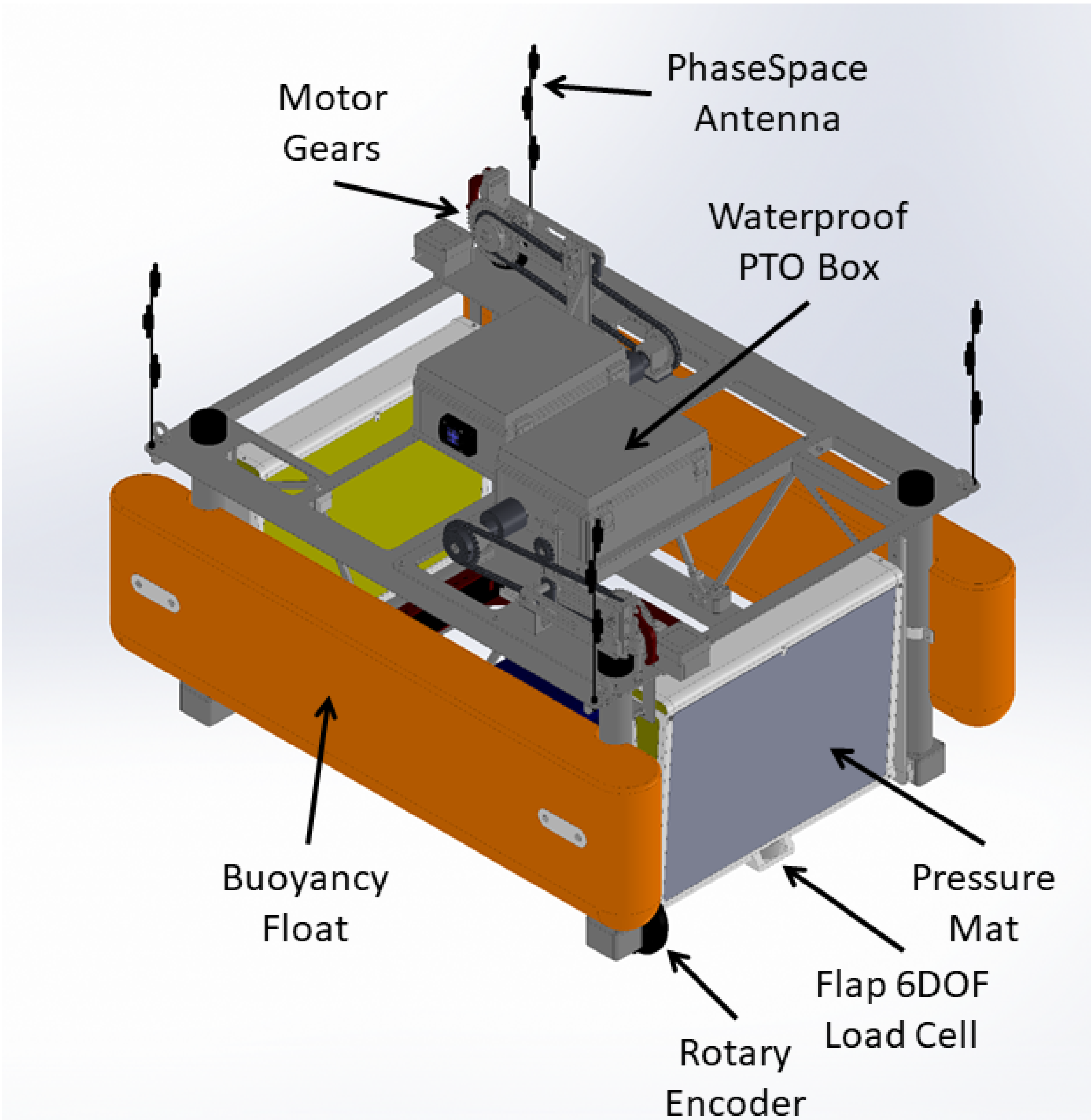


Figure 7-1. FOSWEC Mechanical Design Rendering (Phase 2)

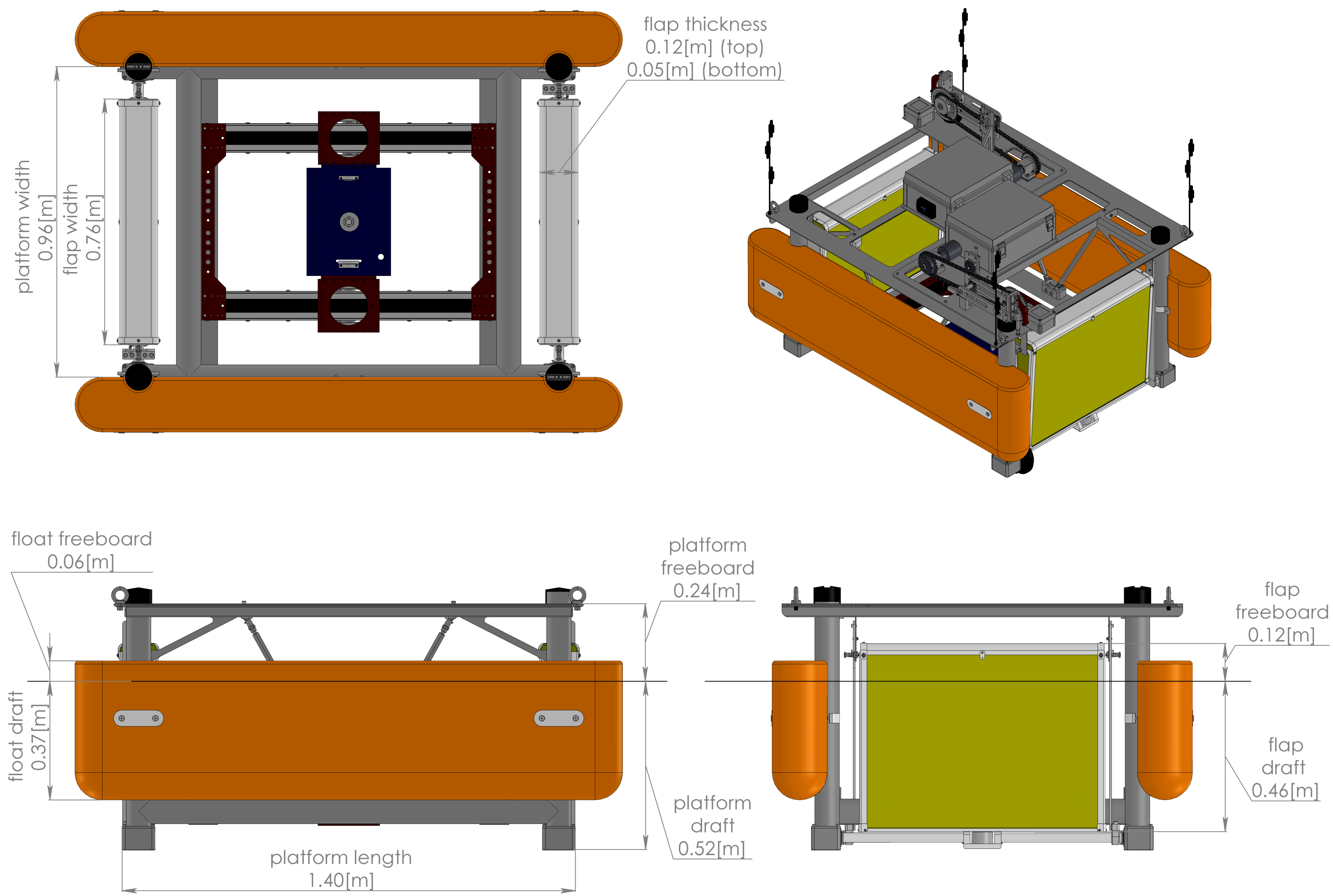


Figure 7-2. FOSWEC Mechanical Design Dimensions (Phase 2)

7.3. EXPERIMENTS

A description of each experiment performed during FOSWEC Phase 2 testing is provided in the following sections. The list of experiments performed during Phase 2 testing and the name of their corresponding directory on the data repository are listed in Table 7-2. A description of the FOSWEC data structure on the data repository is provided in Section 8. Test logs for each experiment performed during Phase 2 testing are provided in Appendix E, and in the '/data/WECSIM2/logs' directory of the FOSWEC data set on the data repository.

Experiment	Directory
Wave Excitation	WaveExcitationReg, WaveExcitationIrr
Forced Oscillation	ForcedOscillation
Damping Optimization	DampingOptimization
Config1	Config1Reg, Config1Irr
Config2	Config2Reg, Config2Irr
Config3	Config3Reg, Config3Irr
Config4	Config4Reg, Config4Irr
Flap Decay (PTO Disconnected)	FlapDecay2
Dry Tests (Phase 2)	N/A

Table 7-2. Phase 2 Experiments

7.3.1. Wave Excitation

Wave excitation tests were performed to determine the wave exciting loads on the FOSWEC with the flaps and platform motions locked (no DOF free), as shown in Figure 7-3. For the wave excitation tests, regular and irregular waves were run while the flaps were held in place in the vertical position using the redesigned mechanical locking mechanism, shown in Figure 6-3. This was done so that the wave exciting loads on the flap could be directly measured using the flap 6DOF load cells, and the loads on the platform measured using the arm 6DOF load cell. This test was successfully completed in Phase 2 for a range of REG and IRR wave cases. Test logs for the wave excitation tests are provided in Appendix E. The corresponding data is provided in the '/data/WECSIM2/inter/WaveExcitationReg' and '/data/WECSIM2/inter/WaveExcitationIrr' directories of the FOSWEC data set on the data repository.

Regular Waves A selection of the calibrated regular waves (listed in Table 4-2) were run for the REG wave excitation tests. The waves selected correspond to the full range of wave periods for the first three wave heights, $H_1 - H_3$. For each trial, waves were generated for 3 minutes, the DAQ captured data for 6 minutes, and there was a minimum of 10 minutes settling time between trials. The REG wave excitation test log is provided in Table E-1.

Irregular Waves All six calibrated irregular wave sea states (listed in Table 4-4) were run for the IRR wave excitation tests, generated using the Peirson-Moskowitz spectra. For each trial, waves were generated for 7 minutes, and there was a minimum of 10 minutes settling time between trials. The IRR wave excitation test log is provided in Table E-2.

Figure 7-3. Wave Excitation Experiment (Phase 2)

7.3.2. Forced Oscillation

Forced oscillation tests were performed to determine the hydrodynamic added mass and damping as a function of oscillation frequency and amplitude. For the forced oscillation tests, the front flap was free to move, the back flap was held in the horizontal position, and the FOSWEC platform was locked in all DOFs (heave, pitch and surge), as shown in Figure 7-5. The front flap was driven by the motor controller to produce sinusoidal flap motion with a prescribed torque amplitude τ_{cmd} and period T. The applied torque caused a peak-to-peak (p2p) flap displacement $|\theta_{obs}|$ close to a targeted angular displacement $|\theta_{tar}|$, and the percent difference is tabulated. Each trial lasted approximately one minute in duration. This test was successfully completed in Phase 2 for a range of periods and amplitudes. Test logs for the wave excitation tests are provided in Appendix E Table E-3. The corresponding data us provided in the '/data/WECSIM2/inter/ForcedOscillation' directory of the FOSWEC data set on the data repository. Observed angles recorded in the test log are approximate, and trials marked in red have been flagged for errors; these trials were *not* removed from the data set, but the data should not be used. It should be noted that, while the motor commanded torque profile was symmetric about the vertical flap position, the resulting flap motion was often non-symmetric.

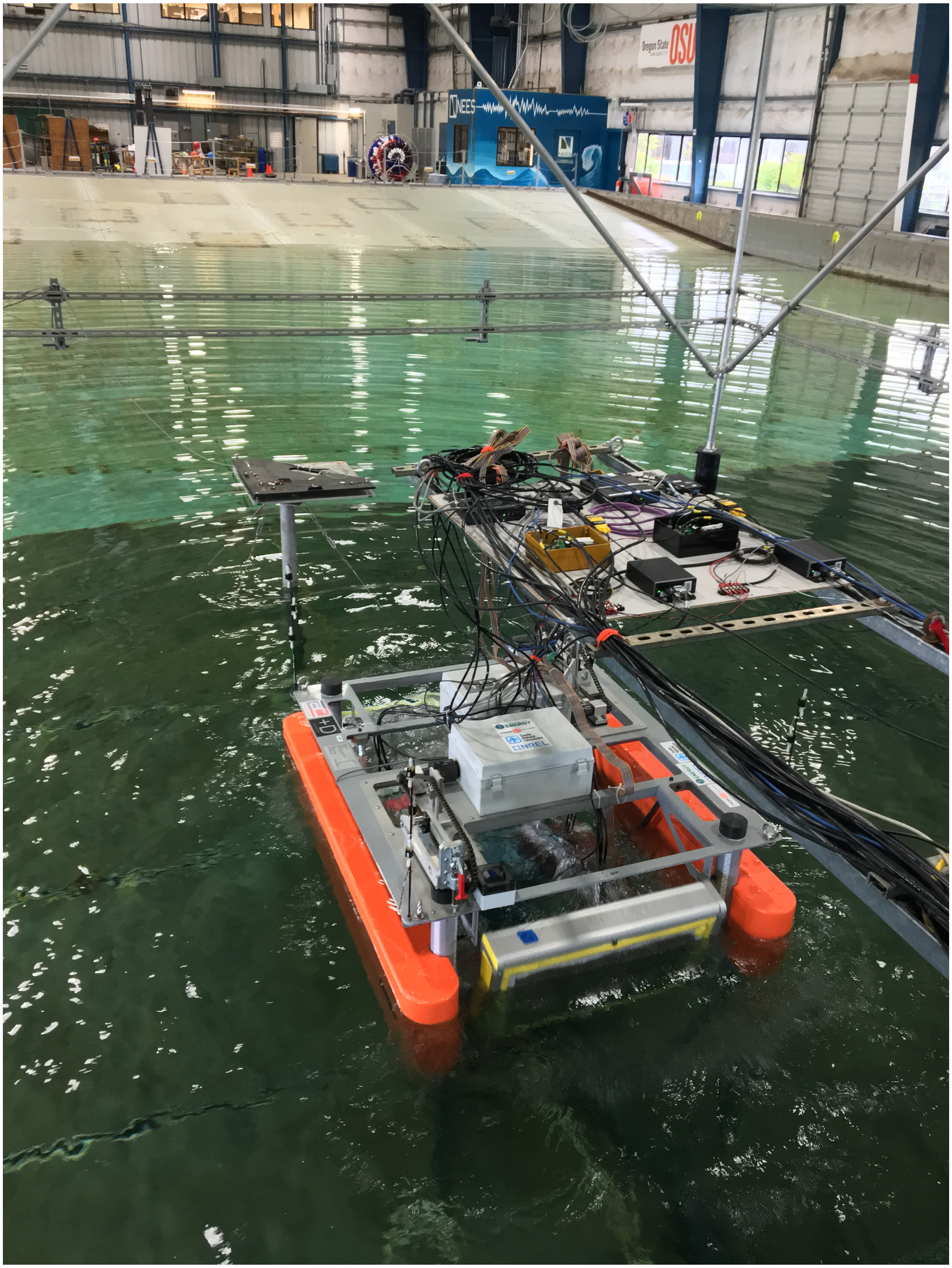


Figure 7-4. Forced Oscillation Experiment (Phase 2)

7.3.3. Damping Optimization

Damping optimization tests were performed to determine an applied damping value that results in optimal power generation. For the damping optimization tests, the front flap was unlocked, the back flap was held in the horizontal position, and the platform is locked in all 3 DOFs, as shown in Figure 7-5. This test was successfully completed in Phase 2 for a selection of the calibrated regular waves (listed in Table 4-2) were run for the damping optimization tests. Test logs for the wave excitation tests are provided in Appendix E Table E-4. The corresponding data us provided in the '/data/WECSIM2/inter/DampingOptimization' directory of the FOSWEC data set on the data repository. Waves were run to excite the model with initial damping applied, and increased by 0.01 [Nms] at set intervals, while the generated power was observed. The initial applied damping, damping range, and intervals are noted in the test log. Based on the real-time power results, a PTO damping value of 0.1 [Nms] was was used for all subsequent FOSWEC wave tests, for all device configurations. It should be noted that the damping is applied at the motor, $\tau_{motor} = 0.1\omega_{motor}$, generating a torque on the flap dependent on the drivetrain gearing ratio (typically 4:1).

7.3.4. Config 1

Configuration tests were performed to characterize the FOSWEC's response (i.e. motion, power, loads) to REG and IRR waves of different periods and wave heights, and with different device configurations. Each of the FOSWEC configurations, Config 1 - Config 4, were tested running the calibrated REG and IRR waves (listed in Table 4-2 and Table 4-4 respectively). All configurations were tested running planar waves with normal incidence to the FOSWEC. They all used the same applied motor damping of 0.1 [Nms], determined from the damping optimization tests described in Section 7.3.3. Config 1 - 4 are described in Table 3-2 and shown in Figure 3-6.

For Config 1, flap 1 is free to move, flap 2 is held horizontal by lead weights, and the platform is locked in all three DOFs, as shown in Figure 7-5. Regular wave test logs are shown in Table E-5, and irregular wave test logs are shown in Table E-6. The corresponding data us provided in the '/data/WECSIM2/inter/Config1Reg' and '/data/WECSIM2/inter/Config1Irr' directories of the FOSWEC data set on the data repository.

As noted during the experiment, the smallest wave height (1.5 cm) does not move the flap much beyond the range of the system backlash. This is reflected in the difference between the flap position measured at the motor encoder and the position measured at the flap axle. Additionally, when the flap is within the backlash range, the motor is not engaged and the damping is not applied.

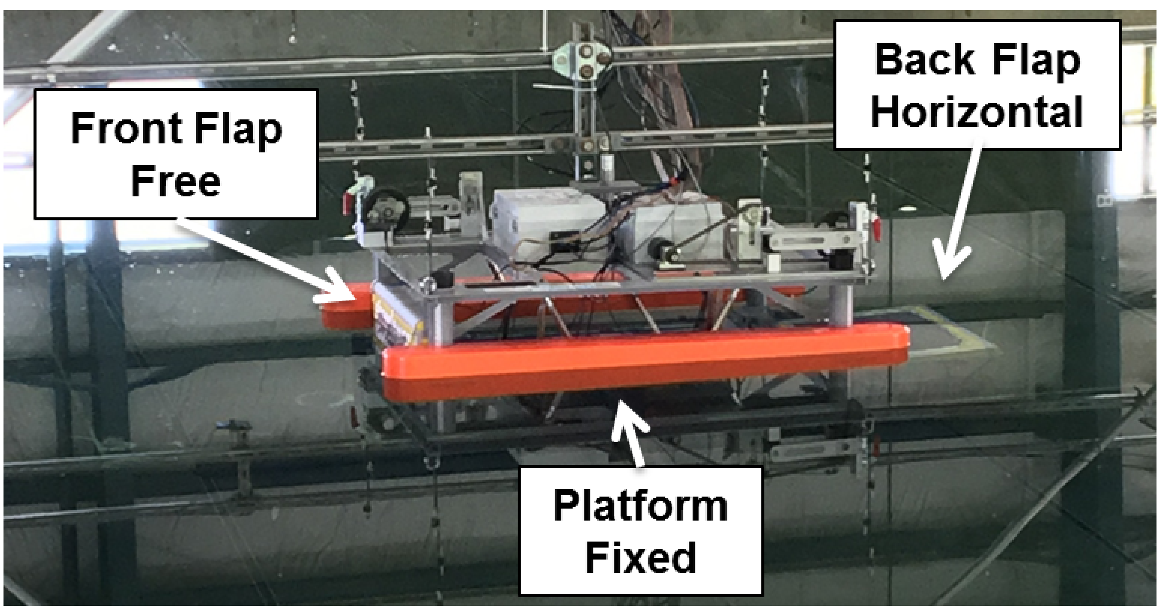


Figure 7-5. FOSWEC Config 1 (Phase 2)

7.3.5. Config 2

For Config 2, both flaps are free to move, and the platform is locked in all 3 DOFs (heave/pitch/surge), as shown in Figure 3-6. Regular wave test logs are shown in Table E-7, and irregular wave test logs are shown in Table E-8. The corresponding data us provided in the '/data/WECSIM2/inter/Config2Reg' and '/data/WECSIM2/inter/Config2Irr' directories of the FOSWEC data set on the data repository. As noted in the test log, the PTO slack was adjusted between regular wave trials.

7.3.6. Config 3

For Config 3, both flaps are free to move, and the platform is free to move in heave (fixed in pitch/surge), as shown in Figure 3-6. Regular wave test logs are shown in Table E-9, and irregular wave test logs are shown in Table E-10. The corresponding data us provided in the '/data/WECSIM2/inter/Config3Reg' and '/data/WECSIM2/inter/Config3Irr' directories of the FOSWEC data set on the data repository.

7.3.7. Config 4

For Config 4, both flaps are free to move, and the platform is free to move in all 3 DOF (heave/pitch/surge), as shown in Figure 3-6. Regular wave test logs are shown in Table E-11, and irregular wave test logs are shown in Table E-12. The corresponding data us provided in the '/data/WECSIM2/inter/Config4Reg' and '/data/WECSIM2/inter/Config4Irr' directories of the FOSWEC data set on the data repository.

7.3.8. Flap Decay (PTO Disconnected)

The flap decay and static offset tests are used to determine the natural frequency (ω_n), the damping value, and the restoring stiffness of the flap in pitch. Flap decay tests were performed again in Phase 2 with the PTO disconnected from the flap in order to isolate the hydrodynamic response of the flap. This was done by removing the chains connecting the motor to the shaft. The test was conducted in the same manner as Phase 1 testing; however this iteration of the flap decay test was performed with the PTO disconnected.

To perform the flap decay tests, the front flap was unlocked, the back flap was locked in its upright position, the platform was locked in all DOF (pitch, heave and surge), and the overhead crane was connected to a load cell attached to the flap. The front flap's PTO was connected but turned off so no external motor damping was applied, however the mechanical drive train was connected which affected the flap's response (Note: the flap decay test was repeated in Phase 2 with the PTO disconnected). A picture of the flap decay experimental setup is shown in Figure 5-13, the same setup used for Phase 1 flap decay tests. The overhead crane was used to rotate the flap to the desired flap displacement ($\Delta\theta$), the load cell value was recorded while the surface of the tank stabilized, whereupon the cable connecting the load cell to the flap was cut. For static offset tests, the pitch hydrostatic force was measured for a range of flap displacements ($\Delta\theta$), but the cable is not cut. Flap static offset tests are used to determine the relationship between flap displacement and the corresponding restoring torque, i.e. hydrostatic stiffness. The flap decay and static offset test log is provided in Table E-13 for the PTO disconnected.

7.4. CONCLUSIONS

Phase 2 testing was more extensive than Phase 1. The goal of Phase 1 was to characterize the wave environment, perform baseline system identification tests, and complete preliminary trials of each of the planned experiments. After Phase 1 testing was complete, the FOSWEC had modifications made based on the lessons learned from Phase 1. The goal of Phase 2 was to complete the remaining planned experiments to characterize the FOSWEC's hydrodynamic excitation and radiation, and the FOSWEC's response to different wave environments. The Phase 2 tests generally progressed from the most simple (i.e. wave excitation tests), to the most complex (i.e. Config4 IRR wave tests).

7.4.1. Lessons Learned

Upon completion of Phase 2 testing, the team had a complete Phase 1 and Phase 2 dataset, and documented lessons learned. The problems encountered and proposed solutions are briefly summarized in Table 7-3. While the lessons learned in Table 7-3 are fairly specific to the FOSWEC, some general lessons learned were also identified. Anyone developing a WEC experimental test plan should: ensure sensors are properly waterproofed, whenever possible use known solutions for the intended application, and identify critical sensors and have backups available should their be a failure. For example, the flap encoder sensor on the FOSWEC was critical because is describes the FOSWEC's response in the DOF generating power. FOSWEC data without an accurate measurement of the flap position is of limited benefit.

7.4.2. Future Work

In future testing of the FOSWEC it would be beneficial to test the directional dependence of the FOSWEC due to different angles of incidence. This was originally scoped within the FOSWEC test plan, but wave directionality tests were not completed due to time constraints. Additionally, it would be of interest to redesign the FOSWEC buoyancy. The buoyancy floats used to keep the FOSWEC at the desired SWL also created a channel within the FOSWEC platform, created complex waveforms inside the channel. Additional future work includes performing code validation studies using the FOSWEC dataset.

Instrumentation: Pressure Mats	
Issue	Pressure mat sensors not functional
Cause	TBD, waterproofing kept sensors dry, but data unusable
Proposed Solution	Address with manufacturer
Instrumentation: Flap Encoder	
Issue	Replacement encoder not functional
Cause	Flap encoder was not properly waterproofed
Proposed Solution	Replaced with backup sensor and custom mount
Instrumentation: Real-Time Interface	
Issue	Unstable, consistent crashing
Cause	Unstable release of Simulink Real-Time
Proposed Solution	Simplify real-time control interface

Table 7-3. Phase 2: Issues, causes, and proposed solutions

8. DATA STRUCTURE

The structure of the FOSWEC data for Phase 1 and Phase 2 testing is shown in Figure 8-1. The FOSWEC data is publicly available on the MHK data repository (MHKDR), and is split into the following top level directories: ’data’, ’doc’, and ’geom’. The ’data’ directory is then subdivided into Phase 1 and Phase 2 subdirectories, ’FOSWEC/data/WECSIM/’ and ”FOSWEC/data/WECSIM2/’ respectively. Within the ’WECSIM’ and ’WECSIM2’ directories are the ’logs’ and ’inter’ subdirectories, which contain the test logs and intermediate data files (described in the following section). The directories ’FOSWEC/data/WECSIM/inter’ and ’FOSWEC/data/WECSIM2/inter’ contain a subdirectory for each experiment, as shown in Figure 8-1. Note that the static offset tests were conducted as a single trial of each corresponding decay test (as noted in the test log). Test logs for Phase 1 and Phase 2 are provided in the ’FOSWEC/data/WECSIM/logs’ and ’FOSWEC/data/WECSIM2/logs’ directories, respectively, and are provided in Appendices D and E.

```
FOSWEC
├── data
│   ├── WECSIM
│   │   ├── inter
│   │   │   ├── FlapDecay1
│   │   │   ├── HeaveDecay
│   │   │   ├── PitchDecay
│   │   │   ├── RandomWaveTuning1
│   │   │   ├── RandomWaveTuning2
│   │   │   ├── RegularWaveTuning1
│   │   │   ├── RegularWaveTuning2
│   │   │   ├── RegularWaveTuning3
│   │   │   ├── RegularWaveTuning4
│   │   │   ├── RegularWaveTuning5
│   │   │   └── SurgeDecay
│   │   └── logs
│   └── WECSIM2
│       ├── inter
│       │   ├── Config1Irr
│       │   ├── Config1Reg
│       │   ├── Config2Irr
│       │   ├── Config2Reg
│       │   ├── Config3Irr
│       │   ├── Config3Reg
│       │   ├── Config4Irr
│       │   ├── Config4Reg
│       │   ├── DampingOptimization
│       │   ├── FlapDecay2
│       │   ├── ForcedOscillation
│       │   ├── WaveExcitationIrr
│       │   └── WaveExcitationReg
│       └── logs
├── doc
└── geom
```

Figure 8-1. FOSWEC Data Structure

8.1. 'INTER' DATA

The 'inter' (or intermediate) data is the FOSWEC data provided on the MHKDR for Phase 1 and Phase 2, 'FOSWEC/data/WECSIM/inter' and 'FOSWEC/data/WECSIM2/inter' respectively. Within the 'inter' directories are subdirectories for each Phase 1 and Phase 2 experiment, as shown in Figure 8-1. The experiment directories (e.g. 'FOSWEC/data/WECSIM/inter/FlapDecay1/') contain subdirectories for each trial (e.g. 'Trial01'). The trial directories contain text files ('.txt') for each sensor's data signal logged by the DAQ, specified in Table 8-1. The 'inter' data was processed by Oregon State University's Hinsdale Wave Research Laboratory from raw data into intermediate data with engineering units. The 'CalibrationUnits' in the text file header for each sensor's data signal is the engineering unit that has been calibrated from the ± 5 V DAQ input. All data was collected synchronously at the time stamps specified in the 'time.txt' file, which are given as UTC days.

8.2. SIGNAL MAPPING

The signal mapping between the sensor and DAQ channel name is shown in Table 8-1. An asterisk indicates that there are multiple sensors, identified by unique numbers in place of the asterisk. For flap sensors, 1 denotes the fore flap, and 2 denotes the aft flap. The DAQ channel name also corresponds to the name of the text file for each sensor's data signal. Refer to Section 5.3 for a description of Phase 1 instrumentation, and Section 7.2 for Phase 2 instrumentation. A complete list of Phase 1 and Phase 2 instrumentation is provided in Appendix B.

Sensor	Description	Unit(s)	Channel Name(s)
Flap encoder	Flap angular position (pitch)	degree	flapPosF*
Flap load cell	Flap loads (surge, sway, heave, roll, pitch, and yaw)	N, N-m	lcFxF*, lcFyF*, lcFzF*, lcTxF*, lcTyF*, lcTzF*
Pressure sensor	Pressure on flap (top, mid, and bottom)	Pa	psTopF*, psMidF*, psBotF*
Tape potentiometer	Platform linear position (surge and heave)	m	platPosx, platPosz
Inclinometer	Platform angular position (pitch)	degree	platPosRy
Phase space	Platform position (surge, sway, heave, roll, pitch, and yaw)	m, rad	surge, sway, heave, roll, pitch, yaw
Arm load cell	Platform loads (surge, sway, heave, roll, pitch, and yaw)	N, N-m	lcFxPlat, lcFyPlat, lcFzPlat, lcTxPlat, lcTyPlat, lcTzPlat
Crane load cell	Static offset force	N	lcCrane, lcLadder
PTO motor encoder	Flap motor position	degree	motPosF*
PTO motor encoder	Flap motor velocity	rad/s	motVelF*
PTO torque transducer	Flap motor torque	N-m	ttTrqF*
PTO motor	Flap motor damping	N-m/(rad/s)	motDampF*
PTO motor	Flap motor current	A	motILoadF*
PTO motor	Flap power supply current	A	motIPwrSupF*
PTO motor	Flap power supply voltage	V	motVPwrSupF*
Resistive wave probe	Wave elevation	m	wg*
Acoustic wave probe	Wave elevation	m	uswg*
Flap wave probe	Wave elevation on flap	m	wgF*

Table 8-1. Mapping of sensors to data structure field (an asterisk indicates multiple sensors).

8.3. PROCESSING SCRIPTS

A GitHub repository hosted the FOSWEC data processing scripts is publicly available at `https://github.com/WEC-Sim/FOSWEC`. The data processing repository is maintained by the WEC-Sim code development team, and will be periodically updated to include new functionality. This repository of FOSWEC data processing scripts is intended to be used in conjunction with the FOSWEC data set publicly available on the MHKDR.

These data processing scripts import the FOSWEC 'inter' data, load them into a MATLAB data structure, and calculate relevant statistics. Running the FOSWEC data processing scripts will generate a 'fina' data directory that contains the MATLAB data structure and figures. For more information about how to use the data processing scripts, refer to the documentation available on the FOSWEC GitHub repository [8].

9. CONCLUSIONS

This report details the experimental testing of a 1:33 scale Floating Oscillating Surge Wave Energy Converter (FOSWEC), completed in the Directional Wave Basin at Oregon State University's Hinsdale Wave Research Laboratory. Testing was performed in two phases; Phase 1 testing was completed in November - December 2015, and Phase 2 testing was completed in May - June 2016. This experimental testing report details the selection and design of a FOSWEC, experimental setup and tests completed, and overview of resulting Phase 1 and Phase 2 data sets. The primary objective of the experimental testing is to generate a publicly available data set that can be used to validate Wave Energy Converter (WEC) numerical codes, such as WEC-Sim [6]. The secondary objective is to provide data and lessons learned relevant to extreme conditions (i.e. WEC loads and response), and other areas of interest identified by the wave energy industry (i.e. innovative measurement techniques).

The device tested is a FOSWEC consisting of a floating platform with two (fore and aft) oscillating flaps connected to an above-water power-take off. The FOSWEC was designed to be tested in four configurations (Config 1-Config 4), each with different allowable degrees of freedom. The examination of individual DOFs utilized a constraint platform that could lock/unlock device DOFs. The device and wave basin were instrumented to characterize loads and motions of the flaps, platform, and power-take off components, as well as the incident wave field. Phase 1 testing included calibration of the wave fields, dry mass/inertia measurement, static offset, and free decay tests. Between the phases of testing, the device, instrumentation, and test plan were modified based on lessons learned from Phase 1 testing. Phase 2 included wave excitation, forced oscillation, and wave response tests for regular and irregular waves with varying device configurations to examine device response with degrees of freedom. This report is intended to accompany the Phase 1 and Phase 2 data sets which are publicly available on the Marine and Hydrokinetic Data Repository (MHKDR), and data processing scripts which are publicly available on the FOSWEC GitHub repository [2, 8].

BIBLIOGRAPHY

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APPENDIX A. SWING TESTS

Written by: Pedro Lomonaco (OSU)

This appendix provides an overview of the theory that as used to calculate the center of gravity and moment of inertia using swing tests.

A.1. CENTER OF GRAVITY

The center of gravity of the different system components were calculated using either the scale test or the pendulum test. The scale test is a simple and accurate method for determining a single center of gravity (COG) value of a body. Referring to Figure A-1, the body is balanced on two sharp supporting points separated along the axis of measurement. One of the sharp supports is placed on a scale, the other is placed on a solid platform the height of the scale, rendering the body axis level. The weight displayed on the scale (at S_2), along with the distance from one end of the body to the support locations (A and B), are measured. The weight (W) at S_1 is equal to the total weight minus the weight at S_2. The COG is then calculated using:

$$Z_{cog} = \frac{S_2}{W}(B - A) \tag{A.1}$$

The COG can also be determined using a pendulum method, applicable to any arbitrary object. It, like the scale method, provides a single COG coordinate.

The body (with total weight W) is suspended by at least two strings and balanced such that the vertical (Z) axis is parallel to the gravity vector, as shown in Figure A-2. A second known mass is added to the body at a known distance (d1) from the vertical axis. This added mass exerts a weight force (F), changing the angle of inclination in the vertical axis, which is measured and used to calculate the COG.

$$d_{cog} = \frac{F d_1}{W sin(\alpha)} \tag{A.2}$$

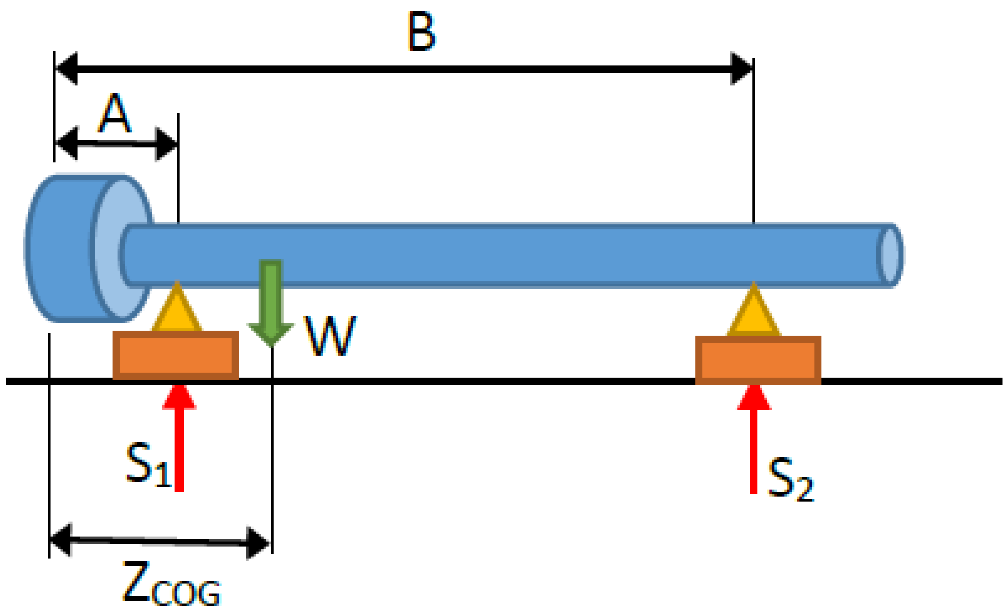


Figure A-1. Center of Gravity Measurement Setup Scale

A.2. MOMENT OF INERTIA

The body Moment of Inertia (MOI) is calculated using a simple pendulum setup. The body is suspended so that it swings freely in a plane perpendicular to the direction of the desired MOI. The body is pushed in that plane and the period of oscillation (T) is recorded. The parallel axis theroem can then be used to calculate the moment of inertia, refer to Figure A-3.

$$l_{cog} = \left(\frac{T}{2\pi}\right)^2 mgd_{cog} - md_{cog}^2 \tag{A.3}$$

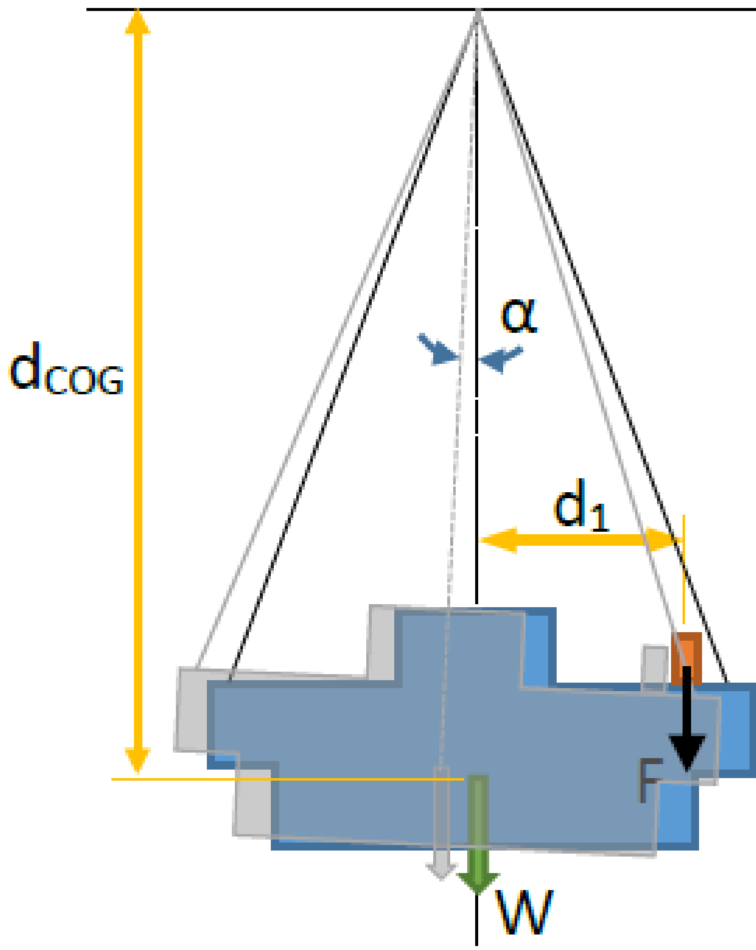
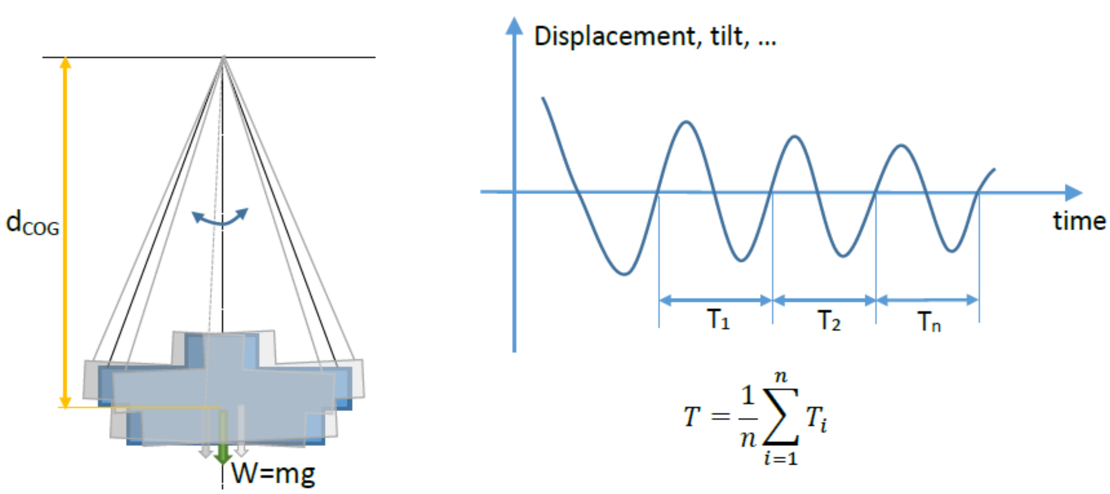


Figure A-2. Pendulum Method for COG



$$T = \frac{1}{n}\sum_{i=1}^{n} T_i$$

Figure A-3. Reference for MOI Calculation

APPENDIX B. INSTRUMENTATION

This appendix provides information about the instruments used in Phase 1 and Phase 2 testing.

B.1. PHASE 1

Sensor	Manufacturer	Model Number	# of Sensors
Flap Encoder	Gil	Blade25	2
Pressure Mat	Tactilus	custom	2
Flap 6DOF Load Cell	ATI	9105-TW-MINI58-R-5-IP68	2
Arm 6DOF Load Cell	ATI	9105-TIF-OMEGA160-IP68	1
Pressure Sensors	Druck	PDCR830	5
PTO Motor	Maxon	ESPOS2	2
PTO Motor Encoder	Maxon	HEDL5540	2
PTO Torque Transducer	Futek	TRS300	2

Table B-1. Phase 1 Instrumentation

B.2. PHASE 2

Sensor	Manufacturer	Model Number	# of Sensors
Flap String Encoder	microEpsilon	WDS-1500-P60-CR-TTL	2
Pressure Mat	Tactilus	custom	2
Flap 6DOF Load Cell	ATI	9105-TW-MINI58-R-5-IP68	2
Arm 6DOF Load Cell	ATI	9105-TIF-OMEGA160-IP68	1
Pressure Sensors	Druck	PDCR830	5
PTO Motor	Maxon	ESPOS2	2
PTO Motor Encoder	Maxon	HEDL5540	2
PTO Torque Transducer	Futek	TRS300	2

Table B-2. Phase 2 Instrumentation

APPENDIX C. DATA ACQUISITION SYSTEM

This appendix provides information about the DAQ used in Phase 1 and Phase 2 testing. The Phase 1 cabling diagram is provided in Figure C-1, and the Phase 2 cabling diagram is provided in Figure C-2,

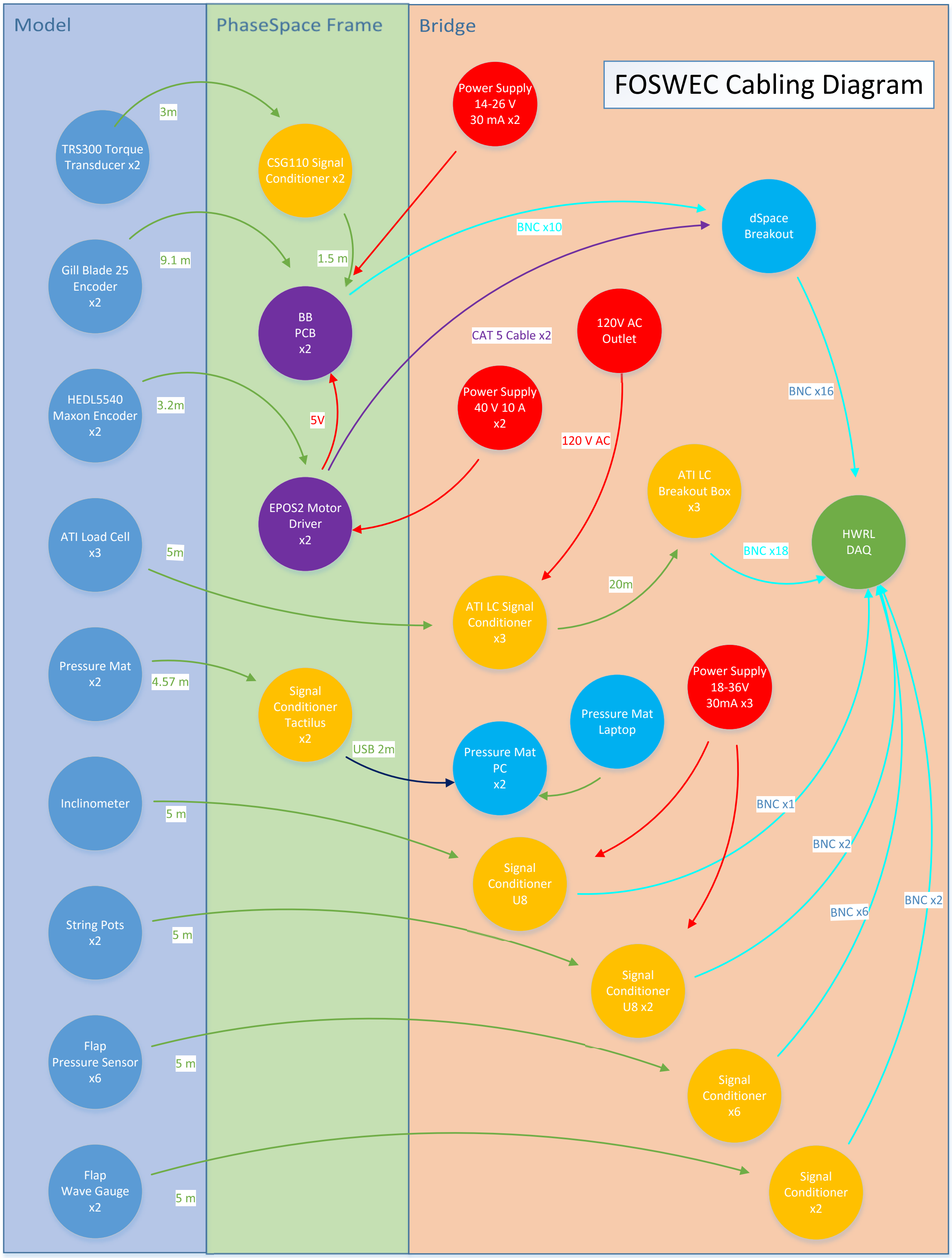


Figure C-1. FOSWEC Cabling Diagram (Phase 1)

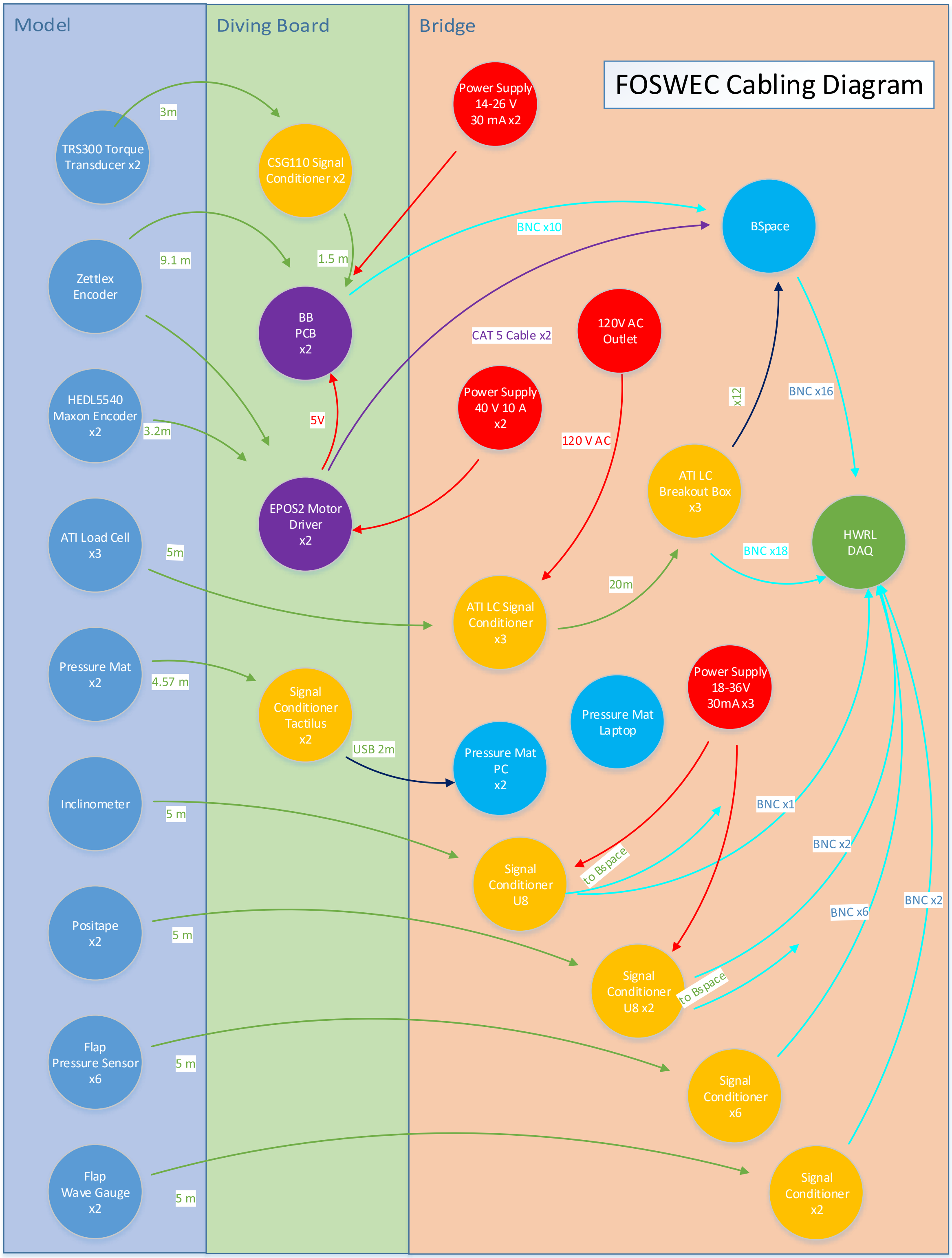


Figure C-2. FOSWEC Cabling Diagram (Phase 2)

APPENDIX D. PHASE 1 TEST LOGS

This appendix provides the test logs for the experiments performed in FOSWEC Phase 2 wave tank testing. Note that all trials marked in red have been flagged for errors; these trials were *not* removed from the data set, but the data should not be used.

D.1. HEAVE DECAY

The following test logs correspond to Heave Decay tests described in Section 5.4.2.

Trial	Δz (cm)	Date	Notes
1	3	11/30/2015	$z_i = 0.311$ m (video), no PhaseSpace
2	5	11/30/2015	$z_i = 0.308$ m (video), no PhaseSpace
3	7	12/1/2015	$z_i = 0.319$ m (video)
4	10	12/1/2015	FAILED: caught wire on PhaseSpace
5	10	12/1/2015	$z_i = 0.318$ m (video)
6	15	12/1/2015	$z_i = 0.319$ m (video)
7	3	12/1/2015	$z_i = 0.317$ m (video)
8	5	12/1/2015	$z_i = 0.316$ m (video)
9	7	12/1/2015	$z_i = 0.316$ m (video)
10	10	12/1/2015	$z_i = 0.317$ m (video)
11	15	12/1/2015	$z_i = 0.316$ m (video)
12	3	12/1/2015	$z_i = 0.316$ m (video)
13	5	12/1/2015	$z_i = 0.317$ m (video)
14	7	12/1/2015	$z_i = 0.316$ m
15	10	12/1/2015	$z_i = 0.316$ m
16	15	12/1/2015	$z_i = 0.318$ m (video)
17	NA	12/1/2015	heave static offset, with crane to lift up
18	NA	12/1/2015	heave static offset, Asher pushed down

Table D-1. Platform Heave Decay Test Log

D.2. PITCH DECAY

The following test logs correspond to Pitch Decay tests described in Section 5.4.3.

Trial	$\Delta\theta$ (°)	Date	Notes
1	2.0	12/1/2015	θ_i=0.83° (video)
2	3.0	12/1/2015	θ_i=0.83° (video)
3	5.0	12/1/2015	θ_i=0.83° (video)
4	7.0	12/1/2015	θ_i=0.83° (video)
5	8.4	12/1/2015	θ_i=0.83°, z_i=0.344m (video)
6	2.0	12/1/2015	θ_i=0.83° (video)
7	3.0	12/1/2015	θ_i=0.83° (video)
8	5.0	12/1/2015	θ_i=0.83° (video)
9	7.0	12/2/2015	θ_i=0.83°
10	8.4	12/2/2015	θ_i=0.83°, z_i=0.351m
11	2.0	12/2/2015	θ_i=0.83°, z_i=0.351m
12	3.0	12/2/2015	θ_i=0.83°, z_i=0.351m
13	5.0	12/2/2015	θ_i=0.83°, z_i=0.351m
14	7.0	12/2/2015	θ_i=0.83°, z_i=0.351m
15	8.4	12/2/2015	θ_i=0.83°, z_i=0.351m
16	NA	12/2/2015	pitch static offset, lifted with crane

Table D-2. Platform Pitch Decay Test Log

D.3. SURGE DECAY

The following test logs correspond to Surge Decay tests described in Section 5.4.4.

Trial	Δx (cm)	Date	Notes
1	NA	12/2/2015	FAILED: surge static offset with crane
2	NA	12/2/2015	FAILED: surge static offset with crane
3	5	12/2/2015	FAILED: one red bungee
4	10	12/2/2015	FAILED: one red bungee
5	25	12/2/2015	FAILED: one red bungee
6	25	12/2/2015	FAILED: two blue bungees
7	25	12/2/2015	FAILED: two blue bungees
8	15	12/3/2015	four blue bungees, θ_i=0.816°, z_i = 0.32m
9	20	12/3/2015	FAILED: ziptie broke, four blue bungees
10	20	12/3/2015	four blue bungees, θ_i=1.5°, z_i = ?m, saw some yaw
11	10	12/3/2015	four blue bungees, θ_i=2°, z_i = 0.32m
12	7	12/3/2015	four blue bungees, θ_i=1.73°, z_i = 0.32m
13	15	12/3/2015	four blue bungees, θ_i=2.4°, z_i = 0.32m
14	20	12/3/2015	four blue bungees, θ_i=?°, z_i = ?m
15	10	12/3/2015	four blue bungees, θ_i=2°, z_i = 0.32m
16	7	12/3/2015	four blue bungees, θ_i=1.8°, z_i = 0.32m
17	15	12/3/2015	four blue bungees, θ_i=2.4°, z_i = ?m
18	20	12/3/2015	four blue bungees, θ_i=2.7°, z_i = ?m
19	10	12/3/2015	four blue bungees, θ_i=2.04°, z_i = ?m, had pulley issue which was resolved mid trial
20	7	12/3/2015	four blue bungees, θ_i=1.73°, z_i = ?m
21	NA	12/3/2015	surge static offset

Table D-3. Platform Surge Decay Test Log

D.4. FLAP DECAY (PTO CONNECTED)

The following test logs correspond to Flap Decay tests described in Section 5.4.5, with PTO Connected.

Trial	$\Delta\theta$ (°)	Date	Notes
1	3	12/4/2015	θ_i=0.91°
2	5	12/4/2015	θ_i=0.4°
3	7	12/4/2015	θ_i=1.4°
4	10	12/4/2015	θ_i=2.4°
5	15	12/4/2015	θ_i=1.5°
6	20	12/4/2015	FAILED: ran out of time
7	20	12/4/2015	θ_i=0.71°
8	5	12/4/2015	θ_i=0.8°
9	7	12/4/2015	θ_i=0.7°
10	10	12/4/2015	θ_i=0.9°
11	15	12/4/2015	θ_i=0.9°
12	20	12/4/2015	θ_i=0.9°
13	5	12/4/2015	θ_i=0.7°
14	7	12/4/2015	θ_i=0.9°
15	10	12/4/2015	θ_i=0.7°
16	15	12/4/2015	θ_i=0.7°
17	20	12/4/2015	θ_i=0.7°
18	25	12/4/2015	θ_i=0.7°
19	NA	12/4/2015	static offset

Table D-4. Flap Pitch Decay with PTO Connected Test Log (Phase 1)

D.5. INITIAL WAVES

The following test logs correspond to Initial Wave tests described in Section 5.4.6.

Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Notes
1	1.57	0.015	9	0.5	12/3/15	Wavemaker Failure
2	1.57	0.015	9	0.5	12/3/15	noDamping, 4 bungees, all DOF free
3	1.57	0.045	9	1.5	12/3/15	noDamping, 4 bungees, all DOF free
4	0.87	0.015	5	0.5	12/3/15	noDamping, 4 bungees, all DOF free
5	0.87	0.045	5	1.5	12/3/15	noDamping, 4 bungees, all DOF free
6	1.91	0.015	11	0.5	12/4/15	noDamping, 4 bungees, all DOF free
7	1.91	0.136	11	4.5	12/4/15	noDamping, 4 bungees, all DOF free
8	3.31	0.136	19	4.5	12/4/15	noDamping, 4 bungees, all DOF free

Table D-5. Initial Waves Test Log

APPENDIX E. PHASE 2 TEST LOGS

This appendix provides the test logs for the experiments performed in FOSWEC Phase 2 wave tank testing. Note that all trials marked in red have been flagged for errors; these trials were *not* removed from the data set, but the data should not be used.

E.1. WAVE EXCITATION

The following test logs correspond to Wave Excitation tests described in Section 7.3.1.

Regular Waves

Continued on next page.

Trial	$T(s)$	$H(m)$	$T_{fs}(s)$	$H_{fs}(m)$	Date	Time	Notes
1	0.87	0.015	5	0.5	5/20/2016	15:22	no BSpace
2	1.22	0.015	7	0.5	5/20/2016	15:42	no BSpace, pressure mat includes Trial1
3	1.57	0.015	9	0.5	5/20/2016	15:52	BSpace worked!
4	1.91	0.015	11	0.5	5/20/2016	16:02	no BSpace
5	2.26	0.015	13	0.5	5/20/2016	16:14	BSpace worked!
6	2.61	0.015	15	0.5	5/20/2016	16:26	no BSpace
7	0.87	0.045	5	1.5	5/20/2016	16:38	no BSpace
8	1.22	0.045	7	1.5	5/20/2016	16:48	no BSpace
9	1.57	0.045	9	1.5	5/20/2016	17:10	no BSpace
10	1.91	0.045	11	1.5	5/20/2016	17:26	no BSpace
11	2.26	0.045	13	1.5	5/23/2016	10:00	Simplified Bspace, no Flap2 pressure mat data
12	2.61	0.045	15	1.5	5/23/2016	10:20	Simplified Bspace, no Flap2 pressure mat data
13	3.31	0.045	19	1.5	5/23/2016	10:32	Simplified Bspace, no Flap2 pressure mat data
14	1.22	0.136	7	4.5	5/23/2016	10:46	Simplified Bspace, no Flap2 pressure mat data, video, flap overtopping
15	1.57	0.136	9	4.5	5/23/2016	11:15	Simplified Bspace, no Flap2 pressure mat data, video, flap overtopping, lots of FOSWEC pitch
16	1.91	0.136	11	4.5	5/23/2016	11:30	Simplified Bspace, no Flap2 pressure mat data, video, lots of FOSWEC pitch

Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Time	Notes
17	2.26	0.136	13	4.5	5/23/2016	11:48	Simplified Bspace, no Flap2 pressure mat data, video, Bret relocked pitch, lots of FOSWEC pitch
18	2.61	0.136	15	4.5	5/23/2016	12:00	Simplified Bspace, no Flap2 pressure mat data, lots of FOSWEC pitch
19	1.22	0.045	7	1.5	5/23/2016	13:26	Repeat Trial 8, no FOSWEC pitch, only H3 caused pitch motion
20	1.91	0.045	11	1.5	5/23/2016	13:41	Repeat Trial 10
21	2.61	0.045	15	1.5	5/23/2016	13:56	Repeat Trial 12
22	1.22	0.136	7	4.5	6/17/2016	16:10	Repeat T14, flap overtopping, TT power supply off
23	1.57	0.136	9	4.5	6/17/2016	16:21	Repeat T15, flap overtopping, TT power supply off
25	2.26	0.136	13	4.5	6/17/2016	-	Aborted-no pressure mat data
26	2.26	0.136	13	4.5	6/17/2016	16:49	Repeat T17
27	1.57	0.136	9	4.5	6/17/2016	-	Repeat2 T15
28	2.61	0.136	15	4.5	6/17/2016	-	-
29	1.22	0.045	7	1.5	6/22/2016	10:35	Repeat of Trial 19, all locked, legs preventing Pitch
30	1.91	0.045	11	1.5	6/22/2016	251:16	Repeat of Trial 20, all locked, legs preventing Pitch
31	2.61	0.045	15	1.5	6/22/2016	11:06	Repeat of Trial 21, all locked, legs preventing Pitch

Table E-1. Regular Wave Excitation Test Log

Irregular Waves

Trial	$T_p(s)$	$H_{m0}(m)$	$T_{p,fs}(s)$	$H_{s,fs}(m)$	Date	Time	Notes
1	1.220	0.015	7	0.495	5/23/2016	14:35	simple Bspace, video, wave train is 7min, DAQ log error
2	2.610	0.015	15	0.495	5/23/2016	14:57	simple Bspace, wave train is 14min, DAQ log error
3	1.220	0.015	7	0.495	5/23/2016	15:15	repeat Trial 1, simple Bspace, wave train is 7min, DAQ log error
4	1.220	0.015	7	0.5	5/23/2016	15:26	repeat Trial 1, simple Bspace, wave train is 7min
5	2.610	0.015	15	0.5	5/23/2016	15:42	repeat Trial 2,simple Bspace, wave train is 14min
6	1.220	0.045	7	1.5	5/23/2016	16:07	simple Bspace, wave train is 7min
7	2.611	0.045	15	1.5	5/23/2016	16:25	simple Bspace, wave train is 14min
8	2.610	0.136	15	4.5	5/23/2016	16:49	simple Bspace, wave train is 14min
9	1.220	0.136	7	4.5	6/22/2016	11:35	7 min wave train

Table E-2. Irregular Wave Excitation Test Log

E.2. FORCED OSCILLATION

The following test logs correspond to Forced Oscillation tests described in Section 7.3.2.

Trial	**T** (s)	$\tau_{\mathbf{cmd}}$ (**Nm**)	$\mathbf{T_{fs}}$ (s)	**Date**	**Time**	**Notes**	$\lvert\theta_{\mathbf{tar}}\rvert$ (**deg**)	$\lvert\theta_{\mathbf{obs}}\rvert$ (**deg**)	**% diff**
1	0.87	9	5	5/24/2016	10:56	tiny ampltitude, no pmat	10	NA	NA
2	3.31	9	19	5/24/2016	11:05	Trial 32, slightly larger than target p2p 10	10	12.00	0.20
3	2.61	15	15	5/24/2016	11:09	error, matlab crashed	10	NA	NA
4	2.61	15	15	5/24/2016	11:25	Trial 33, no wave ramp, slightly larger than target p2p 10	10	11.50	0.15
5	2.26	20	13	5/24/2016	11:31	logged data, matlab crashed at end	10	11.00	0.10
6	1.91	25	11	5/24/2016	11:43	video	10	9.50	-0.05
7	1.57	35	9	5/24/2016	11:51	video	10	10.00	0.00
8	1.22	45	7	5/24/2016	13:15	response non-symmetric	10	8.00	NA
9	1.22	53	7	5/24/2016	13:25	data at begin good, end data non-axisymmetric, matlab crashed at end	10	11.00	0.10
10	0.87	70	5	5/24/2016	13:35	lots of overtopping, data clean, use for 15deg runs, goPro, video	10	15.50	0.55
11	0.87	62	5	5/24/2016	13:44	overtopping, data clean, use for 15deg runs	10	14.70	0.47
12	0.87	55	5	5/24/2016	14:01	overtopping, data clean, goPro	10	13.80	0.38
13	0.87	47	5	5/24/2016	14:15	Trial 35, overtopping, data clean	10	11.50	0.15

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Trial	**T** (s)	$\tau_{\mathbf{cmd}}$ (**Nm**)	$\mathbf{T_{fs}}$ (s)	**Date**	**Time**	**Notes**	$\lvert\theta_{\mathbf{tar}}\rvert$ (**deg**)	$\lvert\theta_{\mathbf{obs}}\rvert$ (**deg**)	**% diff**
14	3.31	12	19	5/24/16	14:27	Trial 39, slightly larger than target p2p 15, GoPro	15	16.6	0.11
15	2.61	20	15	5/24/2016	14:35	Trial 40, no pmat	15	16.10	0.07
16	2.26	28	13	5/24/2016	15:01	goPro	15	15.40	0.03
17	1.91	34	11	5/24/2016	15:10	p2p too small	15	12.80	-0.15
18	1.91	38	11	5/24/2016	15:24	Trial 36, slightly smaller than target p2p 15	15	14.00	-0.07
19	1.57	50	9	5/24/2016	15:30	goPro	15	15.20	0.01
20	1.22	60	7	5/24/2016	15:44	p2p too small, response non-symmetric, goPro	15	12.90	-0.14
21	1.22	70	7	5/24/2016	16:00	matlab crashed, data saved, response non-symmetric, overtopping	15	14.70	-0.02
NA	0.87	70	5	5/24/2016	13:35	Trial 10	15	15.50	0.03
NA	0.87	62	5	5/24/2016	13:44	Trial 11	15	14.70	-0.02
22	3.31	15	19	5/24/2016	16:15	GoPro	20	21.00	0.05
23	2.61	25	15	5/24/2016	16:23	GoPro	20	20.00	0.00
24	2.26	35	13	5/24/2016	16:35	GoPro, no pmat	20	19.60	-0.02
25	1.57	70	9	5/24/2016	16:40	GoPro, no pmat, matlab crashed	20	21.00	0.05
26	1.22	85	7	5/24/2016	17:00	error	20	NA	NA
27	1.22	90	7	5/24/2016	17:15	slightly smaller than target p2p 20	20	18.50	-0.07

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Trial	T (s)	τ_{cmd} (Nm)	T_{fs} (s)	Date	Time	Notes	$\lvert\theta_{tar}\rvert$ (deg)	$\lvert\theta_{obs}\rvert$ (deg)	% diff
28	1.22	97	7	5/25/2016	09:30	slightly smaller than target p2p 20, overtopping and non-symmetric, no pmat	20	18.70	-0.07
29	1.22	110	7	5/25/2016	09:47	overtopping, GoPro, non-symmertric	20	19.90	-0.01
30	0.87	115	5	5/25/2016	10:02	lots of overtopping, GoPro, non-symmertric	20	20.00	0.00
31	3.31	7	19	5/25/2016	10:20	redo Trial 2, slightly less than target p2p 10	10	7.80	-0.22
32	3.31	8	19	5/25/2016	10:26	redo Trial 2	10	10.10	0.01
33	2.61	13	15	5/25/2016	10:35	redo of Trial 4, GoPro, matlab crashed	10	10.10	0.01
34	0.87	44	5	5/25/2016	10:50	redo of Trial 13, slightly less than target p2p 10, GoPro, no pmat	10	11.30	0.13
35	0.87	40	5	5/25/2016	11:00	redo Trial 13	10	10.10	0.01
36	1.91	41	11	5/25/2016	11:13	redo Trial 18, matlab crash	15	15.40	0.03
37	1.22	100	7	5/25/2016	11:25	redo Trial 28, overtopping, no pmat	20	19.30	-0.03
38	3.31	10	19	5/25/2016	11:45	redo of Trial 14, no pmat	15	12.60	-0.16
39	3.31	11	19	5/25/2016	11:51	redo Trial 14, no pmat	15	14.70	-0.02
40	2.61	19	15	5/25/2016	11:58	redo Trial 15	15	15.40	0.03
41	3.31	8	19	5/25/2016	14:11	complete	10	9.20	-0.08
42	2.61	13	15	5/25/2016	14:17	complete	10	9.80	-0.02
43	2.26	20	13	5/25/2016	14:28	no pmat	10	11.40	0.14

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Trial	T (s)	$\tau_{\mathbf{cmd}}$ (Nm)	T_{fs} (s)	Date	Time	Notes	$\lvert\theta_{\mathbf{tar}}\rvert$ (deg)	$\lvert\theta_{\mathbf{obs}}\rvert$ (deg)	% diff
44	2.26	18	13	5/25/2016	14:33	complete, no pmat	10	10.10	0.01
45	1.91	25	11	5/25/2016	14:41	complete, no pmat	10	9.96	-0.00
46	1.57	35	9	5/25/2016	14:51	complete	10	10.90	0.09
47	1.22	53	7	5/25/2016	15:07	complete, matlab crashed	10	11.00	0.10
48	0.87	40	5	5/25/2016	15:22	complete	10	10.00	0.00
49	3.31	11	19	5/25/2016	15:38	complete	15	14.60	-0.03
50	2.61	19	15	5/25/2016	15:47	complete, no pmat	15	15.10	0.01
51	2.26	28	13	5/25/2016	15:53	complete	15	15.70	0.05
52	1.91	41	11	5/25/2016	16:04	complete	15	15.60	0.04
53	1.57	50	9	5/25/2016	16:15	complete, no pmat	15	15.20	0.01
54	1.22	70	7	5/25/2016	16:31	complete, no pmat	15	14.97	-0.00
55	0.87	65	5	5/25/2016	16:43	complete	15	15.20	0.01
56	3.31	15	19	5/26/2016	09:21	complete	20	20.70	0.03
57	2.61	25	15	5/26/2016	09:32	complete	20	20.10	0.01
58	2.26	35	13	5/26/2016	09:43	complete	20	19.70	-0.02
59	1.91	55	11	5/26/2016	09:52	complete, no pmat	20	20.10	0.01
60	1.91	55	11	5/26/2016	10:04	complete, no pmat, matlab crashed	20	20.10	0.01
61	1.57	70	9	5/26/2016	10:16	log error	20	NA	NA
62	1.57	70	9	5/26/2016	10:26	complete, no pmat	20	20.90	0.04
NA	1.22	110	7	5/26/2016	NA	Trial 37	20	NA	NA
63	0.87	115	5	5/26/2016	10:45	complete, video	20	20.70	0.03
64	3.31	8	19	5/26/2016	11:04	log error	10	NA	NA
65	3.31	8	19	5/26/2016	11:09	complete	10	9.80	-0.02
66	2.61	13	15	5/26/2016	11:15	complete	10	10.00	0.00
67	2.26	18	13	5/26/2016	11:19	complete	10	10.00	0.00
68	1.91	25	11	5/26/2016	11:24	complete	10	10.10	0.01
69	1.57	35	9	5/26/2016	11:33	error	10	11.20	0.12
70	1.57	35	9	5/26/2016	11:54	complete	10	10.80	0.08

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Trial	T (s)	τ_{cmd} (Nm)	T_{fs} (s)	Date	Time	Notes	$\lvert\theta_{tar}\rvert$ (deg)	$\lvert\theta_{obs}\rvert$ (deg)	% diff
71	1.22	53	7	5/26/2016	00:57	complete	10	12.00	0.20
72	1.22	51	7	5/26/2016	12:15	REDO 70, lower commanded, complete	10	10.80	0.08
73	0.87	40	5	5/26/2016	12:30	complete	10	10.10	0.01
74	3.31	11	19	5/26/2016	12:43	complete	15	15.13	0.01
75	2.61	19	15	5/26/2016	14:50	complete	15	15.50	0.03
76	2.26	28	13	5/26/2016	15:00	complete	15	16.30	0.09
77	1.91	41	11	5/26/2016	15:10	complete	15	15.90	0.06
78	1.57	50	9	5/26/2016	15:20	complete	15	15.80	0.05
79	1.22	70	7	5/26/2016	15:36	complete	15	14.90	-0.01
80	0.87	65	5	5/26/2016	15:53	complete	15	15.50	0.03
81	3.31	15	19	5/26/2016	16:07	complete, matlab crashed	20	21.10	0.06
82	2.61	25	15	5/26/2016	16:29	complete	20	20.00	0.00
83	2.26	35	13	5/26/2016	16:43	complete	20	20.00	0.00
84	1.91	50	11	5/26/2016	16:48	complete	20	19.80	-0.01
85	1.57	70	9	5/26/2016	16:57	complete	20	21.50	0.07
86	1.22	110	7	5/27/2016	09:21	complete, matlab crashed	20	20.10	0.01
87	0.87	115	5	5/27/2016	09:35	complete, lots of overtopping	20	20.40	0.02

Table E-3. Forced Oscillation Test Log

E.3. DAMPING OPTIMIZATION

The following test logs correspond to Damping Optimization tests described in Section 7.3.3.

Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Time	Notes
1	1.57	0.045	9	1.5	5/27/2016	10:12	damping range from 0-0.7, steps of 0.1 [Nms]
2	1.57	0.136	9	4.5	5/27/2016	10:35	damping range from 0-0.5, steps of 0.1 [Nms]
3	1.57	0.136	9	4.5	5/27/2016	11:09	damping range from 0-0.7, steps of 0.1 [Nms]
4	1.57	0.136	9	4.5	5/27/2016	11:27	damping range from 0-0.7, steps of 0.1 [Nms], no pmat
5	1.57	0.136	9	4.5	5/27/2016	13:50	damping range from 0-0.8, steps of 0.1 [Nms]
6	1.22	0.136	7	4.5	5/27/2016	14:08	damping range from 0-1.3, steps of 0.1, no pmat
7	1.22	0.136	7	4.5	5/27/2016	14:30	damping values 0, 0.2,0.4,0.8
8	1.50	0.136	9	4.5	5/27/2016	15:12	Airy waves, 13 min run, increment by 0.1 from 0 @30s intervals
9	2.25	0.136	13	4.5	5/27/2016	15:35	Airy waves, 12 min run, increment by 0.1 from 0 @40s intervals
10	3.00	0.136	17	4.5	5/27/2016	16:00	Airy waves, 13 min run, increment by 0.1 from 0 @1min intervals
11	1.50	0.136	9	4.5	5/27/2016	16:30	Airy waves 12 min run, increment by 0.01 from 0 @30s intervals

Table E-4. Damping Optimization Test Log

E.4. CONFIG1

The following test logs correspond to Config 1 tests described in Section 7.3.4.

Regular Waves

Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Time	Notes
1	0.87	0.015	5	0.5	5/31/2016	09:53	complete
2	1.22	0.015	7	0.5	5/31/2016	10:08	complete, trial number not incremented at DAQ, check data log
3	1.57	0.015	9	0.5	5/31/2016	10:18	complete
4	1.91	0.015	11	0.5	5/31/2016	10:30	complete, motor encoder data is terrrible, chain barely moving
5	2.26	0.015	13	0.5	5/31/2016	10:39	complete
6	2.61	0.015	15	0.5	5/31/2016	10:50	complete
7	0.87	0.045	5	1.5	5/31/2016	11:05	complete
8	1.22	0.045	7	1.5	5/31/2016	11:15	complete
9	1.57	0.045	9	1.5	5/31/2016	11:26	complete
10	1.91	0.045	11	1.5	5/31/2016	11:41	complete
11	2.26	0.045	13	1.5	5/31/2016	11:56	complete
12	2.61	0.045	15	1.5	5/31/2016	12:08	complete, damping applied @ 70s
13	3.31	0.045	19	1.5	5/31/2016	12:22	complete
14	1.22	0.136	7	4.5	5/31/2016	12:35	complete
15	1.57	0.136	9	4.5	5/31/2016	12:50	complete
16	1.91	0.136	11	4.5	5/31/2016	13:28	complete
17	2.26	0.136	13	4.5	5/31/2016	14:02	complete
18	2.61	0.136	15	4.5	5/31/2016	14:12	complete, video
19	3.31	0.136	19	4.5	5/31/2016	14:23	complete
20	1.22	0.045	7	1.5	5/31/2016	14:35	complete, repeat Trial 8, flap1 p2p 7deg, motor1 p2p 0.5deg
21	1.91	0.045	11	1.5	5/31/2016	15:05	complete, repeat Trial 10, flap1 p2p 11deg, motor1 p2p 4deg
22	2.61	0.045	15	1.5	5/31/2016	15:24	complete, repeat Trial 12, video, flap1 p2p 12.5deg, motor1 p2p 5.5deg

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Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Time	Notes
23	1.220	0.045	7	1.5	5/31/2016	15:38	complete, repeat Trial 8, flap1 p2p 6.7deg, motor1 p2p 0.5deg
24	1.910	0.045	11	1.5	5/31/2016	15:47	complete, repeat Trial 10, flap1 p2p 11deg, motor1 p2p 4deg
25	2.610	0.045	15	1.5	5/31/2016	16:07	complete, repeat Trial 12, flap1 p2p 13deg, motor1 p2p 8.5deg, no damping
26	2.610	0.045	15	1.5	5/31/2016	16:18	complete, repeat Trial 12, flap1 p2p 12.7deg, motor1 p2p 5.5deg, no damping

Table E-5. Config 1 Regular Waves Test Log

Irregular Waves

Trial	T_p(s)	H_{m0}(m)	$T_{p,fs}$(s)	$H_{m0,fs}$(m)	Date	Time	Notes
1	1.22	0.045	7	1.5	5/31/2016	16:36	complete
2	1.22	0.136	7	4.5	5/31/2016	14:53	complete, video
3	2.61	0.045	15	1.5	6/1/2016	09:20	complete
4	2.61	0.136	15	4.5	6/1/2016	09:45	complete, sporadic overtopping, no pmat

Table E-6. Config 1 Irregular Waves Test Log

E.5. CONFIG2

The following test logs correspond to Config 2 tests described in Section 7.3.5.

Regular Waves

Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Time	Notes
1	0.87	0.045	5	1.5	6/1/2016	11:05	complete, no pmat, flap2 appears locked, Peter came and fixed the flap
2	0.87	0.045	5	1.5	6/1/2016	14:29	complete, Bret video, no Flap2 torque data
3	2.26	0.045	13	1.5	6/1/2016	14:39	complete, changed test order, no Flap2 torque data
4	0.87	0.045	5	1.5	6/1/2016	14:57	complete, possibly no motor encoder data
5	1.22	0.045	7	1.5	6/1/2016	15:16	complete, Bspace fixed, observed pto slack and minimal motor encoder data, Asher tightened things up
6	1.57	0.045	9	1.5	6/1/2016	15:55	complete, pto slack tightened up, observed motor encoder data
7	1.91	0.045	11	1.5	6/1/2016	16:04	complete
8	2.26	0.045	13	1.5	6/1/2016	16:19	complete
9	2.61	0.045	15	1.5	6/1/2016	16:30	complete
10	3.31	0.045	19	1.5	6/1/2016	16:42	complete
11	1.22	0.136	7	4.5	6/13/2016	10:00	overtopping, control enabled late, 20sec
12	1.57	0.136	9	4.5	6/13/2016	10:26	Bret video
13	1.91	0.136	11	4.5	6/13/2016	10:43	complete
14	2.26	0.136	13	4.5	6/13/2016	11:00	complete
15	2.61	0.136	15	4.5	6/13/2016	11:13	complete
16	3.31	0.136	19	4.5	6/13/2016	11:27	complete
17	1.22	0.045	7	1.5	6/13/2016	11:47	repeat Trial 5, complete
18	1.91	0.045	11	1.5	6/13/2016	12:05	repeat Trial 7, complete

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Trial	$T(s)$	$H(m)$	$T_{fs}(s)$	$H_{fs}(m)$	Date	Time	Notes
19	2.61	0.045	15	1.5	6/13/2016	13:52	repeat Trial 9, complete
20	1.22	0.045	7	1.5	6/13/2016	14:09	repeat Trial 5, complete
21	1.91	0.045	11	1.5	6/13/2016	14:27	repeat Trial 7, complete
22	2.61	0.045	15	1.5	6/13/2016	14:41	repeat Trial 9, complete

Table E-7. Config 2 Regular Waves Test Log

Irregular Waves

Trial	$T_p(s)$	$H_{m0}(m)$	$T_{p,fs}(s)$	$H_{m0,fs}(m)$	Date	Time	Notes
1	1.22	0.045	7	1.5	6/13/2016	15:08	complete, Bret video
2	2.61	0.045	15	1.5	6/13/2016	15:30	complete, Bret video
3	1.22	0.136	7	4.5	6/13/2016	15:57	complete, Bret video
4	2.61	0.136	15	4.5	6/13/2016	16:15	complete, Bret video

Table E-8. Config 2 Irregular Waves Test Log

E.6. CONFIG3

The following test logs correspond to Config 3 tests described in Section 7.3.6.

Regular Waves

Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Time	Notes
1	0.87	0.045	5	1.5	6/14/2016	12:22	complete, little heave
2	1.22	0.045	7	1.5	6/14/2016	12:38	complete, little heave
3	1.57	0.045	9	1.5	6/14/2016	12:56	complete
4	1.91	0.045	11	1.5	6/14/2016	13:07	error: wavemaker failed
5	1.91	0.045	11	1.5	6/14/2016	14:10	complete, Bret video
6	2.26	0.045	13	1.5	6/14/2016	14:23	complete, Bret video
7	2.61	0.045	15	1.5	6/14/2016	14:35	complete
8	3.31	0.045	19	1.5	6/14/2016	14:46	complete
9	1.22	0.136	7	4.5	6/14/2016	14:58	complete, no pmat
10	1.57	0.136	9	4.5	6/14/2016	15:12	complete, Bret video
11	1.91	0.136	11	4.5	6/14/2016	15:26	complete, no PhaseSpace
12	2.26	0.136	13	4.5	6/14/2016	15:42	complete, no PhaseSpace
13	2.61	0.136	15	4.5	6/14/2016	15:57	complete, no PhaseSpace
14	1.91	0.136	11	4.5	6/14/2016	16:19	complete, redo Trial 11, no PhaseSpace
15	3.31	0.136	19	4.5	6/14/2016	16:49	complete, some PhaseSpace
16	1.22	0.045	7	1.5	6/14/2016	17:07	complete, no PhaseSpace
17	1.91	0.045	11	1.5	6/15/2016	08:50	Manually started triggering for simulink, damping in motors started with a few second delay, data OK
18	2.61	0.045	15	1.5	6/15/2016	09:09	complete, all good
19	1.22	0.045	7	1.5	6/15/2016	09:24	complete, all good
20	1.91	0.045	11	1.5	6/15/2016	09:39	complete, all good
21	2.61	0.045	15	1.5	6/15/2016	09:57	complete, all good
22	1.91	0.136	11	4.5	6/22/2016	14:23	complete, with PhaseSpace, no pmat, overtopping the floats

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Trial	$T(s)$	$H(m)$	$T_{fs}(s)$	$H_{fs}(m)$	Date	Time	Notes
23	2.26	0.136	13	4.5	6/22/2016	14:43	complete, with PhaseSpace, no pmat, overtopping the floats
24	2.61	0.136	15	4.5	6/22/2016	15:00	complete, with PhaseSpace, no pmat, overtopping the floats
25	3.31	0.136	19	4.5	6/22/2016	15:13	complete, with PhaseSpace, no pmat, overtopping the floats

Table E-9. Config 3 Regular Waves Test Log

Irregular Waves

Trial	$T_p(s)$	$H_{m0}(m)$	$T_{p,fs}(s)$	$H_{m0,fs}(m)$	Date	Time	Notes
1	1.22	0.045	7	1.5	6/15/2016	10:16	test complete, all good
2	2.61	0.045	15	1.5	6/15/2016	10:40	test complete, all good
3	1.22	0.136	7	4.5	6/15/2016	11:13	test complete, all good
4	2.61	0.136	15	4.5	6/15/2016	11:34	test complete, all good

Table E-10. Config 3 Irregular Waves Test Log

E.7. CONFIG4

The following test logs correspond to Config 4 tests described in Section 7.3.7.

Regular Waves

Trial	T(s)	H(m)	T_{fs}(s)	H_{fs}(m)	Date	Time	Notes
1	0.87	0.045	5	1.485	6/15/2016	13:35	motors were not ON, run will be repeated
2	0.870	0.045	5	1.485	6/15/2016	13:50	complete - repeating previous run (Trial 1) - all good
3	1.22	0.045	7	1.485	6/15/2016	14:07	complete - all good
4	1.57	0.045	9	1.485	6/15/2016	14:20	complete - all good
5	1.91	0.045	11	1.485	6/15/2016	14:35	complete - all good
6	2.26	0.045	13	1.485	6/15/2016	14:50	complete - all good
7	2.61	0.045	15	1.485	6/15/2016	15:04	complete - all good
8	3.31	0.045	19	1.485	6/15/2016	15:18	complete - all good
9	1.22	0.136	7	4.488	6/15/2016	15:32	complete - all good
10	1.57	0.136	9	4.488	6/15/2016	15:48	complete - all good
11	1.91	0.136	11	4.488	6/15/2016	16:03	complete - all good
12	2.26	0.136	13	4.488	6/15/2016	16:19	complete - all good
13	2.61	0.136	15	4.488	6/15/2016	16:32	complete - all good
14	3.31	0.136	19	4.488	6/15/2016	16:46	complete - all good
15	1.22	0.045	7	1.485	6/15/2016	17:00	complete - all good
16	1.91	0.045	11	1.485	6/16/2016	08:52	Trigger Missed - Measurement not used
17	1.91	0.045	11	1.485	6/16/2016	09:02	complete - no pressure mat data
18	2.61	0.045	15	1.485	6/16/2016	09:15	complete - pressure mat shut down
19	1.22	0.045	7	1.485	6/16/2016	09:29	complete - pressure mat: first several seconds data missing
20	1.91	0.045	11	1.485	6/16/2016	09:41	complete - pressure mat: first several seconds data missing
21	2.61	0.045	15	1.485	6/16/2016	09:57	complete - all good

Table E-11. Config 4 Regular Waves Test Log

Irregular Waves

Trial	$T_p(s)$	$H_{m0}(m)$	$T_{p,fs}(s)$	$H_{m0,fs}(m)$	Date	Time	Notes
1	1.22	0.045	7	1.485	6/16/2016	10:10	Complete
2	2.61	0.045	15	1.485	6/16/2016	10:28	Complete - finished at 10:43
3	1.22	0.136	7	4.488	6/16/2016	10:53	Complete - finished at 11:04
4	2.61	0.136	15	4.488	6/16/2016	11:13	Complete - finished at 11:24

Table E-12. Config 4 Irregular Waves Test Log

E.8. FLAP DECAY (PTO DISCONNECTED)

The following test logs correspond to Flap Decay tests described in Section 7.3.8, with PTO Disconnected.

Trial	θ (°)	Date	Time	Notes
0	0	9/9/2016	02:05	Setup test dry
1	0	9/12/2016	10:08	Setup test wet
2	5	9/12/2016	10:34	For accuracy, take θ_i from the record.
3	7	9/12/2016	10:37	-
4	10	9/12/2016	10:43	-
5	15	9/12/2016	10:48	-
6	20	9/12/2016	10:55	-
7	5	9/12/2016	11:01	-
8	7	9/12/2016	11:06	-
9	10	9/12/2016	11:11	-
10	15	9/12/2016	11:16	-
11	20	9/12/2016	11:21	-
12	5	9/12/2016	11:33	-
13	7	9/12/2016	11:39	-
14	10	9/12/2016	11:43	-
15	15	9/12/2016	11:47	-
16	20	9/12/2016	11:51	Ignore load cell pulse at about 170s - crane was moved.

Table E-13. Flap Pitch Decay with PTO Disconnected Test Log (Phase 2)

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