CWPT Open Water Demonstration
DE-EE0008097.0000
Budget Period 1

Task 2.4.2 Scaled Prototype Tank Testing

Test Setup and Overview

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VARIABLES & DEFINITION

VARIABLES AND CONSTANTS

VARIABLE	DESCRIPTION	UNIT
W	Width	m
L	Length	m
T	Thickness	m
V	Displaced Water Volume by Absorber	m^3
hOp	Operating depth; Vertical distance between mean water line and top of absorber body	m
Alpha	Mooring angle between mooring line/PTO tether and horizontal tank floor	Deg
C	Target PTO Damping Coefficient	Ns/m
K	Target Spring Coefficient	N/m
H	Tank water depth	m
Hs	Significant Wave Height	m
Tp	Dominant Wave Period	s
Te	Energy Period	S
omega	Wave Direction measured in a positive rotation coordinates defined in this document	Deg

FURTHER CONVENTIONS

CalWave is using the following convention for the positioning and orientation of the global coordinate system. This convention is equal to the most common convention used in Naval Architecture and specifically in wave energy conversion related research & development:

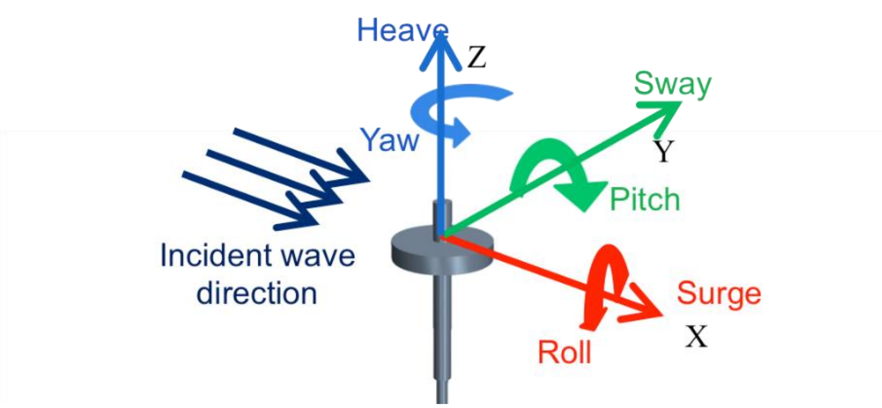

Figure 1: Global Coordinate System Position and Orientation used throughout this report. Picture / Scheme by WECSim - Theory section (https://wec-sim.github.io/WEC-Sim/theory.html)

ABBREVIATIONS

MBL – Minimum Breaking Load (Mooring Line Property)

PTO – Power Take-Off

WEP – Wave Energy Prize

MPC – Model Predictive Control

COG – Center of Gravity

COB – Center of Buoyancy

MOI – Moment of Inertia

AM – Added Hydrodynamic Mass

AD – Added Hydrodynamic Damping

DOF – Degrees of Freedom

EOM – Equation of Motion

Vdc – Volt Direct Current

1. INTRODUCTION

The objective of the project is to advance the Technology Readiness Level (TRL) of the Wave Energy Converter (WEC) developed by CalWave Wave Power Technologies Inc (CalWave) through advanced numerical simulations, dynamic hardware tests, and ultimately a scaled open water demonstration deployment while continuing to exceed DOE's target ACE threshold of 3m/M$. The outcomes of Budget Period 1 will be a detailed design of the scaled demonstration unit and bench testing of the critical hardware components. In Budget Period 2, the key outcomes will be deployment and operation of the demonstration unit at an open water site which replicates full scale ocean conditions, and performance and load measurements will be used to validate the high techno-economic performance (ACE) of the device full scale device, as measured by the "Average Climate Capture Width per Characteristic Capital Cost" (ACE) metric defined for the Wave Energy Prize.

CalWave seeks to conduct experimental tank testing of scaled prototype units early on in the design process to verify device performance for sea states of importance and to perform system identification/PTO tests. These experimental tests primarily aim to assess the wave to structure conversion efficiency and device behavior. Moreover, distinct model parameters of high interest should be experimentally tested to validate numerical device modeling and optimization.

2. TEST OBJECTIVES

CalWave seeks to experimentally test a 1:20 scale prototype and a 1:30 scale prototype for a total duration of 15 working days at the LiR National Test Facility. For nearly all of the below mentioned test objectives the 1:20 scaled prototype will be used, resulting in a smaller signal to noise ratio and a more representative scale for viscous effects. Whenever the capabilities of the basin/wave maker are reached (e.g. survivability tests) the device can be swapped to a 1:30 scale device.

2.1 PTO INTEGRATION AND CONTROLLABILITY

- Anticipated Scale: 1:20 Scale
- Test PTO behavior and stability for a static WEC setup in the basin. The capability of the PTO to winch mooring/PTO line in and out, to submerge the absorber body and bring and holt it at its static equilibrium position and to effectively change the operating depth hOp is tested.
- For a static setup with pretension in the mooring/PTO tether lines (entirely submerged absorber body) the behavior in case of a power loss/PTO software failure is tested to minimize risks/threads of malfunctions during test cases with waves running.
- For a static setup, the behavior of the wrapping of the PTO tether around the PTO drum is tested. Although the line should wrap in a single layer any risk and threats from deviation of this is assessed before running test cases with waves running.

- For a static setup or for a single PTO setup without device connected to the PTO, the PTO is disturbed with a single push/pull. Although the PTO should not get excited in a resonant behavior and rather converge to its set equilibrium position, these tests act as a risk mitigation test and validate a stable PTO behavior. Potential tuning of software settings will accommodate these tests.

- For a static setup or a single PTO setup without the device connected to the PTO the PTO characteristic values such as damping or restoring force coefficient are changed on-line. Accuracy in setting these device parameters should be evaluated and response of the PTO closed control loop assessed for stability and response accuracy.

- For a static setup or a single PTO setup without the device connected to the PTO the PTO function of maintaining a minimum line tension is tested.

2.2 Basic Working Principle Verification

- Anticipated Scale: 1:20 Scale

- For hydrostatic tests and validation of total device buoyancy, respectively pretension in mooring tethers the device in a specified configuration is submerged and tether forces are measured. The operating depth is changed using all four PTO units. Balancing of the tether forces and correction of the absorber level is tested. These tests verify that a specific initial equilibrium setup can be obtained for each wave case.

- Basic working principles of the combined PTO/device setup is tested using small monochromatic wave excitation with small wave heights and mild periods. PTO settings are chosen to be in a mean range of damping / restoring force coefficients. General device behavior is checked and it is ensured that all PTO units work in the same way; the mooring pulleys behave in the desired way and no obvious threats or risks are identified.

- For a full setup of the absorber body connected to all PTO units the device stability is checked by exciting the absorber body (e.g. push or pull) while no waves are running.

2.3 System Identification Tests (SID)

- Anticipated Scale: 1:20 Scale

- Estimation of radiation Frequency Response Function (FRF) using oscillation tests

- Forced oscillation experiments are run in calm water (wave damping mode on wave makers) to obtain a model of the intrinsic device impedance. A pink noise (Inverse frequency signal) is used to excite all PTO units either in phase (1 DOF) or with different uncorrelated pink noise signals (3 or full 6 DOF). Although, the PTO units cannot excite the absorber body in both directions (it is not possible to push on a tether), the positive buoyancy force can effectively be used to "excite" the absorber in the upwards motion. Hence, it must be ensured that the tether tension in the time realization fed to the PTO units never exceeds the PTO pretension.

- For identification of wave excitation characteristics of the device, forced oscillation experiments in presence of waves will be conducted. PTO forces, absorber velocities and wave elevation are measured. Additionally, hull pressure on the absorber body will be measured, allowing for correlation of device behavior and hull pressure fur further system identification.

2.4 Preliminary Performance Evaluation

- Anticipated Scale: 1:20 Scale

- To compare the device performance in the Wave Energy Prize Metric using the ACE metric, for baseline performance evaluation 6 irregular, 0 Degree incident wave cases are tested. The six wave cases follow exactly the WEP metric and results obtained from these tests can be directly used to compare performance against the CalWave concept used during the 1:20 scale US Wave Energy Prize tests. Tests are performed with WEC/PTO target parameters from numerical simulations and deviations from these to check for optimality of parameters.

- To obtain a first estimate of device performance at specific target locations (e.g. Hawaii) the device's performance in energy extraction will be assessed for specific irregular sea stated.

2.5 WEC Survivability Testing

- Anticipated Scale: 1:30 Scale

- To assess the device behavior in severe sea and in extreme wave cases, the 1:30 scale device is used with survival mode enabled.

- To define upper limits of survival cases, the 100 year return wave contour plot for the SETS test side in Oregon, US is used. Multiple cases are defined on that 100 year return contour and wave cases in the basin are tuned to reproduce these sea states until limits of the wave maker/basin are reached.

3. Cork Test Facility

Lir National Ocean Test Facility

Environmental Research Institute,
Beaufort Building, University College Cork,
Ringaskiddy, Co. Cork, Ireland

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lir-notf@ucc.com, + 353 (0) 21 486 4300

LIR NATIONAL OCEAN TEST FACILITY

The experimental testing will be conducted in the National Ocean Test Facility, Ireland, LIR at Cork. The facility consists of state of the art wave tanks and electrical rigs that allow for scaled testing in a controlled environment. The LIR test infrastructure and in-house capabilities have been extended with newly built facilities which comprises 1) Wave Tank testing 2) Power Takeoff Test Rigs 3) Emulators and Microgrids and covers technical support by skilled affiliates and employees.

3.1 Wave Tanks

Multiple wave tanks for experimental research are located on a total space of 2600 square meter at the LIR facilities:

1) **Ocean Basin - 25m x 18m x 1m deep**
   Used for testing a variety of marine structures (wave energy convertors, floating wind platforms, coastal structures, oil & gas platforms). It has capacity for adding a 2.5m deep section and it can produce real and simulated sea states. The wave generation peaks at Hs = 0.16m, Tp = 1.4s and Hmax = 0.32m

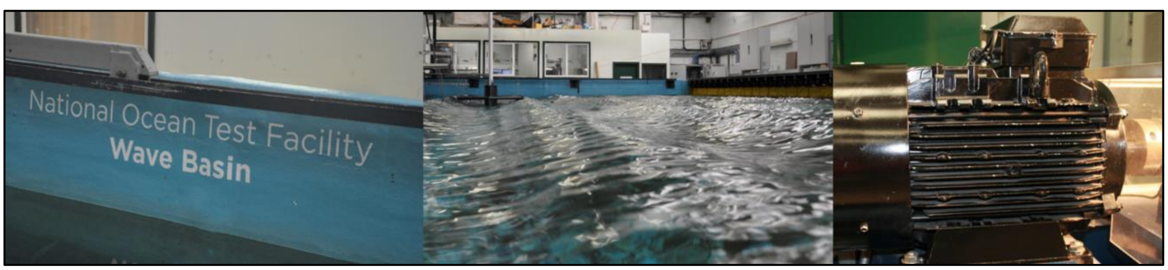


Figure 2: LIR Ocean Basin

2) **Deep Ocean Basin – 35m x 12m x 3m deep**
   It has a movable floor plate to allow the water depth to be adjusted, making it suitable for circa. 1/15 scale operational conditions and 1/50 scale survival waves. Equipped with 16 hinged force feedback paddles capable of a peak wave generation condition of Hs = 0.6m, Tp = 2.7s and Hmax = 1.1m

Figure 3: LIR Deep Ocean Basin

Figure 4: Wave Maker at the LIR Deep Ocean Basin

For the proposed scaled prototype tests the deep ocean wave basin at LIR will be used to test Calwave's scaled protoypes.

3) **Wave & Current Flume - 28m x 3m x 0.6 to 1.2 m deep**
   A multi-purpose facility with the capability of running separate and combined unidirectional wave and current tests. It has 8 hinged force feedback paddles with adjustable height positioning and three thrusters for generating current speeds of greater than 1m/s. The wave generation peaks at Hs = 0.16m, Tp = 1.5s and Hmax = 0.35m. It is fitted with a towing carriage that can operate at speeds up to 1.5m/s

4) **Wave Watch Flume - 15m x 0.75m x 1m deep**
A glass sided flume with a single wave flap for wave generation. Used to provide students with an introduction to tank testing as well as device concept development and stability testing of coastal structures.

3.2 Technical Support and Equipment

Data Acquisition

Each facility is equipped with one *Compact Rio* plus synchronized *EtherCAT* modules when required. A large number of inputs and outputs C-Series modules are available and suitable for most of the standard signals, analogue voltages (+/-10Vdc, 4-20mA, Wheatstone bridges, etc.) or digital signals (0 to 5, 10 or 20 Vdc for system status, encoders, etc.)

The data is acquired and stored in the *Compact Rio* and a real-time display on the control computer shows the relevant variables numerically and graphically.

CalWave seeks to use their own DAQ system. Nevertheless, additional LIR equipment or the LIR DAQ system might be used as a fall back or parallel solution.

Motion Capturing Capabilities

Qualisys or Coda motion measurement systems are available in all the test tanks. They are capable of monitoring, in real time, the x, y and z co-ordinates of markers placed on the physical model and the six-degree motion (including rotations) of a rigid body fitted with at least four markers. The motion data is acquired via proprietary software independent from the Compact Rio which acquires all other parameters. Both systems are synchronized with an electrical pulse.

CalWave highly anticipates using motion capturing during the experimental tests.

Electrical Workshop

Lir-NOTF is equipped with an electrical/instrumentation workshop with support staff available for model modifications that may be required prior to testing or connection to the facility equipment. The workshop includes wiring tools (wires, connectors and soldering), adjustable DC power sources, sink resistors and measurement equipment (multi-meters, oscilloscopes, etc.)

Mechanical Workshop

Lir-NOTF is equipped with a mechanical workshop with support staff available for model construction or modifications that may be required prior to testing. The workshop includes a lathe machine, milling machine, panel saw, horizontal band saw, drilling tools, stick welding and all the basic manual tools.

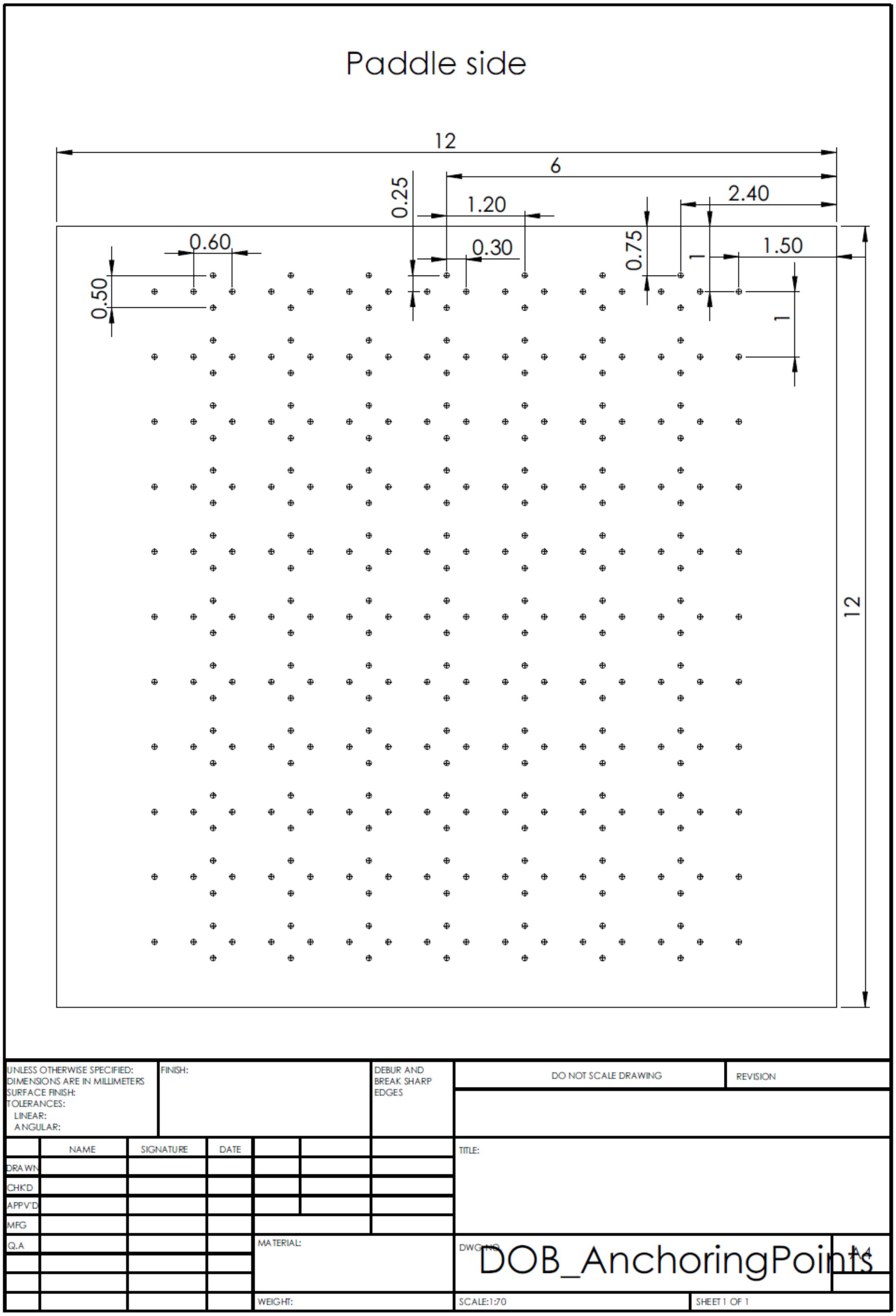


Figure 5: LiR Deep Ocean Basin - Tank Floor bolt pattern.

4. Scaled Model Description

4.1 Device Description and Orientation

The CalWave wave energy converter (WEC) device to be assessed in a scaled model is an offshore submerged pressure differential WEC for deep water operations developed by CalWave Power Technologies Inc. The device includes an absorber body oriented below the water surface for primary wave energy conversion through wave body interaction. As waves pass over the submerged absorber, a pressure differential is created above and underneath, exciting the absorber in multiple degrees of freedom (DOF). Energy is efficiently extracted using multiple independently controllable power take-off (PTO) units (Baseline configuration: Four PTO units). The device is positively buoyant and taut moored, reacting against the sea floor. A simplified rendering of the absorber body including the PTO/Mooring connection tethers can be seen in Figure 1Figure 6.

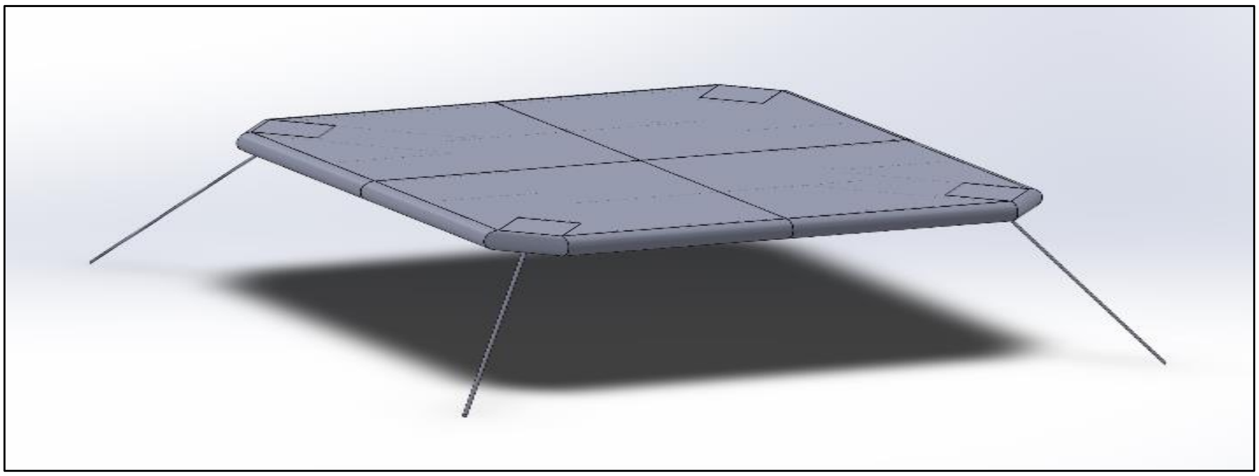


Figure 6: Simplified rendering of the absorber body and the PTO/Mooring Connection tethers

For efficient primary energy conversion, the absorber body is designed to horizontally split the pressure gradient underneath incident waves, creating a pressure differential between its top and bottom side. This pressure differential leads to alternating area loads across the absorber and ultimately to oscillating motion predominantly in the heave, surge, and pitch DOF considering 0 Degree incident waves.

During working/baseline setup, the device is orientated in such a way, that an incident wave with 0-degree angle heading would “see” one of the absorber sides of equal width, respectively length. Figure 7 shows a drawing of the device orientation and the PTO/Mooring connection label convention.

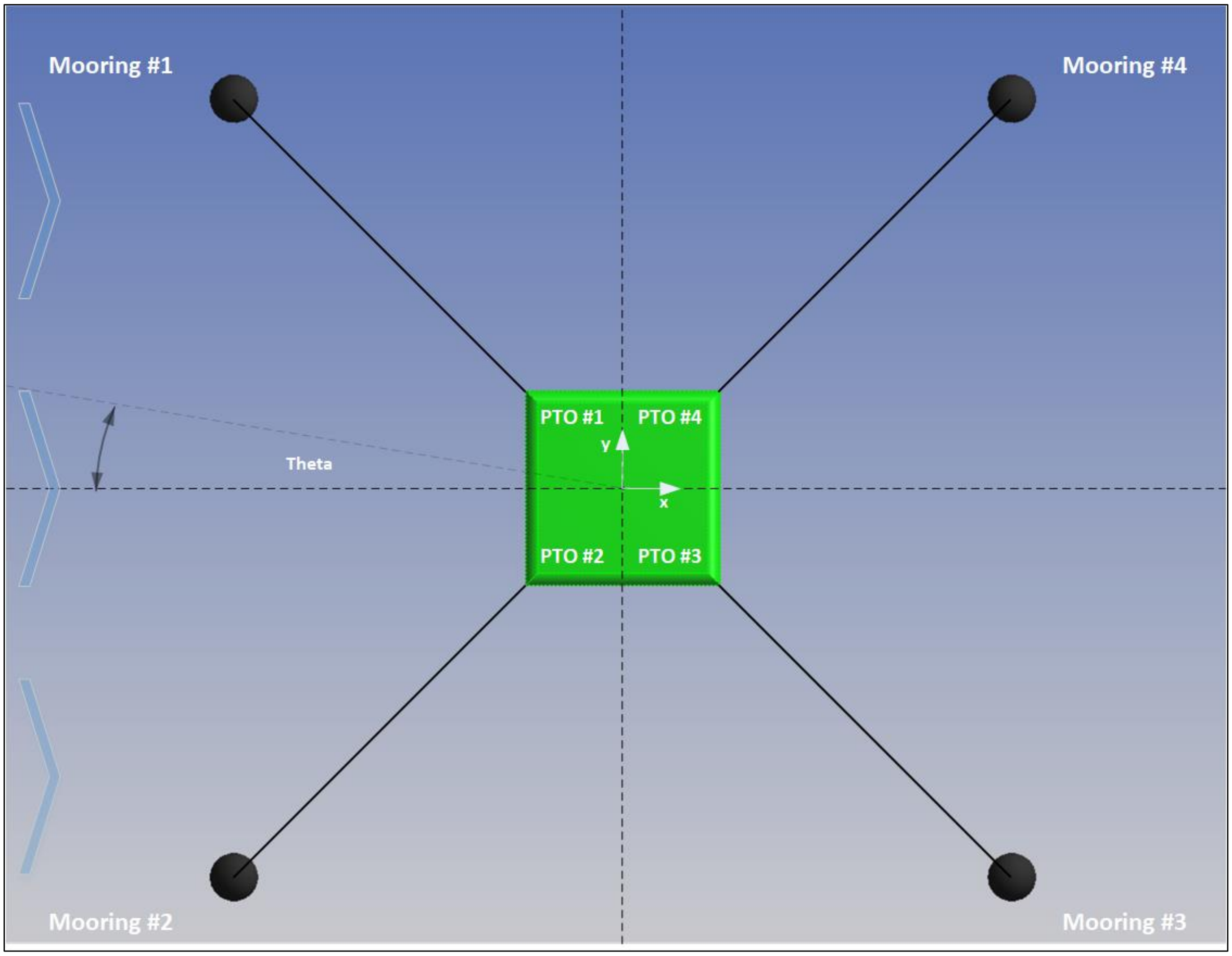


Figure 7: General device orientation and PTO / Mooring location labels. The Theta angle labels the incident wave angle.

4.2 Target Device Properties and Froude Scaling

Target device properties are derived from time domain simulation and other modeling aspects. Froude scaling is used to scale down relevant model parameters. Note, that due to size and weight restrictions the thickness of the absorber body, as well as the weight might slightly deviate in the prototype from ideal values in favor of matching highly relevant parameters (e.g. buoyancy).

Table 1: Targeted/Baseline Device Full Scale and Scaled Prototype Properties

Absorber Body							
Quantity	**Scaling**	**Scaling factor (1:20; 1:30)**	**Full scale values**	**1/20th values from Froude downscaling**	**1/30th values from Froude downscaling**	**Units**	**Notes**
Length (x)	s	0.05; 0.033	20	1	0.667	[m]	
Width (y)	s	0.05; 0.033	20	1	0.667	[m]	
Height* (z)	s	0.05; 0.033	1 – 1.5	0.05 – 0.075	0.033 – 0.05	[m]	Not subject to Froude scaling / deviation in Prototype

Weight*	s^3	1.25e-4; 3.7037E-05	158931.88	19.86	5.88	[kg]	Not subject to Froude scaling/ deviation in Prototype as AM dominates physical mass
Neutrally displaced water volume	s^3	1.25e-4; 3.7037E-05	158.93	0.019866	0.005886	[m^3]	
Target Absorber total displaced water volume	s^3	1.25e-4; 3.7037E-05	494.25	0.061781	0.018306	[m^3]	
Operating Depth	s	0.05; 0.033	2m – 12m	0.1m - 0.6m	0.0667m – 0.4m	[m]	

4.3 Absorber Description

For different testing objectives, a 1:20 and a 1:30 Froude scaled prototype were manufactured. The dimensions / specifications of the full-scale device which were used to derive correlating prototype specifications and dimensions were obtained from an device optimization in a parametric time domain simulation framework.

To maintain highest degree of modularity and possibility to test certain device parameters such as hydrostatic buoyancy/total displaced water, the absorber body was designed not as a single solid body, but as a layered body including one designated top layer, one or multiple middle layers, and one designated bottom part. The prototype top, respectively bottom part of the absorber are custom manufactured and made from a Styrofoam core with the desired dimensions and coated with carbon fiber and epoxy resin. The carbon fiber – epoxy coating significantly reinforces the foam and provides the required stiffness for all anticipated tank tests during this campaign. Figure 8 depicts the 1:20 scale absorber body in a side and top view and includes principle dimensions and labels. Figure 9 shows the equivalent figure with 1:30 scale prototype principle dimensions.

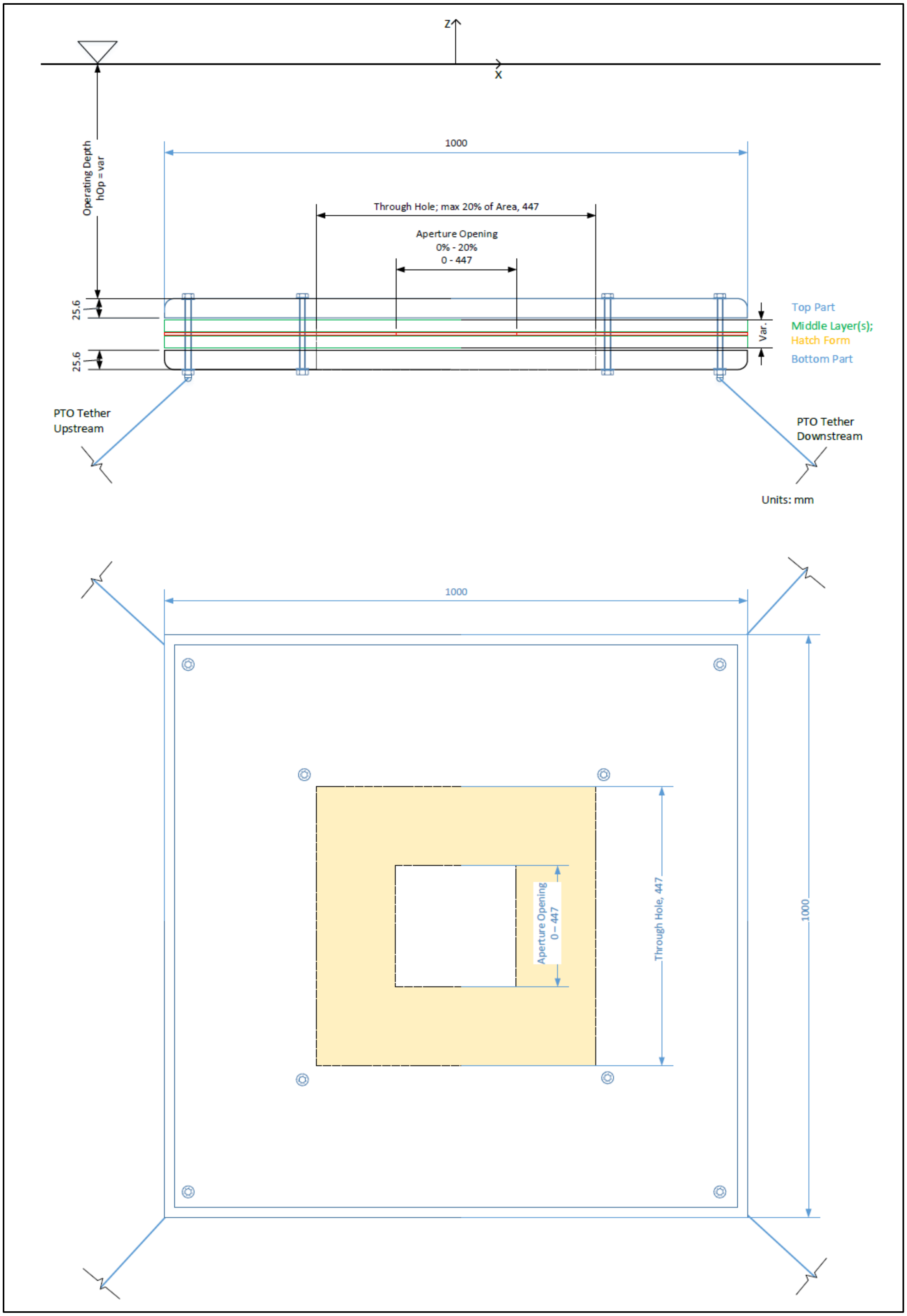


Figure 8: 1:20 Scale Absorber Side (x-z-Pane), and Top (x-y-Pane) View, Dimensions and Labeling

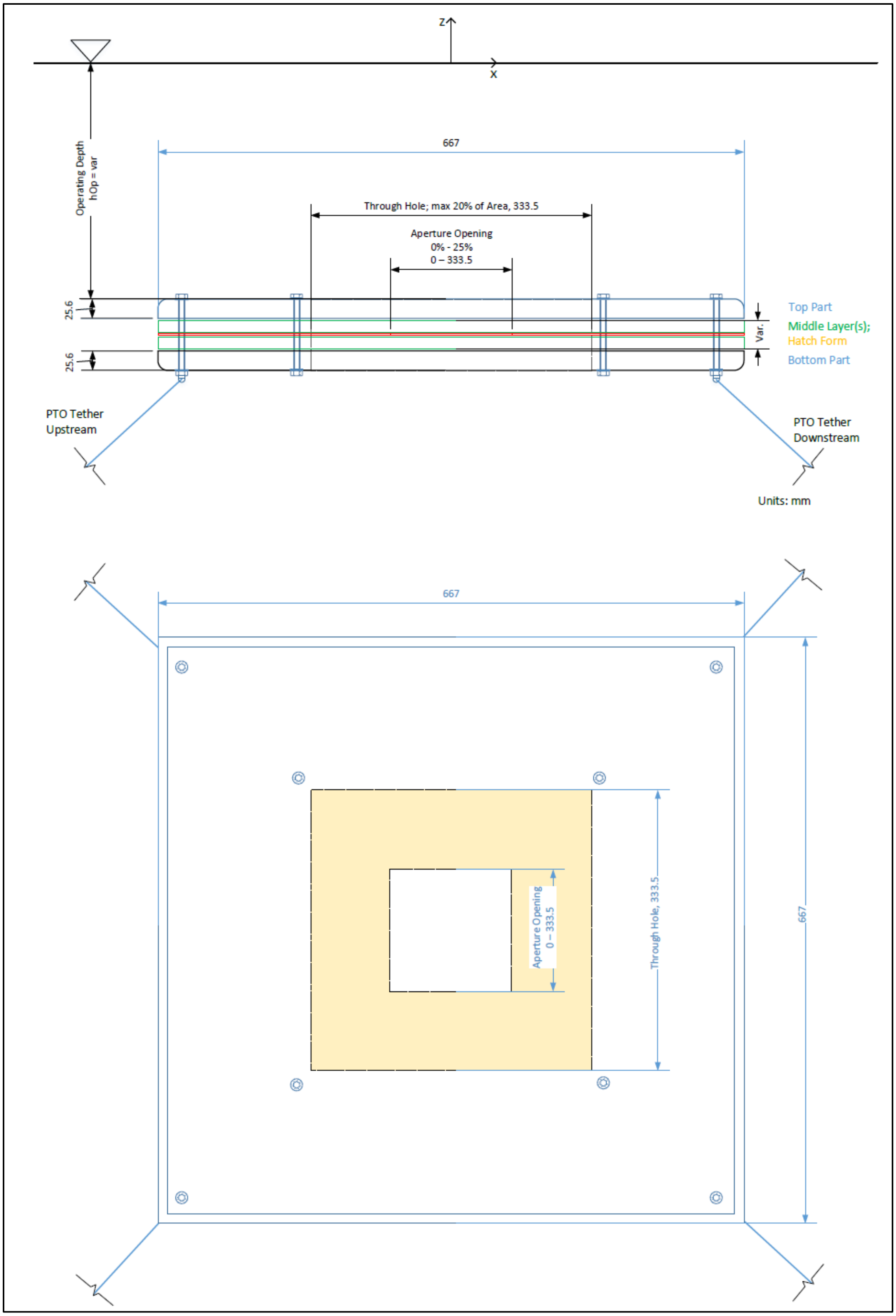


Figure 9: 1:30 Scale Absorber Side (x-z-Pane), and Top (x-y-Pane) View, Dimensions and Labeling

As the total device's hydrostatic buoyancy is an important parameter in terms of the WECs capability to efficiently absorb energy from waves, the amount and type (thickness) of middle layers can be changed to deviate from the baseline configuration. Table 2Table 2: 1:20 scale absorber body layers. Each individually manufactured layer is labeled with a unique part ID. provides an overview of manufactured 1:20 scale layers which can be used to effectively change the total absorber displaced water volume. Each manufactured layer is labeled with a unique part ID.

Table 2: 1:20 scale absorber body layers. Each individually manufactured layer is labeled with a unique part ID.

Uniq Part ID	Label	Part Side Length [m]	Thickness [m]	Thickness [in]	Weight [kg]	Max Hatch %	Hatch Side Length [m]
x20-01	Top/Bottom Part	1	0.0256	1	2.128	20%	0.447
x20-02	Top/Bottom Part	1	0.0256	1	2.038	20%	0.447
x20-03	Top/Bottom Part	1	0.0256	1	1.881	20%	0.447
x20-04	Top/Bottom Part	1	0.0256	1	1.727	20%	0.447
x20-05	Middle Layer Thin	1	0.0124	0.5	0.904	20%	0.447
x20-06	Middle Layer Thin	1	0.0124	0.5	1.01	20%	0.447
x20-07	Middle Layer Thick	1	0.0256	1	1.493	20%	0.447
x20-08	Middle Layer Thin	1	0.0124	0.5	0.931	20%	0.447
x20-09	Middle Layer Thin	1	0.0124	0.5	0.715	20%	0.447
x20-10	Middle Layer Thin	1	0.0124	0.5	0.77	20%	0.447

Table 3 provides an overview of manufactured 1:30 scale layers.

Table 3: 1:30 scale absorber body layers. Each individually manufactured layer is labeled with a uniq part ID.

Uniq ID	Label	Part Side Length [m]	Thickness [m]	Thickness [in]	Weight [kg]	Max Hatch %	Hatch Side Length [m]
x30-01	Top Part	0.66	0.0256	1	0.993	25%	0.165
x30-02	Bottom Part	0.66	0.0256	1	0.872	25%	0.165
x30-03	top/bottom	0.66	0.0256	1	0.817	25%	0.165
x30-04	top/bottom	0.66	0.0256	1	0.772	25%	0.165
x30-05	Middle Layer Thin	0.66	0.0126	0.5	0.528	25%	0.165
x30-06	Middle Layer Thick	0.66	0.0256	1	0.756	25%	0.165

x30-07	Middle Layer Thick	0.66	0.0256	1	0.734	25%	0.165
x30-08	Middle Layer Thick	0.66	0.0256	1	0.646	25%	0.165
x30-09	Middle Layer Thick	0.66	0.0256	1	0.503	25%	0.165
x30-10	Middle Layer Thick	0.66	0.0256	1	0.504	25%	0.165

An additional feature of the CalWave WEC is the capability for effective device/PTO load control and hydrodynamic tuning for power extraction using a variable hole opening in the middle of the absorber plate. Depending on the total open area of the opening and to experimentally assess the effect of different hatch openings multiple different multiple different hatch/aperture layers were manufactures. While the designated top and bottom as well as the regular middle layers were manufactured including a total hatch opening of 20% (1:20), respectively 25% (1:30 scale) of the single sided absorber area, the aperture layer can be mounted in between the middle layers. Thus, the middle layer effectively reduces the maximum opening percentage to the desired value.

Alternatively, for 0% opening two hatch layers can be mounted on top of the top and bottom layer to reduce the hydrodynamic effect of a through hole in the absorber body. Table 4 lists principle dimensions of the hatch layers correlating to the different hole openings for both 1:30 as well as 1:20 scale.

Table 4: Principle Dimensions of 1:20 Scale hatch layers correlating for different hatch opening percentages of the one sided absorber area.

1:20 Scale Hatches	**Hatch Opening %**					
Opening	**0%**	**5%**	**10%**	**15%**	**20%**	**25%**
Hatch Area m^2	0	0.05	0.1	0.15	0.2	NAN
Hatch Side (cm)	0	22.361	31.623	38.730	44.721	NAN
Inner Hatch Side (in)	0	8.80	12.45	15.25	17.61	NAN
1:30 Scale Hatches	**Hatch Opening %**					
Opening	**0%**	**5%**	**10%**	**15%**	**20%**	**25%**
Area m^2	0	0.05	0.1	0.15	0.2	0.25
Hatch Side (cm)	0	22.361	31.623	38.730	44.721	50.000
Hatch Side (in)	0	8.80	12.45	15.25	17.61	19.69

Once a configuration of middle layers and hatch layer is chosen, the layers are mounted together using 8 fiberglass threaded rods running through all layers of the absorber body. For rigidity four rods are used at the outer corners of the layers; additional four rods are used at the inner corners of the through hole. Hex nuts and washers are used to tighten all layers together. The connection to the PTO/Mooring tether is made using an eyebolt of sufficient strength and carabiners for quick connect/disconnect connected to the hex nuts at the bottom layer of the absorber (see Figure 8, respectively Figure 9).

Figure 10 top shows the manufactured 1:30 absorber top, bottom and middle layers as well as one configuration (bottom) including one middle layer and a hatch layer of 0% opening. Figure 11 shows a 1:20 scale absorber configuration with two middle layers.

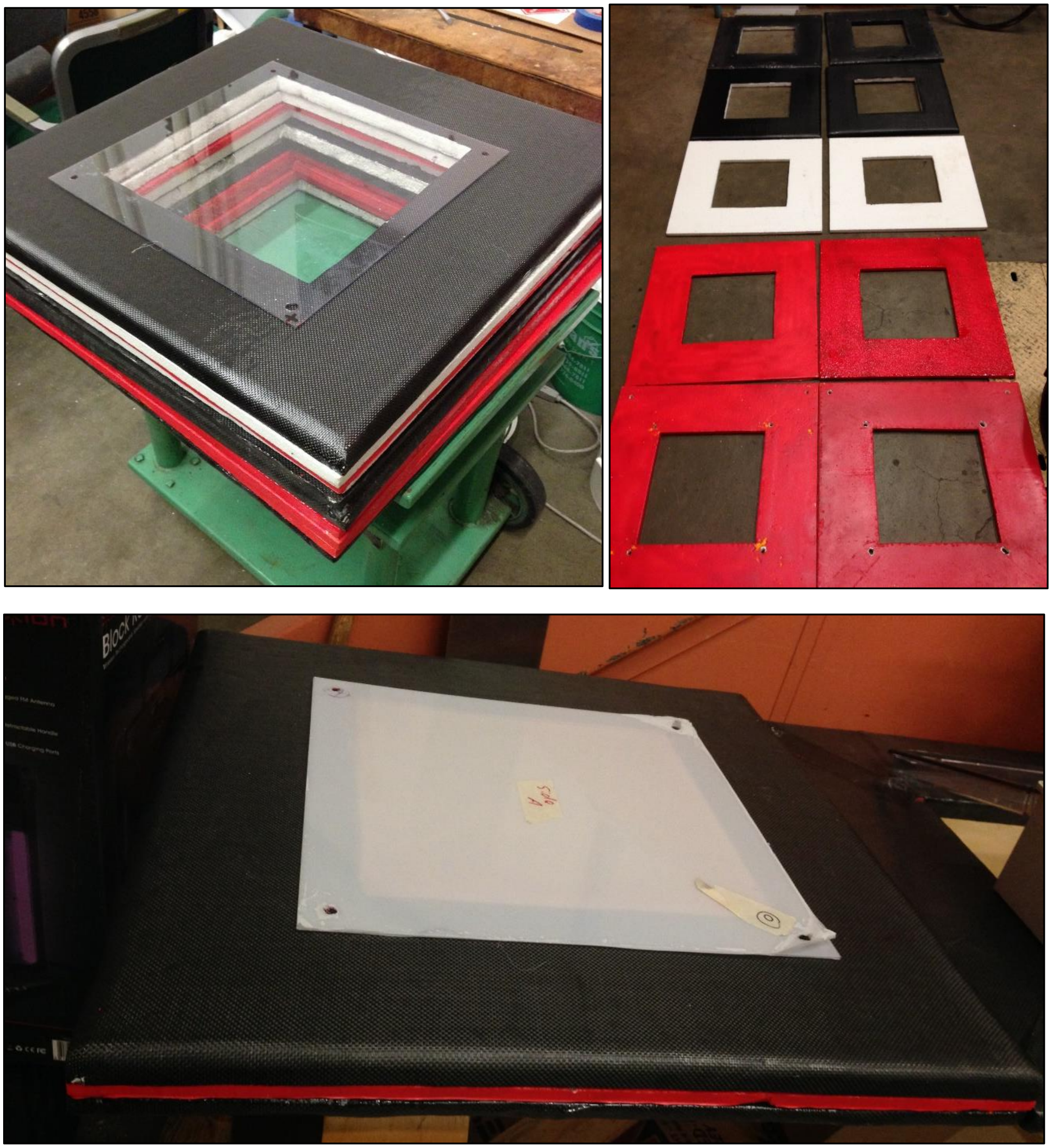


Figure 10: Top: All manufactured top, bottom and middle layers of the 1:30 scale prototype. Bottom: Absorber configuration including one middle layer and a 0% opening hatch layer.

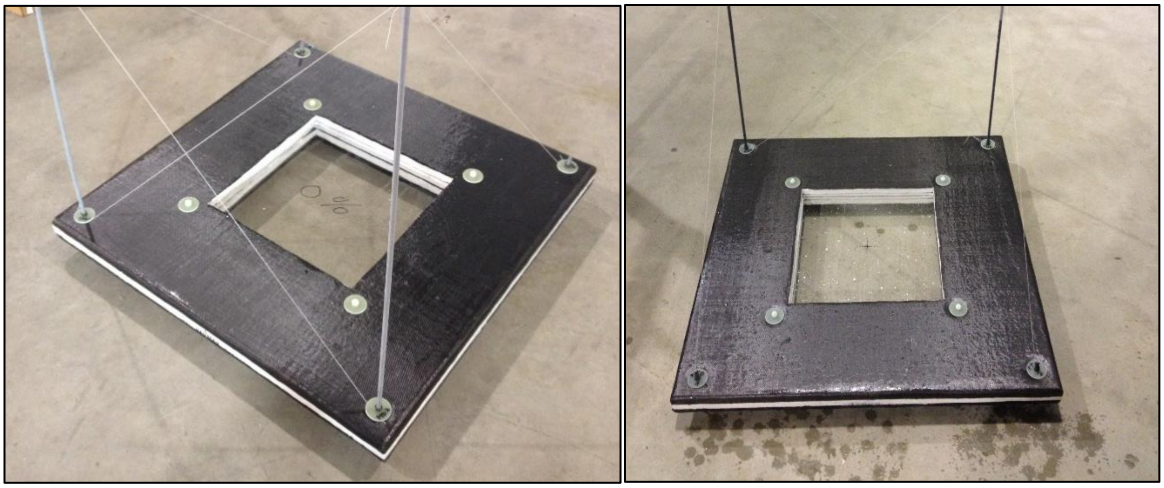


Figure 11: 1:20 scale device assembly including two middle layers. The poles sticking out of the absorber are used to mount reference markers for over water motion tracking.

The following baseline configuration of middle, top, bottom, as well as hatch layer will be used in the experiments. The combination are used as baseline configuration to achieve closest match with the target device properties. A comparison with the Froude scaled target properties, as well as an overview of the configuration is shown in Table 5:

Table 5: Scaled Absorber baseline configurations and properties

Scaled Absorber Configurations								
Configurations	**Scale**	**Label**	**Order (Top 2 Bot)**	**Thickness [m]**	**Weight [kg]**	**Volume [m^3]**	**Buoyancy [N]**	**Pretension p. PTO [N]**
#X20-A	1:20	**Top**	*X20-04*	0.0256	1.727	0.02048	200.9088	-
Standard 1:20		**Middle**	*x20-05*	0.0124	0.904	0.00992	97.3152	-
Scale Model		**Hatch**	*0 Percent Hatch*	0.0025	0.7	0.002	19.62	-
		Middle	*x20-10*	0.0124	0.77	0.00992	97.3152	-
		Bottom	*x20-03*	0.0256	1.881	0.02048	200.9088	-
		Mounting hardware	-	-	0.6	-		-
Calculated / Estimated Values				**Total Expected Thickness [m]**	**Total Body Weight [kg]**	**Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Pretension per PTO [N]**
				0.0785	6.582	0.0628	616.068	154.017
Measured Values				**Av. Measured Total Thickness [m]**	**Measured Total Weight [kg]**	**Measured Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Pretension per PTO [N]**
				0.0772	7.1	-	856	214

Configurations	Scale	Label	Order (Top 2 Bot)	Thickness [m]	Weight [kg]	Volume [m^3]	Buoyancy [N]	Pretension p. PTO [N]
#X20-P	1:20	**Top**	X20-02	0.0256	2.038	0.02048	200.9088	-
(including Pressure Sensors)		**Middle**	X20-08	0.0124	0.931	0.00992	97.3152	-
(with hatch layer)		**Hatch**	0 Percent Hatch	0.0025	0.7	0.0025	24.525	-
		Middle	X20-09	0.0124	0.715	0.00992	97.3152	-
		Bottom	X20-01	0.0256	2.128	0.02048	200.9088	-
		Mouning Hardware	.	.	0.6	-	0	-
Calculated / Estimated Values				**Total Expected Thickness [m]**	**Total Body Weight [kg]**	**Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Pretension per PTO unit [N]**
				0.0785	6.512	0.0633	620.973	155.2433
Measured Values				**Av. Measured Total Thickness [m]**	**Measured Total Weight [kg]**	**Measured Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Measured Pretension per PTO unit [N]**
				0.079	8.12	-	602.32	213.55

Configurations	Scale	Label	Order (Top 2 Bot)	Thickness [m]	Weight [kg]	Volume [m^3]	Buoyancy [N]	Pretension p. PTO [N]
#X20-PS	1:20	**Top**	X20-02	0.0256	2.038	0.02048	200.9088	-
(Pressure Sensors included)		**Middle**	X20-08	0.0124	0.931	0.00992	97.3152	-
(No Hatch layer)		**Hatch**	No Hatch	0	0	0	0	-
		Middle	X20-09	0.0124	0.715	0.00992	97.3152	-
		Bottom	X20-01	0.0256	2.128	0.02048	200.9088	-
		Pressure Sensors	-	-	0.9	-		-
		Mounting Hardware	-	-	1	-		-
Calculated / Estimated Values				**Total Expected Thickness [m]**	**Total Body Weight [kg]**	**Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Pretension per PTO unit [N]**
				0.076	7.712	0.0608	596.448	149.112
Measured Values				**Av. Measured Total Thickness [m]**	**Measured Total Weight [kg]**	**Measured Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Measured Pretension per PTO unit [N]**
				0.0732	8.02	-	615.23	201.22

Configurations	Scale	Label	Order (Top 2 Bot)	Thickness [m]	Weight [kg]	Volume [m^3]	Buoyancy [N]	Pretension p. PTO [N]
#X30-S	1:20	**Top**	x30-01	0.0256	0.993	0.008364		-
Survival 1:30 scale model		**Middle**	No middle layer	0	0	0	0	-
		Hatch	No hatch layer	0	0		0	-
		Middle	No middle layer	0	0	0	0	-
		Bottom	x30-02	0.0256	0.872	0.008364		-
		Mounting hardware	-	-	0.3	-	-	-
Calculated / Estimated Values				**Total Expected Thickness [m]**	**Total Body Weight [kg]**	**Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Pretension per PTO unit [N]**
				0.0512	2.165	0.0167	164.02	41.007
Measured Values				**Av. Measured Total Thickness [m]**	**Measured Total Weight [kg]**	**Measured Total Absorber Volume [m^3]**	**Total Absorber Buoyancy [N]**	**Measured Pretension per PTO unit [N]**
				0.05	2.2	-	144.2	55.32

4.2 Power Takeoff Description

Following the WEC concept's full-scale power takeoff, electric Power Takeoff units were build which can be used for both 1:30 as well as 1:20 scale testing. An electric power takeoff has the advantage to be easily tunable in terms of restoring force coefficient k, as well as damping coefficient b without the need of changing the hardware of the setup.

A scheme of a possible PTO setup at the Cork DOB can be seen in Figure 12 (only one PTO included in the scheme). The location of the mooring pulley used to guide the PTO tether to the PTO assembly on the side of the tank effectively sets the PTO angle which is a device parameter.

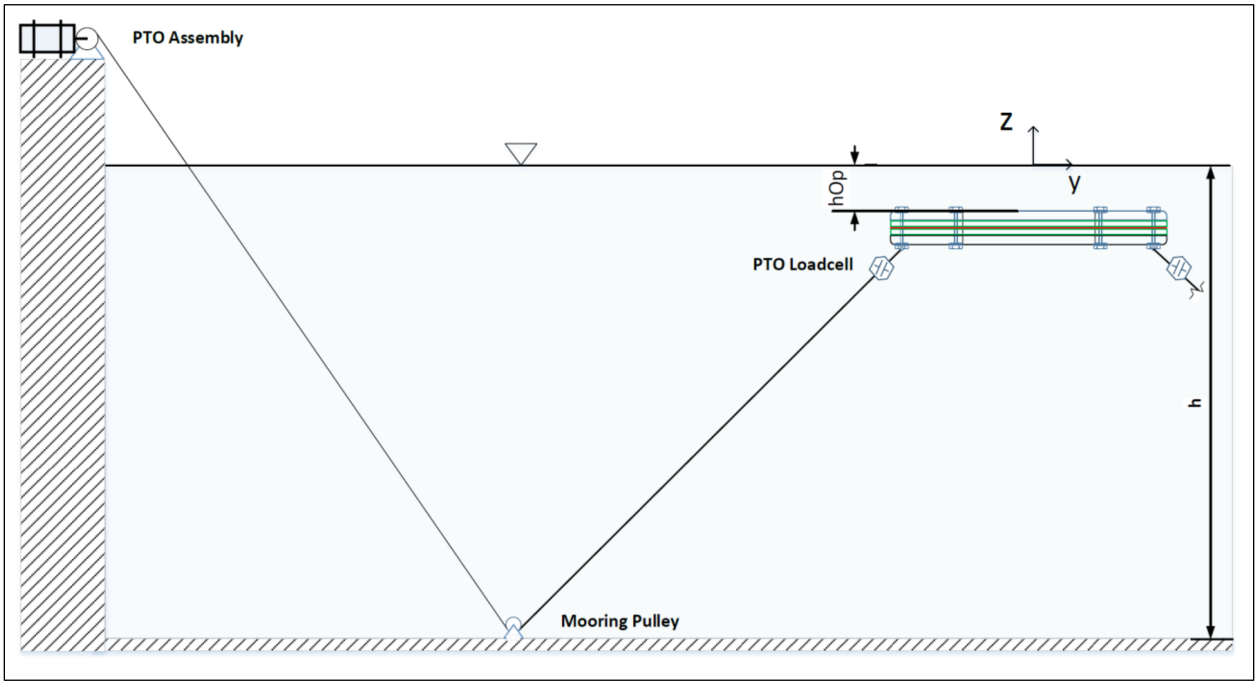


Figure 12: Schematic PTO setup for scaled testing. The PTO assembly is connected to the PTO loadcell and through the mooring pulley to the bottom side of the absorber body. The location of the mooring pulley effectively sets the "PTO angle" which is a device parameter.

Due to weight and size restrictions in the scaled prototype body, it was decided to remove the PTO hardware from the device and place it on the wave tank side/bridge.

One PTO unit consists of a 4-pole, NEMA-34 frame BLDC electric motor/generator (ElectroCraft RP34-217V24-100-D; see Appendix) connected to a winch shaft around which de PTO tether wraps in a single layer. A planetary gearbox (SureGear PGCN34-1050; see Appendix) with a 1:10 gear ratio is mounted in between the winch shaft and the motor shaft effectively changing the speed to force ratio in a favorable direction. The motor shaft is coupled to the planetary gearbox, so that the low-speed side of the gearbox shares the same speed and torque as the winch shaft. The taut mooring/PTO tether connected to the bottom of the absorber body is guided through a pulley sitting on the basin floor back to the PTO location. It then wraps (in a single layer) around the

PTO drum. Motor, Gearbox, and PTO shaft, as well as fairlead to guide the PTO tether towards the drum are rigidly connected in a frame. Table 2 lists the basic motor specifications.

Table 6: Motor/Generator High Level Specifications

Model Number	**ElectroCraft RP34-217V24-100-D**
Design Voltage	24 VDC
Number of Poles	4
Peak Torque	536 Ncm
Stall Torque	217 Ncm
Voltage Constant	7.2 V/kRPM
Torque Constant	6.85 Ncm/A
Winding Resistance	0.1 Ohms
Electrical Constant	5.5 msec
Mechanical Constant	4.3 msec
Rotor Inertia	1822 g-cm2
Frame Size	NEMA 34

Figure 13 shows a picture of the actual PTO assembly including the assembly frame (1), guide (2), drum (3) & shaft collars (4), coupling & spider (5), 1:10 ratio planetary gearbox (6) and motor assembly (7). A total of 5 units were manufactured with 1 entire assembly as a backup.

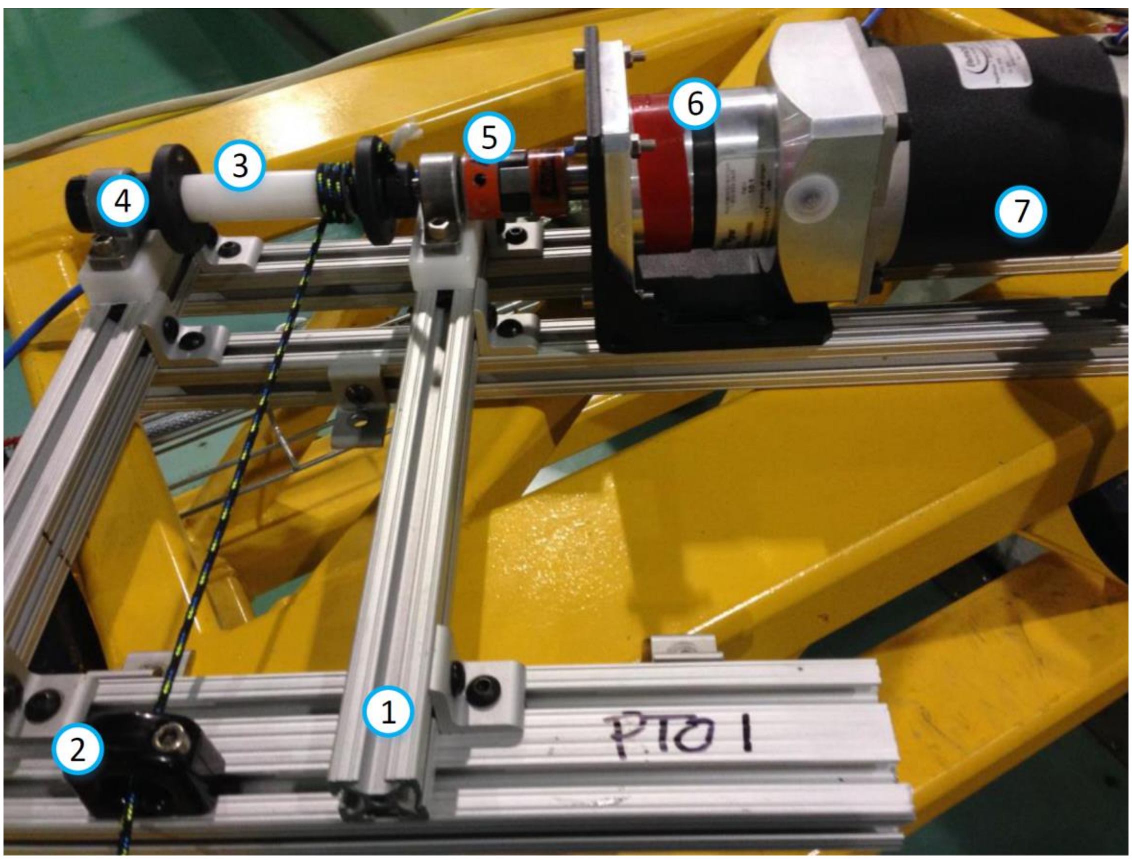


Figure 13: PTO assembly including frame (1), guide (2), drum (3) & shaft collars (4), coupling & spider (5), 1:10 ratio planetary gearbox (6) and motor assembly (7).

Additional PTO dimensions and parameters are listed in Table 7.

Table 7: Additional PTO assembly dimensions and parameter.

Parameter	Value	Unit
Shaft Diameter	0.01905	m
Rope Diameter	0.0022	m
Gearbox Ratio	1:10	-
Max Count rate	200	kHz
Resolution	1000	counts/rev
Max rev per sec	0.2	rev/sec
Max rev per min that can be resolved on the motor	12000	rpm
Max rev per min that can be resolved on the winch shaft with X4 Counting	1200	rpm
Max rev per min that can be resolved with cRIO counting	300	rpm

4.3 Froude Scaling and Comparison

The following tables deliver an overview of the weight, thickness, and buoyancy/volume comparison between the full-scale target parameter, the 1:20 scaled theoretical values, and the actual 1:20 scale prototype values.

Table 8: Full Scale, 1:20 Froude Scale, and 1:20 prototype weight, thickness, and buoyancy/volume comparison of the baseline configuration #X20-A.

Configurations		**Scale**	
#X20-A	1:20	Full Scale Theory	1:20 Theory
Thickness [m]	0.08	1.25	0.0625
Error Thickness [%]	0	0	-19%
Weight [kg]*	7.10	92697	11.59
Error Weight [%]	0	0	63%*
Volume [m^3]	0.06	494	0.06
Error Volume [%]	0	0	0.03%
Buoyancy [N]	605.87	4848601	606.08
Error Buoyancy [%]	0	0	0.03%

*Note, that the physical weight of the absorber body is an order of magnitude smaller than the added mass of the submerged absorber. Thus, deviation from the Full Scale theoretical absorber weight does not have a significant effect on the hydrodynamics/kinematics of the device!

Table 9: Full Scale, 1:20 Froude Scale, and 1:20 prototype weight, thickness, and buoyancy/volume comparison of the pressure sensor configuration #X20-P

Configurations	Scale		
#X20-P	1:20	Full Scale Theory	1:20 Theory
Thickness [m]	0.08	1.25	0.0625
Error Thickness [%]	0	0	-20%
Weight [kg]	8.712	92697	11.59
Error Weight* [%]	0	0	33%*
Volume [m^3]	0.06	494	0.06
Error Volume [%]	0	0	-1.62%
Buoyancy [N]	616.07	4848601	606.08
Error Buoyancy [%]	0	0	-1.62%

*Note, that the physical weight of the absorber body is an order of magnitude smaller than the added mass of the submerged absorber. Thus, deviation from the Full Scale theoretical absorber weight does not have a significant effect on the hydrodynamics/kinematics of the device!

Table 10: Full Scale, 1:30 Froude Scale, and 1:30 prototype weight, thickness, and buoyancy/volume comparison of the survival test device.

Configurations	Scale		
#X30-S	1:30	Full Scale Theory	1:20 Theory
Thickness [m]	0.05	1.25	0.0417
Error Thickness [%]	0	0	-17%
Weight [kg]	2.2	92697	3.43
Error Weight [%]	0	0	56%*
Volume [m^3]	0.04	494	0.02
Error Volume [%]*	0	0	-51.19%
Buoyancy [N]	367.88	4848601	179.58
Error Buoyancy [%]	0	0	-51.19%

*Note, that the physical weight of the absorber body is an order of magnitude smaller than the added mass of the submerged absorber. Thus, deviation from the Full Scale theoretical absorber weight does not have a significant effect on the hydrodynamics/kinematics of the device!

5. PTO Control Strategy

The prototype PTO units are designed to obtain the largest degree of flexibility in setting PTO parameter, as well as to be able to execute any kind of desired force tracking. To achieve this, an entire electric prototype PTO scheme was chosen. The electric PTO can effectively be used to achieve any kind of PTO behavior and most important for this testing campaign, allows to set any restoring force coefficient k and damping coefficient c with a very high precision. The settings can be changed “on the fly” and no hardware changes are needed. In fact, any kind of PTO behavior based on the feedback measurements, PTO/Tether force, PTO velocity and displacement, can be implemented. Additionally, the PTO can be controlled in such a way, that the device can be submerged to a specific operating depth precisely.

A scheme of the force feedback closed PTO control loop is shown in Figure 14, exemplary shown for a linear spring-damper PTO scheme with an additional F0 offset which respresents the necessary pre-tension of the PTO unit due to the positively buoyant absorber body.

As shown, the PTO control includes a surveilance, if the PTO/Tether tension reaches a certain minimum line tension, respectively a maximum line tension, representative of a maximum generator torque. If one of these max/min tension limits is reached, the PTO control effectively ensures that the tension does not drop below / shoot above the specified value by increasing/decreasing the PTO velocity. This feature is essential to ensure that the PTO tethers never go slack and is envisioned to be implemented in a similar way in a larger scale PTO unit.

For system identification tests it was desired to feed the PTO units with a pink noise signal which was achieved by cutting open the closed loop and feeding a force set point signal representing pink noise excitation.

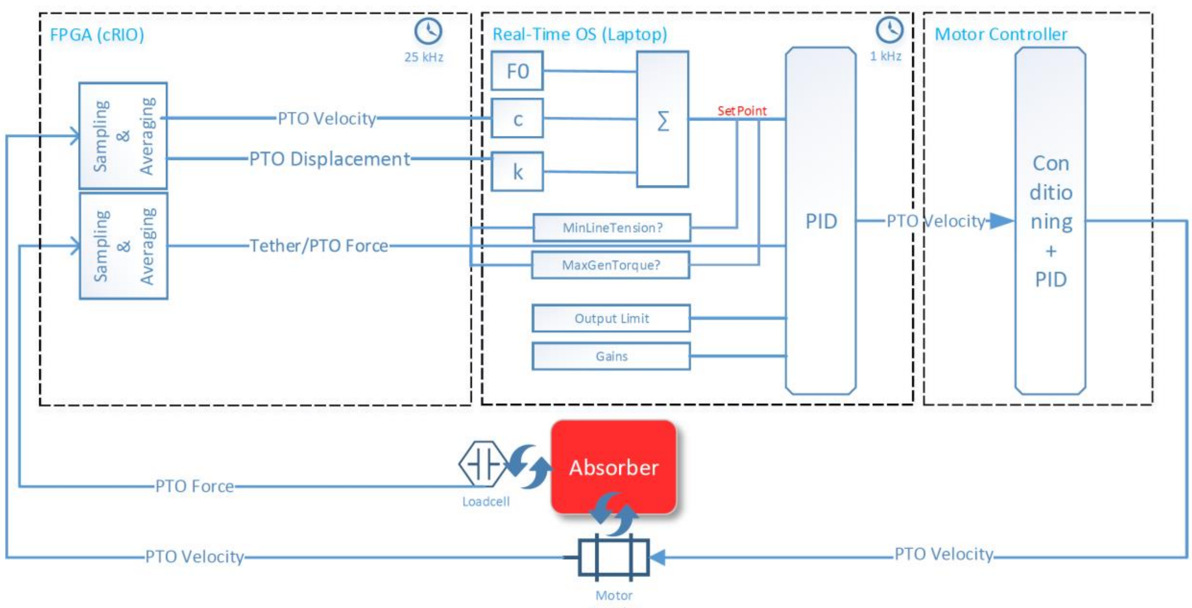


Figure 14: Simple force feedback control of the motor used for tracking any desired set point signal (here, simple linear spring-damper model).

The PID controller in the closed PTO control loop as well as the PID controller inside the motor controller were tuned previous to the experiments. However, potential re-tuning of the units/control once the prototype is installed in the tank is possible/might be required to achieve a quick and stable response of the PTO units.

The achieved force set point tracking capabilities shows an overall very good behavior. For a random irregular excitation (displacement) of the PTO the force set point and actual tracking signal is compared in Figure 15.

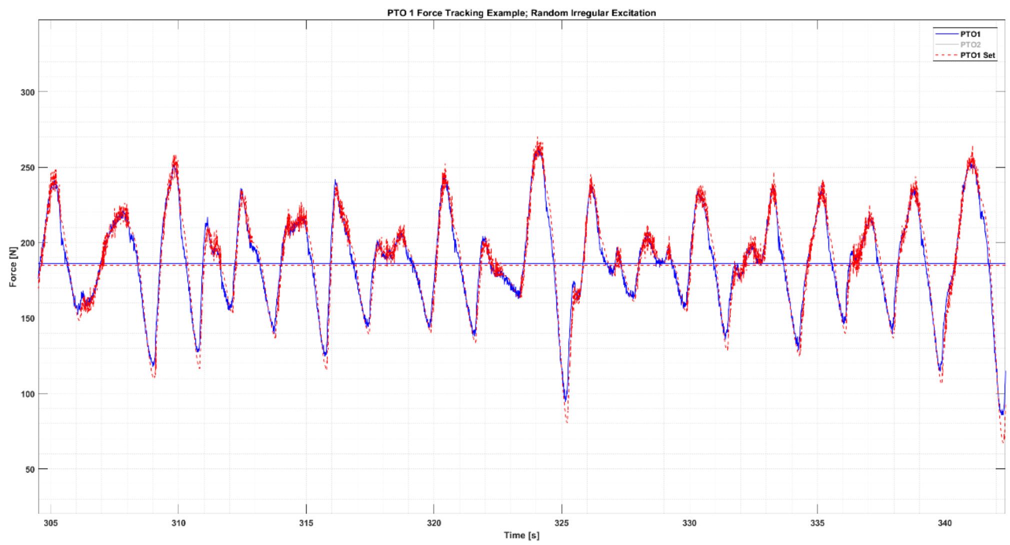


Figure 15: Exemplary Force set point and tracking signal showing a good set point tracking capability of the PTO units. Here, the PTO unit was randomly excited with an irregular signal with a common period and magnitude

A huge advantage of the setup is, that due to the location of the PTO/Tether loadcells directly at the swivel on the absorber body, the closed loop control acounts for any kind of friction in the system. That being said, friction on the PTO winch, friction at the PTO tether pulleys mounted on the basin floor etc are compensated for, to strictly achieve the desired PTO behavior right at the PTO/Tether connection point on the absorber body.

Figure 16 shows the PTO damping force scattered over the PTO velocity measured for a random irregular excitation of the PTO unit. A specific constant damping coefficient (here, 1000 Ns/m) was chosen.

Although the plot show a slight hysteresis around the set point line , the fit of the average actual damping achieved with the PTO units is in very good agreement with the set damping coefficient.

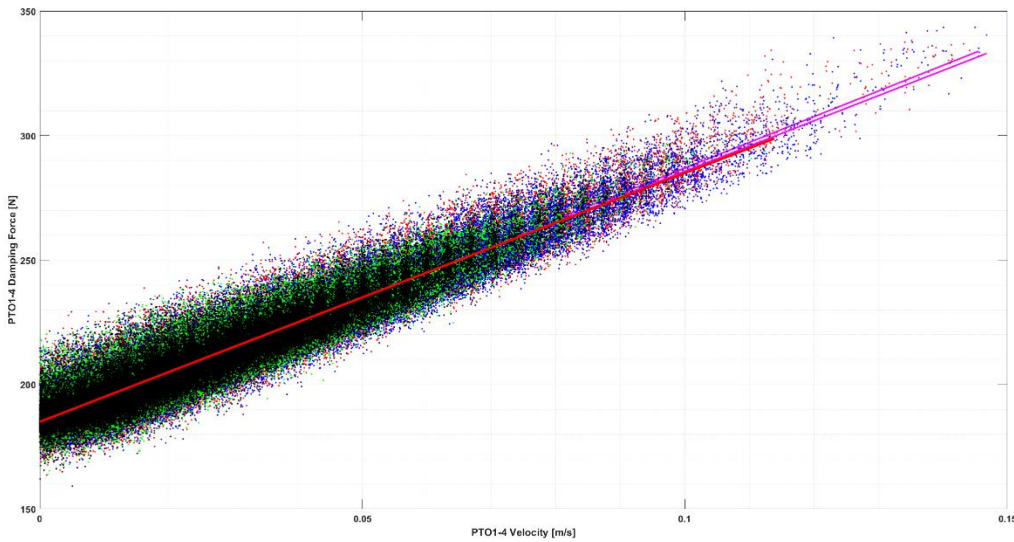


Figure 16: PTO damper force over PTO velocity (damping correlation) plotted for one PTO units which was randomly excited with an irregular pattern of common period and magnitude. The desired force-velocity correlation (damping coefficient of 1000 Ns/m) in red can be very well tracked with the PTO control/system.

6. Test Matrix

6.1 PTO Integration and Controllability

Task	To Do	Scale	Waves
#1	▪ Check motor drive direction setting, input voltage setting (220 V!), update drive firmware with tuning parameters.	1:20	No Waves
#2	▪ Check implementation of standard PTO control in LabView.	1:20	No Waves
#3	▪ For a static setup or for a single PTO setup without device connected to the PTO, the PTO is disturbed with a single push/pull. Although the PTO should not get excited in a resonant behavior and rather converge to its set equilibrium position, these tests act as a risk mitigation test and validate a stable PTO behavior. Potential tuning of software settings will accommodate these tests. This can be done by setting the damping to zero and check for behavior with only a restoring force coefficient.	1:20	No Waves
#4	▪ For a static setup, the behavior of the wrapping of the PTO tether around the PTO drum is tested. Although the line should wrap in a single layer any risk and threats from deviation of this is assessed before running test cases with waves running. This test should be done for all four PTOs. An initial wrap configuration with the device at the surface should have a minimum of ~3 wraps around the drum.	1:20	No Waves
#5	▪ Test PTO behavior and stability for a static WEC setup in the basin. The capability of the PTO to winch mooring/PTO line in and out, to submerge the absorber body and bring and holt it at its static equilibrium position and to effectively change the operating depth hOp is tested. QUALISYS Motion Tracking should be tested at this point	1:20	No Waves

#6	▪ For a static setup with pretension in the mooring/PTO tether lines (entirely submerged absorber body) the behavior in case of a power loss/PTO software failure is tested to minimize risks/threads of malfunctions during test cases with waves running. The equivalent test is to disabeling the motors using the Analog Output Module.	1:20	No Waves
#7	▪ For a static setup or a single PTO setup without the device connected to the PTO the PTO characteristic values such as damping or restoring force coefficient are changed on-line. Accuracy in setting these device parameters should be evaluated and response of the PTO closed control loop assessed for stability and response accuracy.	1:20	No Waves
#8	▪ For a static setup or a single PTO setup without the device connected to the PTO the PTO function of maintaining a minimum line tension is tested. For this the minimum line tension is set as a value below the force set point.	1:20	No Waves

6.2 Basic Working Principle Validation

Task	To Do	Scale	Waves
#1	▪ For hydrostatic tests and validation of total device buoyancy, respectively pretension in mooring tethers the device in a specified configuration is submerged and tether forces are measured. The operating depth is changed using all four PTO units. Balancing of the tether forces and correction of the absorber level is tested. These tests verify that a specific initial equilibrium setup can be obtained for each wave case.	1:20	No Waves
#2	▪ For a full setup of the absorber body connected to all PTO units the device stability is checked by exciting the absorber body (e.g. push or pull) while no waves are running.	1:20	No Waves
#3	▪ Basic working principles of the combined PTO/device setup is tested using small monochromatic wave excitation with small wave heights and mild periods. PTO settings are chosen to be in a mean range of damping / restoring force coefficients. General device behavior is checked and it is ensured that all PTO units work in the same way; the mooring pulleys behave in the desired way and no obvious threats or risks are identified.	1:20	Mono-chromatic Waves

6.3 System Identification Tests

Task	To Do	Scale	Waves
#1	▪ 1 DOF (Heave Only) symmetric Pink signal excitation of all four PTO units. SiSo experiment for intrinsic impedance in heave. Experiments will be done for two different PTO gains to reveal system nonlinearities. ▪ 3 x 5 min repeat time of pink noise excitation signal ▪ PTO tether Force feedback controlled	1:20	No Waves
#2	▪ 1 DOF (Heave Only) symmetric pink signal excitation of all four PTO units; simultaneous pink wave excitation. MiSo experiment for intrinsic impedance and lock-out excitation tests. ▪ 3 x 5 min repeat time of pink noise excitation signal (for both, wave and pto excitation) ▪ Repeat time of wave and PTO noise signal must be synchronized ▪ PTO tether Force feedback controlled	1:20	Pink Wave Excitation Signal
#3	▪ 3 DOF (Heave, Pitch, Surge) pink signal excitation of all four PTO units; ▪ Front two PTO units excited differently than back two PTO units ▪ MiMo experiment for intrinsic impedance ▪ 3 x 5 min repeat time of pink noise excitation signal ▪ Two different PTO gains ▪ Two different submergence depths ▪ PTO tether Force feedback controlled; Alternatively, PTO velocity feedback controlled	1:20	No Waves
#4	▪ 3 DOF (Heave, Pitch, Surge) pink signal excitation for PTO units; simultaneous wave excitation with pink noise ▪ Front two PTO units excited differently than back two PTO units ▪ MiMo experiment for intrinsic impedance and lock-out wave excitation tests ▪ 3 x 5 min repeat time of pink noise excitation signal (for both, wave and PTO excitation) ▪ Repeat time of wave and PTO noise signal must be synchronized ▪ Two different PTO & wave excitation gains ▪ Two different submergence depths ▪ PTO tether Force feedback controlled; Alternatively, PTO velocity feedback controlled	1:20	Pink Wave Excitation Signal

6.5 Performance Evaluation

For first estimates of the devices performance in capturing power from irregular wave, it is envisioned to assess the device behavior in at least six irregular wave cases representing the most occurring climates along the US west cost. Moreover, in terms of assessing the device in the common “ACE” metric used in the US Wave Energy prize, the device’s performance will be evaluated in the six irregular wave cases known as IWS1 – IWS6. However, most of the assessed wave cases are run with 0 Degree wave heading. The largest deviation from the initially used IWS cases in the Wave Energy Prize is found for IWS Case #3, which was run at an incident wave angle of -70°. Nevertheless, this wave case only marginally contributes to the most common US west coast climates.

Next to the common IWS cases, additional custom wave cases (CWS) are run. These additional wave cases are chosen in such a way, which allows a more precise interpolation of performance in the joint distribution diagrams (JPDs) of specifically Hawaii, WETS as well as Oregon, SETS. The “bulls-eye” of occurrence for these locations are thus covered via experimental assessment, allowing for a more precise assessment of performance evaluation during post-processing.

All irregular wave states will be run for a minimum of 2 minutes ramp up time to allow for reflection of the waves to converge/for the waves in the basin to converge to the desired sea states + 14 minutes evaluation period.

Task	To Do	Scale	Waves
#1	▪ IWS 1 – IWS 6 cases are run with the previous determined device setting (PTO damping, restoring force coefficient, submergence depth) ▪ PTO parameter for most important cases (IWS1, IWS2, IWS4) and operating depth are tuned to check for optimal power absorption if time allows	1:20	IWS1 – IWS 6
#2	▪ Most important CWS Case #1 (WETS) and CWS Case #3 (SETS) are run with previous determined device settings (PTO damping, restoring force coefficient, submergence depth) ▪ PTO parameters are slightly tuned to check for optimal power absorption if time allows	1:20	CWS1 & CWS3
#3	▪ If time remains the remaining CWS Cases #2 (WETS2) and #4 (SETS2) are run with previous determined device settings	1:20	CWS2 & CWS4

6.6 WEC Survivability Testing

The survivability of the device including the unique load reduction mechanisms are subject to be tested for multiple extreme wave events. Next to extreme waves, the device's behavior is being tested during severe irregular sea, in which extreme wave events statistically occur with a somewhat high probability.

To quantify the effect of the load reduction mechanisms (aperture load reduction), severe sea cases might be run with both, disengaged as well as fully engaged (fully open aperture) mechanism. To protect the prototype from breaking, this is now the case for extreme wave events.

Task	To Do	Scale	Waves
#1	▪ Severe sea cases (IWS 3 and IWS5 5) are run with no safety mechanisms applied (aperture fully closed) and with safety mechanism fully applied (aperture fully open). ▪ Operating depth is kept constant at intermediate depth and PTO settings are chosed to detune the device from the waves (overdamped and off resonance restoring force coefficient)	1:30	IWS 3; IWS 5;
#2	▪ The 1:30 scaled device is tested in the most extreme irregular sea state that can be safely generated in the LiR Deep ocean basin. Device's safety features are fully engaged (fully open aperture). PTO units are set to detune the device from incident waves. ▪ Target wave Hs; Tp parameters are taken from the peak of the 100 year return contour for SETS. ▪ Scaled peak wave heights of up to 25 meters should occur during these tests. ▪ If device and PTO loads are sufficiently low for the most sheltered configuration of the device, the operating depth is reduced to assess how far up in the water column the device can be placed while the other load reduction mechanism (aperture) is fully engaged.	1:30	Ex 3

7. Wave Cases & Calibration

To facilitate a realistic scaled wave environment for the various test objectives, different monochromatic, operating irregular waves states (IWS and CWS), as well as extreme waves were defined prior to testing. Additionally, for System Identification purposes pink noise signals were derived as a time signal for the wavemakers.

To avoid damage of the prototype/setup, for some of the extreme wave and pink noise cases during testing, the wavemaker gain is increased stepwise until the targeted magnitude of the spectrum is reached.

7.1 Monochromatic Waves (MWS)

Monochromatic waves were solely used for basic working principle verification. Additionally, the M2S80 case was used as a reoccurring baseline case to test the experimental setup in the same device configuration at the beginning of every testing day to ensure consistency of device settings and the physical setup.

Table 11: Monochromatic Waves for basic working principle validation. M2S80 was used as a daily reoccurring baseline case.

Monochromatic Waves - Ms80- Parameter Assessment - 1:20 Scale					
#	Monochromatic Waves	Period	wave height	inverse steepness	Incident Direction
	k	T	H	S^{-1}	θ
-	-	[s]	[m]	[--]	[deg]
1	M1S80	1.3	0.035	80	0
2	M2S80	1.7	0.05	80	0
3	M3S80	2.0	0.08	80	0
4	M4S80	2.3	0.11	80	0
5	M5S80	2.7	0.14	80	0
6	M6S80	3.0	0.17	80	0
7	M7S80	3.4	0.21	80	0
Monochromatic Waves - Ms40- Parameter Assessment					
#	Index	Period	wave height	inverse steepness	Incident Direction
	k	T	H	S^{-1}	θ
-		[s]	[m]	[--]	[deg]
8	M1s40	1.3	0.07	40	0
9	M2s40	1.7	0.11	40	0
10	M3s40	2.0	0.16	40	0
11	M4s40	2.3	0.21	40	0
12	M5s40	2.7	0.28	40	0

7.2 Irregular Wave cases (IWS) & Custom Irregular Wave Cases (CWS)

IWS cases were used for baseline performance assessment (ACE) of the device. The wave cases were directly taken from the Wave Energy Prize rules. However, for most of the cases 0 Degree wave heading was used. Additionally, custom irregular wave cases (CWS) were used for a better interpolation across specific JPD diagrams (e.g. Hawaii, or SETS).

TYPE	#	Tp [s]	Hs [m]	Gamma	Dir	Spread	Te [s]
IWS (Brettschneider)	1	1.63	0.117	1	0	INF	1.4
	2	2.2	0.132	1	0	INF	1.89
	3	2.58	0.268	1	0	INF	2.22
	4	2.84	0.103	1	0	INF	2.44
	5	3.41	0.292	1	0	INF	2.93
	6	3.69	0.163	1	0	INF	3.17
CWS (Custom Wave States)	7	1.25	0.063	1	0	INF	1.1
	8	1.63	0.075	1	0	INF	1.4
	9	1.92	0.175	1	0	INF	1.6
	10	2.3	0.225	1	0	INF	2

7.3 Extreme Wave Cases (XWS)

Extreme wave cases are derived from the 100 year contour plot for SETS. As some of the wave cases are too large to be generated in the LiR wave basin even at 1:30th scale, the wave maker gain was slowly increased to max the capabilities of the tank during wave calibration (see spectral power density plots in the Appendix).

Full Scale - Survivability Cases					
TYPE	#	Tp [s]	Te [s]	Hs [m]	Description
Extreme Cases (100 yr contour)	1	19.4	16.6	17.31	Peak of 100yr contour
	2	12.2	10.5	11.66	Peak energy contribution Te at SETS = 10.5s
	3	7.5	6.44	4.62	Device heave resonance Te = 6.44s
	4	24.7	21.2	14.27	Longest Te in SETS SNL HsTe diagram = 21.18s
				Scale 1:	**20**
TYPE	#	Tp [s]	Te [s]	Hs [m]	Description
Extreme Cases (100 yr contour)	1	4.33	3.71	0.87	Peak of 100yr contour
	2	2.73	2.35	0.58	Peak energy contribution Te at SETS = 10.5s
	3	1.68	1.44	0.23	Device heave resonance Te = 6.71s
	4	5.52	4.74	0.71	Longest Te in SETS SNL HsTe diagram = 21.18s
				Scale 1:	**30**
TYPE	#	Tp [s]	Te [s]	Hs [m]	Description
Extreme Cases (100 yr contour)	1	3.53	3.03	0.58	Peak of 100yr contour
	2	2.23	1.92	0.39	Peak energy contribution Te at SETS = 10.5s
	3	1.37	1.18	0.15	Device heave resonance Te = 6.71s
	4	4.50	3.87	0.48	Longest Te in SETS SNL HsTe diagram = 21.18s

7.4 Pink Noise Waves Cases (PinkWaves)

Wave maker pink noise for system identification cases are derived from a multisine generation Matlab script. A return period of 300 seconds, respectively 5 minutes was chosen. With 3 repeats this leads to a total pink noise wave case duration of 15 minutes.

Derived from BEM solutions the highest and lowest frequency values of the pink noise signals are derived for the 1:20 scale model as fmin = 0.25 Hz and fmax = 0.922 Hz. Thus, the equivalent full scale system excitation lies in the range of 4.85s < T < 17.88s, covering the entire range of common waves at the US West coast climates.

Figure 17 shows the frequency components (bottom) and an exemplary time series plot (top) used for wave generation. Note, that the time resolved signal is normalized before being fed to the wave maker. Thus, the wave amplitude can conveniently be controlled using the wave maker gain.

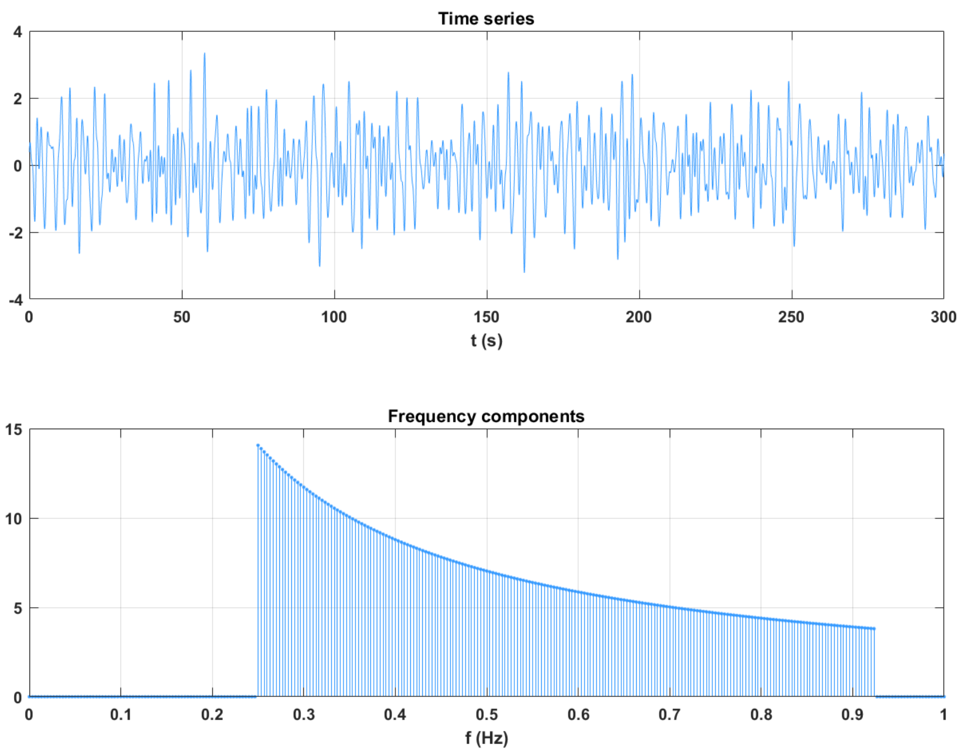


Figure 17: Frequency components and an exemplary time series realization of the Pink Noise signal used for wave generation.

8. Experimental Setup and Methods

7.1 General Mooring Layout and Properties

The baseline configuration of the WEC comprises of a symmetric, 45-Degree (x-z-Pane and x-y Pane) mooring setup. As the PTO units are located at the side of the tank the PTO/Mooring Tether must be guided to these using a pulley system mounted to the basin floor, which has a bolt pattern. The pulleys can be mounted to the floor and the PTO mooring line can be guided through these while the floor is in lifted position. Once the floor is lowered to the operating water depth the PTO units can be connected to the mooring line on the tank sides and the device can be connected using the carabiners. Figure 18 depicts the mooring connection points and device location on the basin bolt pattern for the 1:20 scale device. **Error! Reference source not found.** shows the mooring connection points and device location for the 1:30 scale device.

Table 12: Mooring Option 1 - Anchor Locations and Mooring Angles (45 Degree Setup)

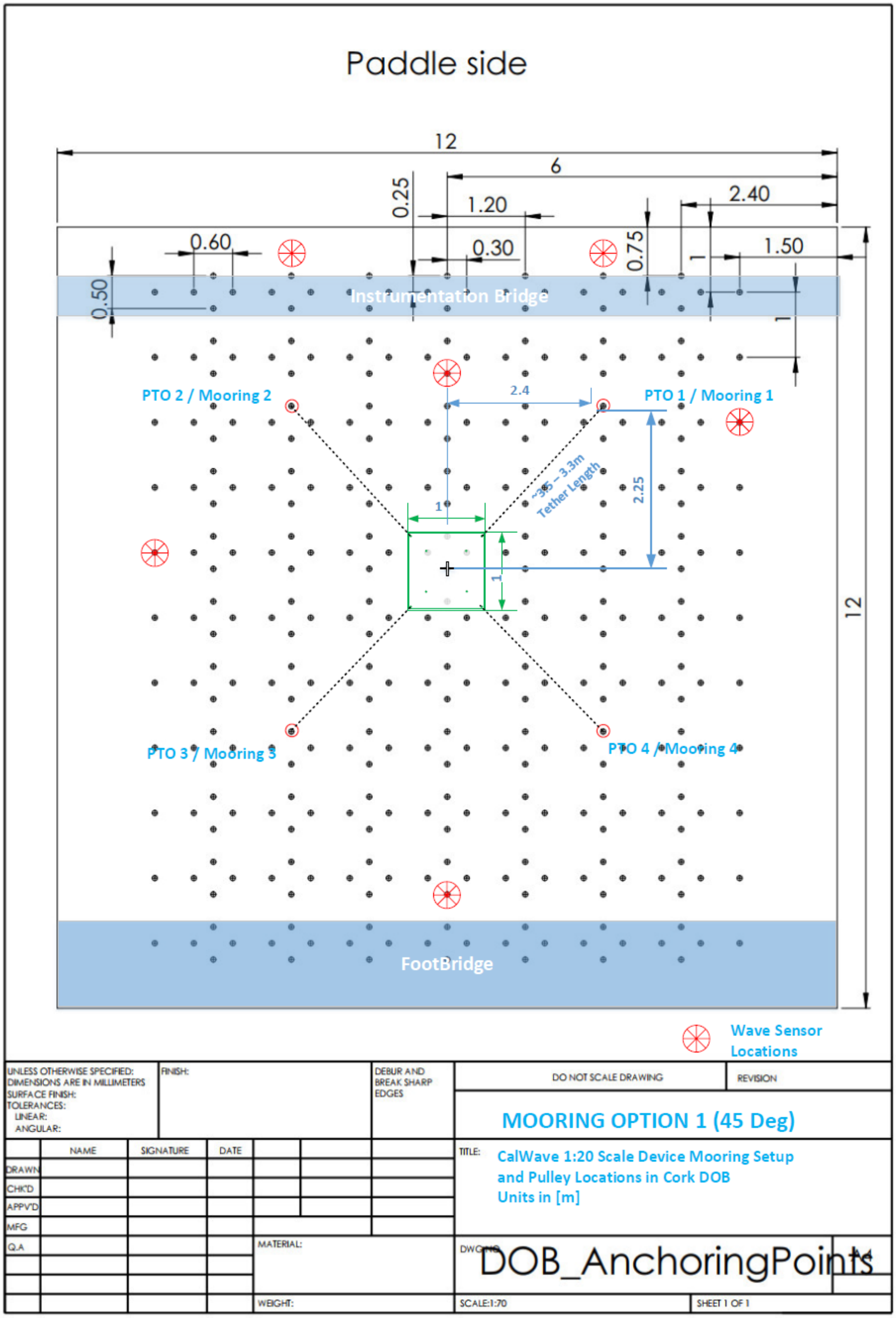
Mooring Option 1 - Anchor Locations 60m water depth					
Dimension	**Full Scale**	**1:20 Scale**	**1:30 Scale**	**Actual 1:20**	**Unit**
Water Depth	60	3	2	3	m
Design Operating Depth	7	0.35	0.23	0.35	m
Mooring Angle (x-z)	45	45	45.00	44.63	Deg
Design Mooring X Location	46.46	2.323	1.549	2.25	m
Design Mooring Y Location	46.46	2.323	1.549	2.4	m
Operating Depth Min	2	0.1	0.07	0.1	m
Operating Depth Max	15	0.75	0.50	0.75	m
Mooring X location for hOp min	49.5	2.475	1.65	-	m
Mooring y Location for hOp min	49.5	2.475	1.65	-	m
Mooring X location for hOp Max	40.4	2.02	1.35	-	m
Mooring y Location for hOp Max	40.4	2.02	1.35	-	m
Mooring Line Length Min (hop Max)	43	2.02	1.35	3.62	m
Mooring Line Length Max (hop Min)	56	2.15	1.43	3.62	m

Table 13: Mooring Option 2 - Anchor Locations and Mooring Angles (35 Degree Setup)

Mooring Option 2 - Anchor Locations 60m water depth					
Dimension	**Full Scale**	**1:20 Scale**	**1:30 Scale**	**Actual 1:20**	**Unit**
Water Depth	60	3	2	3	m
Design Operating Depth	7	0.35	0.23	0.35	m
Mooring Angle (x-z)	**35.3**	**35.3**	**35.3**	**35.3**	Deg
Design Mooring X Location	**60.9**	**3.045**	**2.030**	3.05	m
Design Mooring Y Location	**60.9**	**3.045**	**2.030**	3.05	m
Operating Depth Min	2	0.1	0.07	0.1	m
Operating Depth Max	15	0.75	0.50	0.75	m
Mooring X location for hOp min	65.9	3.295	2.20	3.295	m
Mooring y Location for hOp min	65.9	3.295	2.20	3.295	m
Mooring X location for hOp Max	52.9	2.645	1.76	2.645	m
Mooring y Location for hOp Max	52.9	2.645	1.76	2.645	m
Mooring Line Length Min (hop Max)	60.7	3.035	2.02	3.035	m
Mooring Line Length Max (hop Min)	79	3.95	2.63	3.95	m

For both, 1:20 as well as 1:30 scaled prototype testing, a sufficient stiff mooring, respectively PTO tether is used. Maximum breaking load (MBL) is sufficiently high to withstand all forces expected during all tests conducted.

Full scale mooring line stiffness might deviate from scaled prototype testing. However, as the stiffness in the mooring line is in parallel to the PTO stiffness, the prototype line stiffness c_{Tether} can be effectively included as a fixed constant into the PTO restoring force coefficient such that $c_{PTO,Total} = c_{PTO} + c_{Tether}$.


Paddle side
12
6
2.40
1.20
0.25
0.60
0.30
0.75
1.50
1
0.50
1
Instrumentation Bridge
PTO 2 / Mooring 2
PTO 1 / Mooring 1
2.4
2.25
~3.5 – 3.3m
Tether Length
1
1
12
PTO 3 / Mooring 3
PTO 4 / Mooring 4
FootBridge
Wave Sensor Locations
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
MOORING OPTION 1 (45 Deg)
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
CalWave 1:20 Scale Device Mooring Setup
and Pulley Locations in Cork DOB
Units in [m]
MATERIAL:
DWG NO.
DOB_AnchoringPoints
A4
WEIGHT:
SCALE:1:70
SHEET 1 OF 1

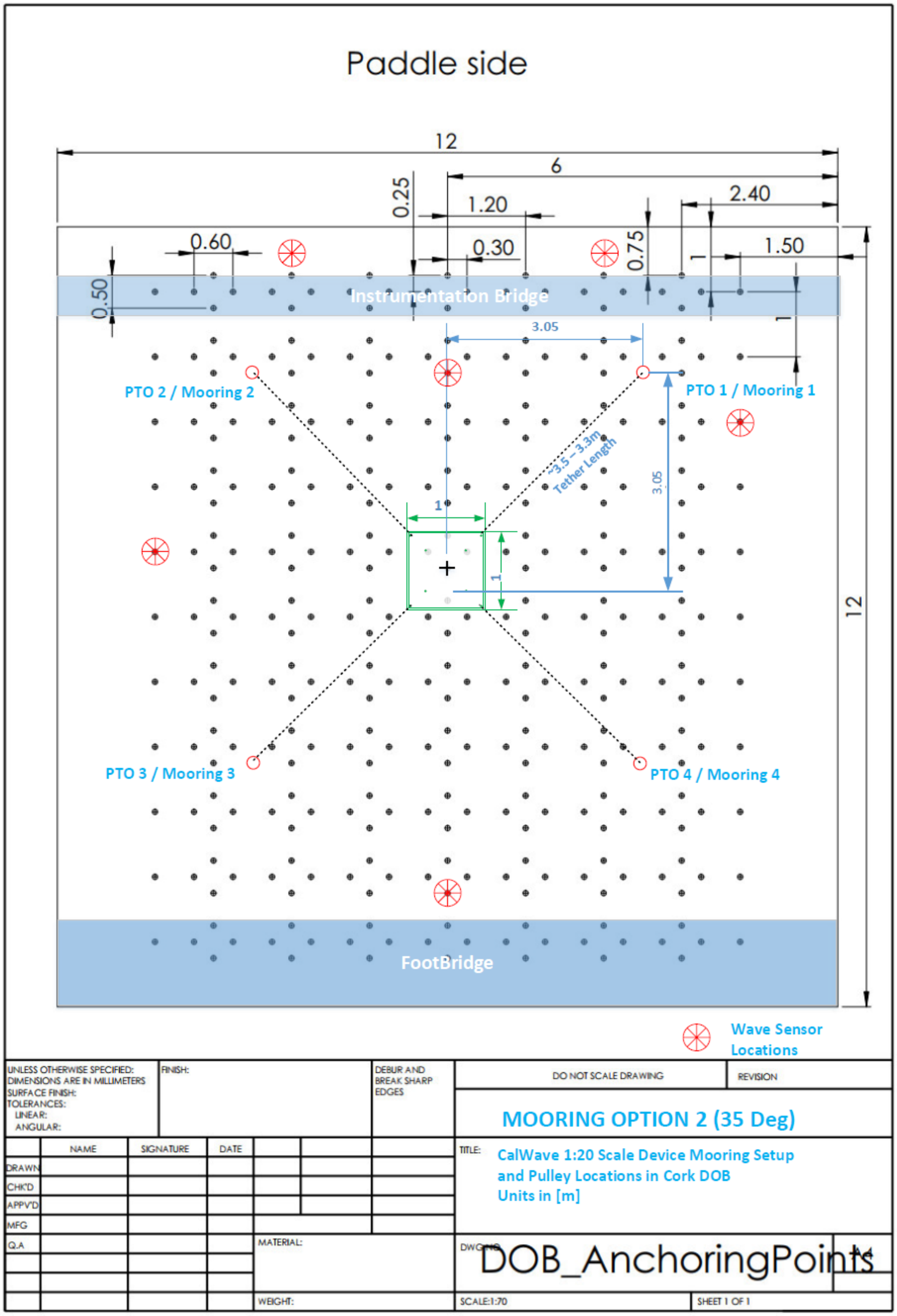


Figure 18: CalWave 1:20 Scale Device Mooring Setup – Mooring Option 1 (45 Degree) in the Deep Ocean Basin and Mooring Option 2 (35 Degree)

7.2 INSTRUMENTATION

The total experimental setup includes multiple sensors to measure PTO kinematic and kinetic signals, device displacement and velocity, as well as absorber hull pressure and incident wave elevation. A list of all sensors used in the setup can be found in Table 14:

Table 14: Sensor List

#	Measurement	Sensor	Unit	Data Logging Rate [Hz]
1	Wave Elevation	Capacitive Wave Probe	mm	50
2	Wave Elevation	Capacitive Wave Probe	mm	50
3	Wave Elevation	Capacitive Wave Probe	mm	50
4	Wave Elevation	Capacitive Wave Probe	mm	50
5	Wave Elevation	Capacitive Wave Probe	mm	50
6	Wave Elevation	Capacitive Wave Probe	mm	50
7	Absorber x	QualiSys Motion Tracking	cm	100
8	Absorber y	QualiSys Motion Tracking	cm	100
9	Absorber z	QualiSys Motion Tracking	cm	100
10	Absorber Rx	QualiSys Motion Tracking	cm	100
11	Absorber Ry	QualiSys Motion Tracking	cm	100
12	Absorber Rz	QualiSys Motion Tracking	cm	100
13	PTO 1 Tension	Loadcell	N	100
14	PTO 2 Tension	Loadcell	N	100
15	PTO 3 Tension	Loadcell	N	100
16	PTO 4 Tension	Loadcell	N	100
17	PTO 1 Encoder Pos	Motor Encoder	cm	100
18	PTO 2 Encoder Pos	Motor Encoder	cm	100
19	PTO 3 Encoder Pos	Motor Encoder	cm	100
20	PTO 4 Encoder Pos	Motor Encoder	cm	100
21	PTO 1 Encoder Vel	Motor Encoder	cm/s	100
22	PTO 2 Encoder Vel	Motor Encoder	cm/s	100
23	PTO 3 Encoder Vel	Motor Encoder	cm/s	100
23	PTO 4 Encoder Vel	Motor Encoder	cm/s	100
24	Hull Pressure 1	Pressure Sensor	Pa	100
25	Hull Pressure 2	Pressure Sensor	Pa	100
26	Hull Pressure 3	Pressure Sensor	Pa	100

For data acquisition and control of most of the sensors/hardware a NI cRIO unit is used. This allows for highly precise control and data sampling with rates up to 25 kHz (FPGA processor). The following Table 15 provides a preliminary summary of DAQ channel for both measuring signals from hardware/sensors as well as control of the PTO units.

Table 15: DAQ cRIO channel list including PTO affiliation, the specific signal measured, the processor used for control/DAQ as well as the sample rate.

Module	Channel	PTO	Hardware	Signal/Command	Processor	Sample Rate
9361 Digital Counter	CTR0	PTO1	Motor Encoder	PTO1 Displacement	FPGA	25 kHz
	CTR1	PTO2	Motor Encoder	PTO2 Displacement	FPGA	25 kHz
	CTR2	PTO3	Motor Encoder	PTO3 Displacement	FPGA	25 kHz
	CTR3	PTO4	Motor Encoder	PTO4 Displacement	FPGA	25 kHz
	CTR4	PTO1	Motor Encoder	PTO1 Velocity	FPGA	25 kHz
	CTR5	PTO2	Motor Encoder	PTO2 Velocity	FPGA	25 kHz
	CTR6	PTO3	Motor Encoder	PTO3 Velocity	FPGA	25 kHz
	CTR7	PTO4	Motor Encoder	PTO4 Velocity	FPGA	25 kHz
9237 Analog Bridge	Bridge 0	PTO1	Interface WMC Loadcell	PTO1 Tether Force	FPGA	25 kHz
	Bridge 1	PTO2	Interface WMC Loadcell	PTO2 Tether Force	FPGA	25 kHz
	Bridge 2	PTO3	Interface WMC Loadcell	PTO3 Tether Force	FPGA	25 kHz
	Bridge 3	PTO4	Interface WMC Loadcell	PTO4 Tether Force	FPGA	25 kHz
9401A DIO	Driver 1	PTO1	CPP Universal Servo Driver	Enabling Motor Driver	Real Time OS	1 kHz
	Driver 2	PTO2	CPP Universal Servo Driver	Enabling Motor Driver	Real Time OS	1 kHz
	Driver 3	PTO3	CPP Universal Servo Driver	Enabling Motor Driver	Real Time OS	1 kHz
	Driver 4	PTO4	CPP Universal Servo Driver	Enabling Motor Driver	Real Time OS	1 kHz
9263 AO	AO0	PTO1	CPP Universal Servo Driver	Motor Speed Control	Real Time OS	1 kHz
	AO1	PTO2	CPP Universal Servo Driver	Motor Speed Control	Real Time OS	1 kHz
	AO2	PTO3	CPP Universal Servo Driver	Motor Speed Control	Real Time OS	1 kHz
	AO3	PTO4	CPP Universal Servo Driver	Motor Speed Control	Real Time OS	1 kHz
9205 AI	AI0	PTO1	CPP Universal Servo Driver	Read Motor Speed	Real Time OS	1 kHz
	AI1	PTO2	CPP Universal Servo Driver	Read Motor Speed	Real Time OS	1 kHz
	AI2	PTO3	CPP Universal Servo Driver	Read Motor Speed	Real Time OS	1 kHz
	AI3	PTO4	CPP Universal Servo Driver	Read Motor Speed	Real Time OS	1 kHz
	AI4	Absorber	Pressure Sensor	Hull Pressure	Real Time OS	1 kHz
	AI5	Absorber	Pressure Sensor	Hull Pressure	Real Time OS	1 kHz
	AI6	Absorber	Pressure Sensor	Hull Pressure	Real Time OS	1 kHz
	AI7	Absorber	Pressure Sensor	Hull Pressure	Real Time OS	1 kHz
	AI8	Wave Gage	Cork Wave Gage	Wave Elevation eta	Real Time OS	1 kHz

	AI9	Wave Gage	Cork Wave Gage	Wave Elevation eta	Real Time OS	1 kHz
	AI10	Wave Gage	Cork Wave Gage	Wave Elevation eta	Real Time OS	1 kHz
	AI11	Wave Gage	Cork Wave Gage	Wave Elevation eta	Real Time OS	1 kHz
	AI12	Wave Gage	Cork Wave Gage	Wave Elevation eta	Real Time OS	1 kHz
	AI13	Wave Gage	Cork Wave Gage	Wave Elevation eta	Real Time OS	1 kHz
	AI14	Wave Gage	Cork Wave Gage	Wave Elevation eta	Real Time OS	1 kHz
	AI15	Wave Gage	...	Wave Elevation eta	Real Time OS	1 kHz

A detailed channel list (preliminary, might be subject to change during setup at Cork) with Pin labeling can be found in the Appendix.

7.3 Motion Tracking

A QualiSys motion tracking system provided by the LiR facility was used to measure all 6 DOF of the absorber body during most of the experiments. The system comprises of 4 high precision cameras mounted on a large frame on top of the wave basin and are orientated to look at the device deployment position at an angle. The system cannot track under water objects and thus, additional rods with markers were mounted on the absorber body. Reflective markers were mounted on top of these extension rods which were additionally secured with lightweight yarn to restrict oscillation or vibrations of the markers, effectively creating an above-water reference point of the absorber body to use the QualiSys system.

9. Data Processing and Analysis

8.1 Data Quality

Data quality assurance will be provided on site with first order post processing after each test. Data collection will start before waves are started and continue for at least 1 minute once wave generation stops. This ensures that data captures initial setup condition (e.g. mooring pretension from hydrostatic buoyancy) and transient ramp-up/down effects).

“Raw” data from all sensors are logged including Sensor ID, timestamp, units, and measured values and saved in the LabView “TDMS” format. Sensors measured with other DAQ systems than the NI hardware are saved in an appropriate file format (e.g. text or CSV files).

Motion Tracking Data (3 rotational, 3 translational DOFs) are stored in MATHWORKS Matlab .mat files. Wave Elevation is stored in .txt files with one column for each of the introduced wave gages.

8.2 Synchronization and Measurement procedure

Synchronization of data is straight forward with all data acquired with sensors running on NI hardware / via the main LabView DAQ software as sampling follows the cRIO hardware clock. Synchronization of signals from LiR (e.g. Wave Probes, Motion Tracking) is facilitated using an analog trigger signal.

Measurements are started in the following order:

1. Motion tracking and recording is started
2. Wave probes measuring is started
3. All NI Labview data acquisition is started
4. Wavemaker is started; This triggers a signal
5. Absolute timestamp for all NI Labview DAQ is reset to 0 for synchronization
6. Wave Case is running and waves stop after a specified time
7. Motion tracking recording is stopped manually; Wave probe recording is stopped manually
8. NI Labview DAQ is stopped manually1

10 LIR DOB RUN-TABLE SUMMARY

CalWave X20 - RunTable - Cork																					
Run ID	Time		Device	Waves					PTO #1		PTO #2		PTO #3		PTO#4		DataFile	hOp - FS	PTO Gain [N]	Note
-	Day	TimeStamp	ID	Spectrum	Dir (°)	Tp	Hs	Gain	Damping c	Restoring Force k	Damping c	Restoring Force k	Damping c	Restoring Force k	Damping c	Restoring Force k	-	[m]		-
#1	19-Jan	4:18 PM	#X20-A	N/A	0°	N/A	N/A	1	NON	NON	NON	NON	NON	NON	NON	NON	001_Cork	2.06	NON	Lowered BasinFloor
#2			#X20-A	N/A	0°	N/A	N/A	1	NON	NON	NON	NON	NON	NON	NON	NON	002_Cork	2.06	NON	Submerge Device
#3			#X20-A	N/A	0°	N/A	N/A	1	NON	NON	NON	NON	NON	NON	NON	NON	003_Cork	2.06	NON	Sinusoidal Excitation
#4	22-Jan	4:03 PM	#X20-A	N/A	0°	N/A	N/A	1	1500	NON	1500	NON	1500	NON	1500	NON	004_Cork	-0.06	NON	Submerge, hold in position, reference position analysis
#5		4:53 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	005_Cork	-5.96	NON	Initial Position for run #6
#6		4:53 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	006_Cork	-5.96	NON	continuation of 5
#7		5:11 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	007_Cork	-3.12	NON	Baseline Working principle
#8		5:46 PM	#X20-A	IWS1	0°	1.63	0.117	1	1000	3250	1000	3250	1000	3250	1000	3250	008_Cork	-6.04	NON	IWS 1 10 meters submerged
#9	23-Jan	11:55 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	009_Cork	-5.96	NON	PID Loop Tuning
#10		12:06 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	010_Cork	-5.96	NON	PID Loop Tuning
#11		12:23 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	011_Cork	-5.96	NON	PID Loop Tuning
#12		12:27 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	012_Cork	-5.96	NON	PID Loop Tuning
#13		12:37 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	013_Cork	-5.96	NON	PID Loop Tuning
#14		2:10 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	014_Cork	-5.96	NON	PID Loop Tuning
#15			#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	015_Cork	-5.96	NON	Updated Drive
#16		4:18 PM	#X20-A	NON	0°	NON	NON	1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	016_Cork	-5.96	20	Pink Noise Testcase (qualitative)
#17	24-Jan	3:02 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	017_Cork	-6.04	NON	Baseline
#18		3:30 PM	#X20-A	IWS1	0°	1.63	0.117	1	1000	3250	1000	3250	1000	3250	1000	3250	018_Cork	-6.04	NON	IWS with new PID Loop Tuning
#19		3:58 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	019_Cork	-4.64	75	System ID: Pink Noise PTO, No waves
#20		4:30 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	020_Cork	-4.80	112.5	System ID: Pink Noise PTO, No waves
#21		4:50 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	021_Cork	-4.80	112.5	System ID: Pink Noise PTO, No waves
#22		5:09 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	022_Cork	-4.82	131.5	System ID: Pink Noise PTO, No waves
#23		5:34 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	023_Cork	-3.22	NON	IWS 2
#24	25-Jan	10:57 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	024_Cork	-5.96	NON	Baseline
#25		-	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	025_Cork	-5.96	0.5	2Input SID - Gain 05 - Experiment1 - 10mDepth
#26		11:29 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	026_Cork	-6.00	0.5	2Input SID - Gain 05 - Experiment2 - 10mDepth
#27		12:01 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	027_Cork	-6.00	0.5	2Input SID - Gain 05 - Experiment3 - 10mDepth
#28		2:14 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	028_Cork	-5.90	0.5	2Input SID - Gain 05 - Experiment4 - 10mDepth
#29		3:22 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	029_Cork	-6.02	0.75	2Input SID - Gain 0.75 - Experiment1 - 10mDepth
#30		3:41 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	030_Cork	-6.02	0.75	2Input SID - Gain 0.75 - Experiment2 - 10mDepth
#31		4:12 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	031_Cork	-6.02	0.75	2Input SID - Gain 0.75 - Experiment3 - 10mDepth
#32		5:12 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	032_Cork	-2.94	0.5	2Input SID - Gain 0.75 - Experiment1 - 7.12 mDepth
#33		5:30 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	033_Cork	-2.94	0.5	2Input SID - Gain 0.75 - Experiment2 - 7.12 mDepth
#34		5:47 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	034_Cork	-2.94	0.5	2Input SID - Gain 0.75 - Experiment2 - 7.12 mDepth
#35	26-Jan	9:56 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	035_Cork	-6.04	NON	Baseline
#36		-	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	036_Cork	-6.16	0.05	2Input SID - Gain 05 - Experiment1 - 10mDepth
#37		10:48 AM	#X20-A	IWS1	0°	1.63	0.117	1	1000	3250	1000	3250	1000	3250	1000	3250	037_Cork	-2.84	NON	IWS1
#38		11:09 AM	#X20-A	IWS2	0°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	038_Cork	-2.84	NON	IWS2
#39		11:40 AM	#X20-A	IWS4	0°	2.84	0.103	1	750	2250	750	2250	750	2250	750	2250	039_Cork	-2.84	NON	IWS4
#40		12:03 PM	#X20-A	IWS1	0°	1.63	0.117	1	1000	2750	1000	2750	1000	2750	1000	2750	040_Cork	-2.84	NON	IWS1
#41		12:24 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	1750	1000	1750	1000	1750	1000	1750	041_Cork	-2.78	NON	IWS2
#42		1:49 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	1750	1000	1750	1000	1750	1000	1750	042_Cork	-2.76	NON	IWS2
#43		2:23 AM	#X20-A	IWS4	0°	2.84	0.103	1	750	1750	750	1750	750	1750	750	1750	043_Cork	-2.68	NON	IWS4
#44		2:50 AM	#X20-A	IWS1	0°	1.63	0.117	1	500	3250	500	3250	500	3250	500	3250	044_Cork	-2.66	NON	IWS1
#45		3:07 PM	#X20-A	IWS2	0°	2.2	0.132	1	500	2250	500	2250	500	2250	500	2250	045_Cork	-2.66	NON	IWS2
#46		3:37 PM	#X20-A	IWS4	0°	2.84	0.103	1	750	2250	750	2250	750	2250	750	2250	046_Cork	-2.66	NON	IWS4
#47		4:16 PM	#X20-A	IWS1	0°	2.84	0.103	1	1000	3250	1000	3250	1000	3250	1000	3250	047_Cork	-0.94	NON	IWS1
#48		4:44 PM	#X20-A	IWS1	0°	2.84	0.103	1	1000	3250	1000	3250	1000	3250	1000	3250	048_Cork	-5.02	NON	IWS1
#49		5:05 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	049_Cork	-5.02	NON	IWS2
#50		5:29 PM	#X20-A	IWS4	0°	2.84	0.103	1	750	2250	750	2250	750	2250	750	2250	050_Cork	-5.02	NON	IWS4

#51	29-Jan	9:31 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	051_Cork	-6.00	NON	Swapped Mooring Loadcells due to failure
#52		5:34 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	052_Cork	-6.02	NON	Baseline
#53		5:54 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	053_Cork	-6.02	0.005 m	PinkPTO; Position Controlled; 5cm Amplitude
#54	30-Jan	9:51 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	054_Cork	-5.90	NON	Baseline
#55		10:07 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	055_Cork	-5.90	0.05 m	Voltage limited to +/-1 V; Run was good, Desired Position a
#56		10:14 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	056_Cork	-5.90	0.05 m	NO DATA Acquisition started
#57		10:31 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	057_Cork	-6.04	0.025 m	2 Input SID - Gain 0.025m - Experiment 1 - 5m depth
#58		10:56 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	058_Cork	-6.14	0.025 m	2 Input SID - Gain 0.025m - Experiment 2 - 5m depth
#59		11:20 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	059_Cork	-6.06	0.04 m	2 Input SID - Gain 0.04 m - Experiment 1 - 5m depth
#60		11:41 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	060_Cork	-6.10	0.04 m	2 Input SID - Gain 0.04 m - Experiment 2 - 5m depth
#61		12:50 PM	#X20-A	PinkWaves1	0°	-	33%	0.33	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	061_Cork	-6.10	0.025 m	3 Input SID - Gain 0.025 m - Experiment 1 - 5 m depth
#62		1:57 PM	#X20-A	PinkWaves2	0°	-	33%	0.33	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	062_Cork	-5.94	0.025 m	3 Input SID - Gain 0.025 m - Experiment 2 - 5 m depth
#63		2:26 PM	#X20-A	PinkWaves3	0°	-	33%	0.33	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	063_Cork	-6.00	0.025 m	3 Input SID - Gain 0.025 m - Experiment 2 - 5 m depth
#64		2:59 PM	#X20-A	IWS6	0°	3.69	0.163	1	500	1000	500	1000	500	1000	500	1000	064_Cork	-6.80	NON	IWS6
#65		3:19 PM	#X20-A	IWS6	0°	3.69	0.163	1	500	1000	500	1000	500	1000	500	1000	065_Cork	-4.80	NON	IWS6
#66		3:39 PM	#X20-A	IWS5	0°	3.41	0.19272	0.66	1000	2000	1000	2000	1000	2000	1000	2000	066_Cork	-9.82	NON	IWS 5, Closed Hatch, 66%
#67		4:16 PM	#X20-A	CWS1	0°	1.25	0.063	1	500	3000	3000	3000	3000	3000	3000	3000	067_Cork	-2.78	NON	WETS CWS1
#68		4:45 PM	#X20-A	CWS1	0°	1.25	0.063	1	500	3000	3000	3000	3000	3000	3000	3000	068_Cork	-1.70	NON	WETS CWS1
#69		5:12 PM	#X20-A	CWS3	0°	1.92	0.175	1	1000	2750	2750	2750	2750	2750	2750	2750	069_Cork	-5.00	NON	SETS Bulls Eye
#70	31-Jan	12:07 PM	#X20-P	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	070_Cork	-5.96	NON	Baseline
#71		1:30 PM	#X20-P	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	071_Cork	-6.02	NON	Baseline
#72		1:46 PM	#X20-P	M3S80	0°	2.0	0.08	1	2000	2000	2000	2000	2000	2000	2000	2000	072_Cork	-6.02	NON	Baseline
#73		2:03 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	073_Cork	-6.90	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment1
#74		2:36 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	074_Cork	-6.90	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment2
#75		2:36 PM	#X20-P	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	075_Cork	-6.98	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment1
#76		3:20 PM	#X20-P	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	076_Cork	-6.98	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment2
#77		3:45 PM	#X20-P	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	077_Cork	-6.96	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment3
#78		4:11 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	078_Cork	-7.04	56.5N	2 Input SID - MISO - Gain 56.5N - Experiment1
#79		4:37 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	079_Cork	-6.96	56.5N	2 Input SID - MISO - Gain 56.5N - Experiment2
#80		4:56 PM	#X20-P	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	080_Cork	-7.02	37.5N	3 Input SID - MISO - Gain 37.5N - Wave Gain Higher - Exper
#81		5:13 PM	#X20-P	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	081_Cork	-6.96	37.5N	3 Input SID - MISO - Gain 37.5N - Wave Gain Higher - Exper
#82		5:37 PM	#X20-P	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	082_Cork	-7.02	37.5N	3 Input SID - MISO - Gain 37.5N - Wave Gain Higher - Exper
#83	1-Feb	10:18 AM	#X20-P	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	083_Cork	-5.96	NON	Baseline
#84		10:28 AM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	084_Cork	-4.04	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment1 - 4m depth
#85		10:28 AM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	085_Cork	-4.02	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment2 - 4m depth
#86		11:07 AM	#X20-P	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	086_Cork	-4.02	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment1
#87		11:30 AM	#X20-P	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	087_Cork	-4.04	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment2
#88		11:46 AM	#X20-P	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	088_Cork	-3.98	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment3
#89		12:15 PM	#X20-P	IWS2	20°	1.7	0.05	1	1000	2250	1000	2250	1000	2250	1000	2250	089_Cork	-5.02	NON	Angeled Wave Case IWS 2 (equivalent to 70 Degree and 20
#90		1:30 AM	#X20-P	CWS3	0°	1.92	0.175	1	1000	2750	2750	2750	2750	2750	2750	2750	090_Cork	-5.02	NON	SETS Bulls Eye
#91		1:54 PM	#X20-P	CWS3	0°	1.92	0.175	1	1000	2750	2750	2750	2750	2750	2750	2750	091_Cork	-5.06	NON	SETS Bulls Eye
#92		3:43 PM	#X20-PS	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	092_Cork	-6.08	NON	Baseline Open Hatch
#93		3:57 PM	#X20-PS	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	093_Cork	-6.90	25N	2 Input SID - MISO - Gain 25N - Experiment1 - 7m depth
#94		4:15 PM	#X20-PS	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	094_Cork	-6.98	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#95		4:35 PM	#X20-PS	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	095_Cork	-7.04	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#96		4:53 PM	#X20-PS	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	096_Cork	-7.04	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#97		5:15 PM	#X20-PS	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	097_Cork	-7.04	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#98		5:40 PM	#X20-PS	IWS3	0°	2.58	0.268	1	1000	3500	1000	3500	1000	3500	1000	3500	098_Cork	-10.06	NON	IWS3, Open Hatch, Survival Mode, Detuned PTO
#99	2-Feb	9:46 AM	#X20-PS	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	099_Cork	-6.00	NON	Baseline
#100		9:55 AM	#X20-PS	IWS2	20°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	100_Cork	-5.00	NON	IWS2 Comparison Hatch open/close 20 Deg
#101		10:17 AM	#X20-PS	IWS5	0°	3.41	0.292	1	1000	3000	1000	3000	1000	3000	1000	3000	101_Cork	-6.04	NON	IWS 5, Open Hatch, Full gain
#102		10:43 AM	#X20-PS	M3S80	0°	2.0	0.08	1	see pattern	see pattern	see pattern	see pattern	see pattern	see pattern	see pattern	see pattern	102_Cork	-5.02	NON	PTO Tuning
#103		11:51 AM	#X30-S	M3S80	0°	1.370	0.0365	1	725	888	725	888	725	888	725	888	103_Cork	-6	NON	Baseline Case 1:30
#104		12:04 AM	#X30-S	Ex2	0°	2.2329	0.39	1	360	1500	360	1500	360	1500	360	1500	104_Cork	-10	NON	Survival Case, 25% Hatch opening, 10 meters hop
#105		12:21 PM	#X30-S	Ex2	0°	2.2329	0.39	1	360	1500	360	1500	360	1500	360	1500	105_Cork	-15	NON	Survival Case, 25% Hatch opening, 15 meters hop
#106		2:05 PM	#X30-S	Ex2	0°	2.2329	0.39	1	360	1500	360	1500	360	1500	360	1500	106_Cork	-10	NON	Survival Case, 25% Hatch opening, 10 meters hop, MinLineT
#107		2:13 PM	#X30-S	IWS2	0°	1.7963	0.088	1	360	1000	360	1000	360	1000	360	1000	107_Cork	0	NON	IWS Case 2 , 25% Hatch opening, Device on Surface, MinLin
#108		2:30 PM	#X30-S	IWS2	0°	1.7963	0.088	1	360	1000	360	1000	360	1000	360	1000	108_Cork	-4	NON	IWS Case 2 , 25% Hatch opening, -4m hop, PTO 2 slack,
#109		2:41 PM	#X30-S	Waves continued to run on purpose				1	360	1000	360	1000	360	1000	360	1000	108_Cork	-4	NON	IWS Case 2 , 25% Hatch opening, -4m hop, PTO 2 slack,

APPENDIX A: MOTOR/GENERATOR & DRIVE SPECIFICATIONS

ElectroCraft powering innovation™

RP34

RapidPower™ BLDC Motor

Compact - high performance.

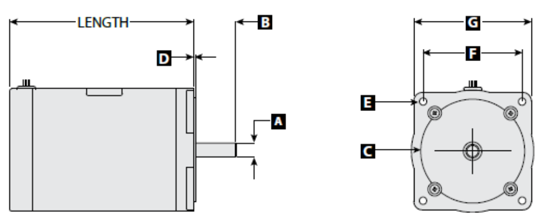
RP34 RAPIDPOWER™ BLDC MOTOR

Good-Performance. Good Price.

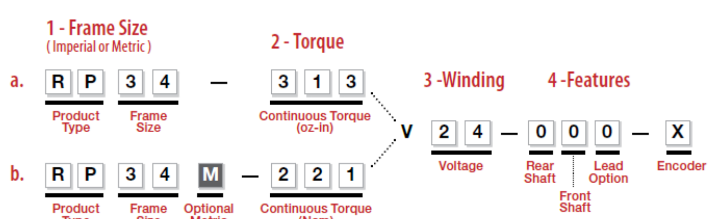
Our ElectroCraft RapidPower™ Nema 34 is a compact, high-performance brushless motor incorporating ball bearing construction, a low cogging electro-magnetic design with both low audible and magntic noise. It is available with a hall-effect commutation encoder or a variety of optical encoders for higher precision applications.

RP34 RapidPower™ BLDC Motor	
Size:	Nema 34
Peak Torque:	to 1096 oz-in or 774 Ncm

Model	MAX Length	A Front Shaft Diameter	B Front Shaft Length	C Pilot Diameter	D Pilot Length (Ref)	E Mount Hole Pattern (Ref)	F Mount Hole Spacing (Ref)	G Flange External Dimension (Ref)	H Rear Shaft Diameter	I Rear Shaft Length	J Encoder Length (Ref) Single Ended / Differential
RP34-112	2.84 in	0.3750 in 0.3745 in	1.25 in ±0.03	2.875 in 2.873 in	0.06 in	[4] 0.220 in ± 0.010 on 3.875 in D.B.C.	2.74 in	3.38 in	0.2500 in 0.2495 in	0.500 in ±0.040	0.35 in / 0.55 in
RP34-217	4.15 in										
RP34-313	5.47 in										
RP34-79	72 mm	14.000 mm 13.989 mm	30 mm ±0.8	80.012 mm 79.993 mm	1.5 mm	[4] 7 mm +0.36/−0.00 on 3.875 in D.B.C.	70.71 mm	85.85 mm	6.3424 mm 6.3297 mm	11.4 mm ±0.7	8.9 mm / 14.0 mm
RP34-153	105 mm										
RP34-221	139 mm										



BLDC Model Number



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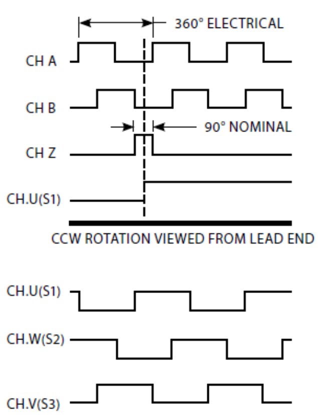
RP34 Mechanical / Winding Data

Stack Size Models	RP34- 112	RP34- 217	RP34- 313
Continuous Stall Torque (oz-in)	112	217	313
Continuous Stall Torque (Ncm)	79	153	221
Peak Torque (oz-in)	392	759	1095
Peak Torque (Ncm)	277	536	773
Motor Constant (oz-in / √ Watt)	18.10	29.10	35.50
Motor Constant (Nm / √ Watt)	12.78	20.55	25.07
Electrical Constant (msec)	4.80	5.50	6.00
Mechanical Constant (msec)	6.70	4.30	4.40
Rotor Inertia (oz-in^2)	0.0149	0.0258	0.0385
Rotor Inertia (gm-cm^2)	1052.2	1822.0	2718.9
Thermal Resistance (C / Watts)	2.0	1.5	1.0
Weight (oz)	64.0	100.0	143.0
Weight (Kg)	1.8	2.8	4.1
Length (inches)	2.8	4.2	5.5
Length (mm)	71.1	106.7	139.7
Number of Poles	4	4	4

Winding Models	112V24	112V48	112V90	112V160	217V24	217V48	217V90	217V160	313V24	313V48	313V90	313V160
	79V24	79V48	79V90	79V160	153V24	153V48	153V90	153V160	221V24	221V48	221V90	221V160
Design Voltage (VDC)	24	48	90	160	24	48	90	160	24	48	90	160
Continuous Current (Amps)	24.4	12.1	6.1	3.2	22.3	16.9	8.9	5.0	22.7	17.0	11.3	6.8
Peak Current (Amps)	85.5	42.4	21.2	11.2	78.0	59.1	31.1	17.6	79.3	59.6	39.7	16.5
Voltage Constant ±10% (VDC/kRPM)	3.4	6.8	13.7	25.9	7.2	9.5	18.1	31.8	10.2	13.6	20.4	34.0
Torque Constant ±10% (oz-in / Amp)	4.6	9.2	18.5	35.0	9.7	12.8	24.4	43.0	13.8	18.4	27.6	46.0
Torque Constant ±10% (Ncm / Amp)	3.248	6.497	13.064	24.715	6.850	9.039	17.230	30.365	9.745	12.993	19.490	32.483
Resistance ±10% (Ohms)	0.1	0.2	0.8	4.0	0.1	0.2	0.7	2.2	0.2	0.3	0.5	1.6
Inductance ±10% (mH)	0.3	1.2	4.8	20.3	0.6	1.1	3.9	12.0	1.0	1.7	3.9	11.0

RP34 Connection

Output Configuration:



Hall Pinouts	
Color	Function
ORANGE	+4.5-24 VDC
BLACK	GROUND
YELLOW	S1
GREY	S2
GREEN	S3

Low Profile Encoder	
Character	Lines
J	500 CPR
K	1000 CPR
L	2000 CPR
Encoder Pinouts	
Color	Function
BLACK	GROUND
ORANGE	CHANNEL Z
YELLOW	CHANNEL A
RED	+5 VDC
BLUE	CHANNEL B
GREEN	S1
BROWN	S2
WHITE	S3
BRN	S2

Differential Encoder	
Character	Lines
C	500 CPR
D	1000 CPR
E	2000 CPR
Encoder Pinouts	
Color	Function
YELLOW	CH A
YEL/WHT	CH A COMP
BLUE	CH B
BLU/WHT	CH B COMP
ORANGE	CH Z
ORG/WHT	CH Z COMP
GREEN	S1
GRN/WHT	NOT USED
BROWN	S2
BRN/WHT	NOT USED
WHITE	S3
GREY/WHT	NOT USED
RED	VCC
BLACK	GROUND
GREY	NOT USED

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ElectroCraft® powering innovation™

CPP-A24V80A-SA-USB

ElectroCraft CompletePower™ Plus Universal Servo Drive

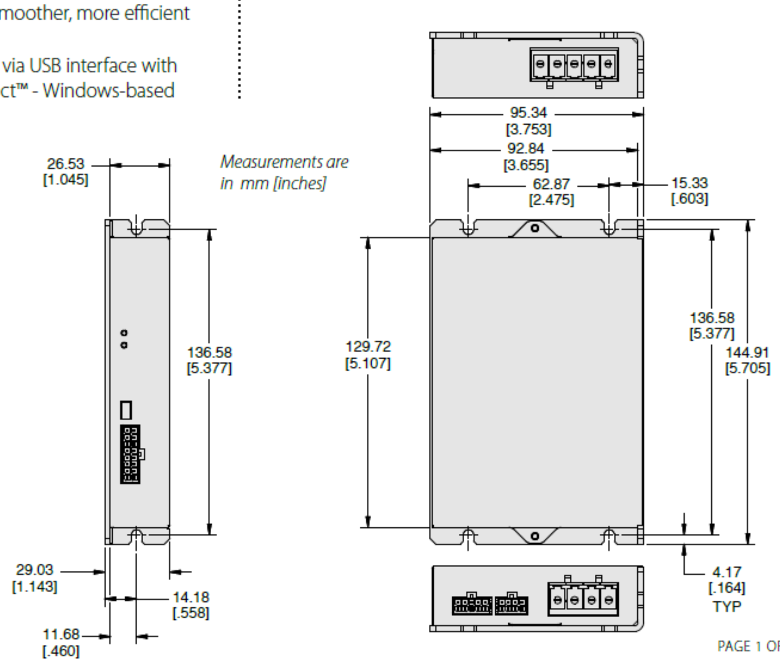
More Power in a Smaller Package

Introducing ElectroCraft's Universal Drive, the newest addition to the ElectroCraft CompletePower™ Plus family of DC motor drives.

Introducing ElectroCraft's Universal Drive, the newest addition to the ElectroCraft CompletePower™ Plus family of DC motor drives. The Universal Drive takes performance, efficiency and flexibility to the next level, utilizing state-of-the-art digital drive technology combined with an intuitive and highly configurable user interface. Perfect for a wide range of industrial, commercial market, and consumer product applications. The CPP-A24V80A-SA-USB is one of three standard capacities in the model lineup. Customized versions are also offered to meet large volume OEM requirements.

- Driven by design to be one of the most space efficient, low voltage, digital servo drives available.
- Utilizing the latest in digital drive architecture to provide software selectable control mode operation.
- Compatible with Brushless motors from 12 to 80 VDC and up to 24A continuous, 60A peak current.
- Sine-wave commutation using either hall sensor or encoder feedback provides smooth torque for demanding motion control requirements.
- Advanced Field Oriented Control provides high dynamic response resulting in a robust motor controller with low torque ripple that produces smoother, more efficient motion!
- Easy setup and configuration via USB interface with ElectroCraft CompleteArchitect™ - Windows-based software.

CPP-A24V80A-SA-USB Universal Servo Drive	
Output Power, Peak:	4800 Watts
Phase Current Peak:	60 Amps (peak of sine)
Phase Current Cont.:	24 Amps (peak of sine)
Output:	+12 to +80 VDC
Output Frequency:	20, 40, 80 kHz (selectable)



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APPENDIX B: GEARBOX SPECIFICATIONS

SureGear Planetary Gearboxes for NEMA Motors

SureGear® Planetary Gear Reducers for NEMA Motors – Overview

The SureGear PGCN series is a great gearbox (gear reducer) value for servo, stepper, and other motion control applications requiring a NEMA size input/output interface. It offers the best quality available for the price point.

Features

- Wide range of ratios (5, 10, 25, 50, and 100:1)
- Low backlash of 30 arc-min or less
- 20,000 hour service life
- Maintenance free; requires no additional lubrication
- NEMA sizes 17, 23, and 34
- Includes hardware for mounting to SureStep stepper motors
- Optional shaft bushings available for mounting to other motors

Applications

- Material handling
- Pick and place
- Automation
- Packaging
- Other motion control applications requiring a NEMA input/output

SureGear® NEMA Planetary Gearboxes

Model-Specific Specifications

Part Number	Price	Ratio	NEMA Frame Size	Nominal Output Torque (N·m [lb·in])	Maximum Acceleration Torque (N·m [lb·in])	Emergency Stop Torque (N·m [lb·in])	Standard Output Backlash (arc-min)	Allowable Radial Load (N [lb])	Allowable Axial Load (N [lb])	Torsional Stiffness (N·m/arc-min [lb·in/arc-min])	Mass Moment of Inertia (kg·cm² [lb·in²])	Efficiency (%)	Approx Weight (kg [lb])	Fits SureStep Stepper Motor
PGCN17-055M	<--->	5:1		6.5 [58]	13 [115]	26 [230]	<25			0.8 [7.5]	0.0096 [0.003]	94	0.45 [1.0]	
PGCN17-105M	<--->	10:1		5.0 [44]	10 [89]	20 [177]	<25			0.5 [4.4]	0.0078 [0.003]	94	0.45 [1.0]	
PGCN17-255M	<--->	25:1	17	16 [142]	20 [177]	32 [283]	<30			0.8 [7.5]	0.0096 [0.003]	92	0.55 [1.2]	STP-MTR-170xx(D)
PGCN17-505M	<--->	50:1		16 [142]	20 [177]	32 [283]	<30			0.8 [7.5]	0.0078 [0.003]	92	0.55 [1.2]	
PGCN17-1005M	<--->	100:1		5.0 [44]	10 [89]	20 [177]	<30			0.5 [4.4]	0.0078 [0.003]	92	0.55 [1.2]	
PGCN23-0525	<--->	5:1		6.5 [58]	13 [115]	26 [230]	<20	361 [81]	298 [67]	0.9 [8.0]		94	0.45 [1.0]	
PGCN23-1025	<--->	10:1		5.0 [44]	10 [89]	20 [177]	<20			0.6 [5.3]		94	0.45 [1.0]	
PGCN23-2525	<--->	25:1	23	16 [142]	20 [177]	32 [283]	<25			0.9 [8.0]	0.04 [0.014]	92	0.55 [1.2]	STP-MTR(H)-230xx(D)
PGCN23-5025	<--->	50:1		16 [142]	20 [177]	32 [283]	<25			0.9 [8.0]		92	0.55 [1.2]	
PGCN23-10025	<--->	100:1		5.0 [44]	10 [89]	20 [177]	<25			0.6 [5.3]		92	0.55 [1.2]	
PGCN34-0550	<--->	5:1		26 [230]	44 [389]	84 [743]	<15			2.4 [21.2]	0.36 [0.123]	94	1.1 [2.4]	
PGCN34-1050	<--->	10:1		16 [142]	24 [212]	62 [549]	<15			1.3 [11.5]	0.34 [0.116]	94	1.1 [2.4]	
PGCN34-2550	<--->	25:1	34	42 [372]	52 [460]	84 [743]	<20	476 [107]	425 [96]	2.4 [21.2]	0.36 [0.123]	92	1.4 [3.1]	STP-MTR(H)-34xxx(D)
PGCN34-5050	<--->	50:1		42 [372]	52 [460]	84 [743]	<20			2.4 [21.2]	0.34 [0.116]	92	1.4 [3.1]	
PGCN34-10050	<--->	100:1		16 [142]	24 [212]	62 [549]	<20			1.3 [11.5]	0.34 [0.116]	92	1.4 [3.1]	

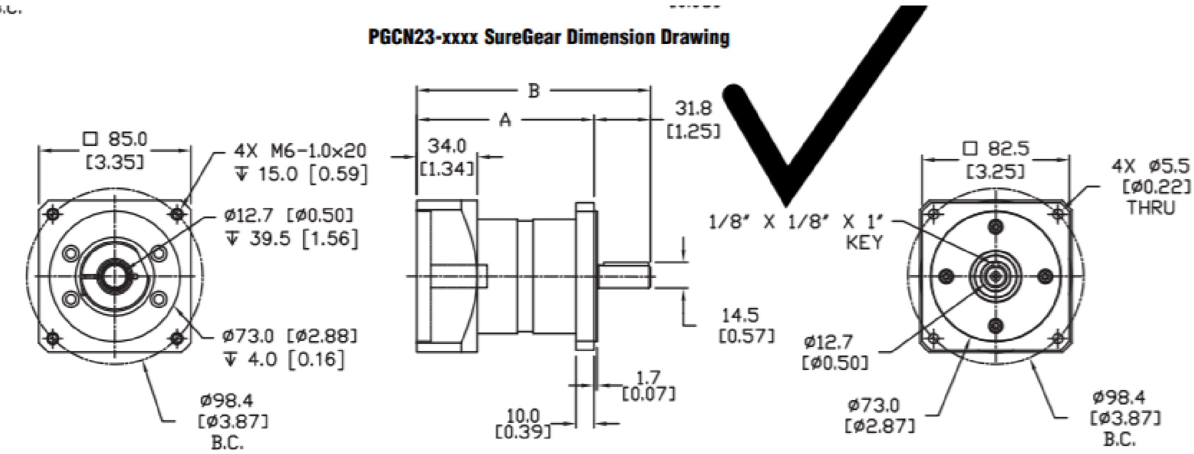
Specifications Applicable to All PGCN Gearboxes

Nominal Speed (rpm)	3500
Maximum Input Speed (rpm)	6000
Mounting Orientation	can be mounted in any orientation
Environmental Rating	IP64
Operating Temperature	-20 to 90 °C [-4 to 194 °F]
Lubrication	Mineral Grease EPO
Service Life (hrs)	>20,000

NOTE: SureGear PGCN gearboxes (gear reducers) are not designed for back driving.

B.C.

PGCN23-xxxx SureGear Dimension Drawing



PGCN34-xxxx SureGear Dimension Drawing

SureGear® NEMA Planetary Gearbox Dimensions (dimensions = mm [in])					
NEMA-17 Part Number	***PGCN17-055M***	***PGCN17-105M***	***PGCN17-255M***	***PGCN17-505M***	***PGCN17-1005M***
dimension A	84.0 [3.31]		99.8 [3.93]		
dimension B	109.4 [4.31]		125.2 [4.93]		
NEMA-23 Part Number	***PGCN23-0525***	***PGCN23-1025***	***PGCN23-2525***	***PGCN23-5025***	***PGCN23-10025***
dimension A	77.6 [3.06]		95.2 [3.75]		
dimension B	103.0 [4.06]		120.6 [4.75]		
NEMA-34 Part Number	***PGCN34-0550***	***PGCN34-1050***	***PGCN34-2550***	***PGCN34-5050***	***PGCN34-10050***
dimension A	99.3 [3.91]		121.3 [4.78]		
dimension B	131.1 [5.16]		153.0 [6.02]		

APPENDIX C: LOADCELL SPECIFICATIONS

The Leader in Force Measurement — Interface

Model WMC Miniature Sealed Stainless Steel Load Cell

Capacities 5-500 lbf (22-2200N)

- Proprietary Interface temperature compensated strain gages
- Tension & compression
- Small size
- Environmentally sealed

STANDARD CONFIGURATION

5 ft. (1.5m) Integral Cable

OPTIONS

Extra Cable Length
Submersible

ACCESSORIES

Instrumentation

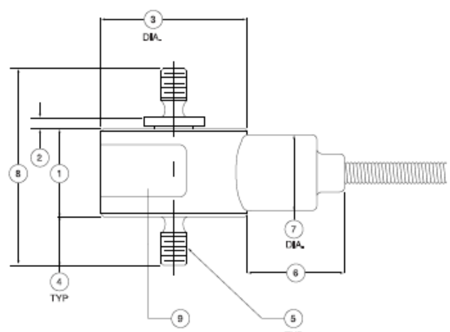
DIMENSIONS

See Drawing	CAPACITY					
	5, 10 lbf 22, 45 N		25, 50, 100 lbf 110, 220, 450 N		250, 500 lbf 1100, 2200 N	
	inch	mm	inch	mm	inch	mm
(1)	0.45	11.4	0.52	13.2	0.53	13.4
(2)	0.06	1.5	0.03	0.8	0.03	0.8
(3)	0.75	19.1	1.00	25.4	1.00	25.4
(4)	0.25	6.4	0.25	6.4	0.38	9.7
(5)	6-32 UNC M4x0.7		10-32 UNF M5x0.8		1/4-28 UNF M6x1	
(6)	0.50	12.7	0.50	12.7	0.50	12.7
(7)	0.39	9.9	0.39	9.9	0.39	9.9
(8)	1.01	25.7	1.05	26.7	1.32	33.5
(9)	label		label		label	

Deflection @ RO - inch (mm)						
5	10	25	50	100	250	500
0.0012 (0.030)	0.0010 (0.025)	0.0014 (0.036)	0.0010 (0.025)	0.0007 (0.018)	0.0026 (0.066)	0.0025 (0.064)

SPECIFICATIONS

ACCURACY – (MAX ERROR)	
Nonlinearity–% FS	±0.15
Hysteresis–% FS	±0.15
Nonrepeatability–% RO	±0.05
Creep, in 20 min–%	±0.05
TEMPERATURE	
Compensated Range–°F	15 to 115
Compensated Range–°C	-10 to 45
Operating Range–°F	-65 to 250
Operating Range–°C	-54 to 121
Effect on Output–%/°F – MAX	±0.002
Effect on Zero– % RO/°F – MAX	±0.005
ELECTRICAL	
Rated Output–mV/V (Nominal)	2.0
Zero Balance–%RO	±2.0
Bridge Resistance–Ohm (Nominal)	350
Excitation Voltage–MAX	12.0 VDC
Insulation Resistance–Megohm	> 5000
MECHANICAL	
Calibration	T & C
Safe Overload–% CAP	
5, 10 lbf (22, 45 N)	150
25-500 lbf (110-2200 N)	150
Cable length	5 ft. (1.5m)
Weight	0.05 - 0.12 (lb) 22.7 - 54.4 (g)



WMC Mini 5-500 lbf
4/6/12

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APPENDIX D: Pressure Sensor Specifications

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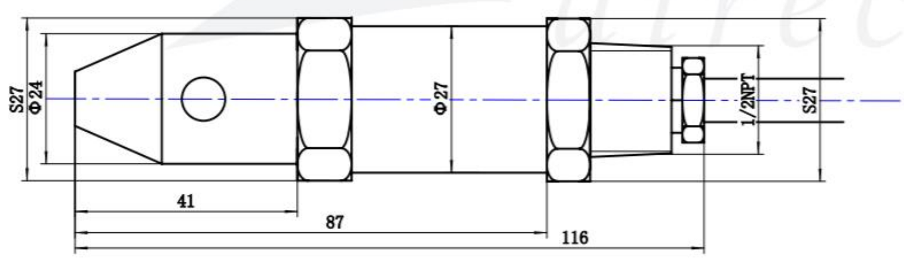
"APPLYING TODAY'S TOOLS WITH YESTERDAY'S EXPERIENCE PROVIDING OUR CUSTOMERS THE SOLUTIONS OF TOMORROW."

Introducing the Low Cost TDH80 series Submersible Pressure Transducer.

FEATURES

- Advanced piezoresistance technology
- All stainless steel construction
- Industry-standard 4-20mA output
- Pressure ranges 0-2.5, 0-10 and 0-15 PSIG (custom ranges available)
- Accuracy of 0.5%
- Long-term stability
- Nose cone or NPT thread available

DIMENSIONS



Dimensions are in mm and for reference only

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"APPLYING TODAY'S TOOLS WITH YESTERDAY'S EXPERIENCE PROVIDING OUR CUSTOMERS THE SOLUTIONS OF TOMORROW."

INSTALLATION & WIRING

Output: 4-20mA

Function	Color
Supply +	Green
Output +	White

SPECIFICATIONS

Performance @ 25°C (77°F)	
Accuracy	± 0.5% FS
Stability	<±0.2% FS/year, typical
Over pressure protection	1.5X Rated Pressure
Burst Pressure	3X minimum
Pressure Cycles	>4 Million
Environmental Data	
Operating temp	-20 to +80°C (-40 to +176°F)
Compensated range	-10 to 75°C (+14 to +167°F)
Electrical Data	
Excitation	12-36 Vdc
Loop resistance @ 24 Vdc:	≤ 750 Ohm
Zero offset	<±1.0% of FS
Span tolerance	<±1.0% of FS
Physical data	
Diaphragm material	316SS
Sealing material	Fluoro Rubber
Body material	316SS
Cable pull strength	300 lb.
Pressure connection	Bullet-Nose, 1/4" NPT
Electrical Connection	Molded, vented submersible cable (Polyethylene outer jacket)

ORDERING

Series	Output	Pressure Type	Pressure Range	Pressure Connection	Electrical Connection	Cable Length	Accuracy
TDH80	B	G	0050	00	C	20	3
TDH80 = 316 stainless steel	B= 4-20mA	G = Gauge	0025=0-2.5psi (69"WC) 0050= 0-5 psi (138" WC) 0100= 0-10 psi (277" WC) 0150= 0-15 psi (415" WC) 0200= 0-20 psi (554" WC) 0250= 0-25 psi (692" WC) 0500= 0-50 psi (1380" WC) **	00= Nose Cone 03= 1/4" NPT Male **	C= Cable	05 = 5 meter (16.4 ft) 10 = 10 meter (32.8 ft) 15 = 15 meter (49.2 ft) 20 = 20 meter (65.6 ft) 25 = 25 meter (82 ft) 30 = 30 meter (98.4 ft) **	3= 0.5% **

**= Consult factory for further options.

REV: 10.14

APPENDIX E: ACCELEROMETER SPECIFICATIONS

ADXL335

SPECIFICATIONS

T_A = 25°C, V_S = 3 V, C_X = C_Y = C_Z = 0.1 µF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Interaxis Alignment Error			±0.1		Degrees
Cross-Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	V_S = 3 V		±0.01		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)					
0 *g* Voltage at X_{OUT}, Y_{OUT}	V_S = 3 V	1.35	1.5	1.65	V
0 *g* Voltage at Z_{OUT}	V_S = 3 V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			150		µ*g*/√Hz rms
Noise Density Z_{OUT}			300		µ*g*/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency			5.5		kHz
SELF-TEST[6]					
Logic Input Low			+0.6		V
Logic Input High			+2.4		V
ST Actuation Current			+60		µA
Output Change at X_{OUT}	Self-Test 0 to Self-Test 1	−150	−325	−600	mV
Output Change at Y_{OUT}	Self-Test 0 to Self-Test 1	+150	+325	+600	mV
Output Change at Z_{OUT}	Self-Test 0 to Self-Test 1	+150	+550	+1000	mV
OUTPUT AMPLIFIER					
Output Swing Low	No load		0.1		V
Output Swing High	No load		2.8		V
POWER SUPPLY					
Operating Voltage Range		1.8		3.6	V
Supply Current	V_S = 3 V		350		µA
Turn-On Time[7]	No external filter		1		ms
TEMPERATURE					
Operating Temperature Range		−40		+85	°C

[1] Defined as coupling between any two axes.
[2] Sensitivity is essentially ratiometric to V_S.
[3] Defined as the output change from ambient-to-maximum temperature or ambient-to-minimum temperature.
[4] Actual frequency response controlled by user-supplied external filter capacitors (C_X, C_Y, C_Z).
[5] Bandwidth with external capacitors = 1/(2 × π × 32 kΩ × C). For C_X, C_Y = 0.003 µF, bandwidth = 1.6 kHz. For C_Z = 0.01 µF, bandwidth = 500 Hz. For C_X, C_Y, C_Z = 10 µF, bandwidth = 0.5 Hz.
[6] Self-test response changes cubically with V_S.
[7] Turn-on time is dependent on C_X, C_Y, C_Z and is approximately 160 × C_X or C_Y or C_Z + 1 ms, where C_X, C_Y, C_Z are in microfarads (µF).

APPENDIX F: GENERAL FROUDE SCALING TABLE

Table 16: Froude Scaling Table

Quantity	Froude Scaling	Reynolds Scaling
wave height and length	s	s
wave period and time	$s^{0.5}$	s^{2}
wave frequency	$s^{-0.5}$	s^{-2}
power density	$s^{2.5}$	s^{-2}
linear displacement	s	s
angular displacement	1	1
linear velocity	$s^{0.5}$	s^{-1}
angular velocity	$s^{-0.5}$	s^{-2}
linear acceleration	1	s^{-3}
angular acceleration	s^{-1}	s^{-4}
mass	s^{3}	s^{3}
force	s^{3}	1
torque	s^{4}	s
pressure	s	s^{-2}
power	$s^{3.5}$	s^{-1}
linear stiffness	s^{2}	
angular stiffness	s^{4}	
linear damping	$s^{2.5}$	
angular damping	$s^{4.5}$	

APPENDIX G: DETAILED CRIO MODULE CHANNEL LIST

Module:	**NI 9361**				
Run on:	FPGA				
Description:	Module with 8 counter channels - we are using to read all 4 motor encoders				
Notes:	Not enough channels to read Z. Velocity counters use the same inputs as position counters. Encoder counts likely to range between +/-50,000 counts/s (+/- 300 rpm). Encoder is 1000 counts/rev.				
PTO	Counter	Measurement Type	Encoder Channel	Pin Function	Pin
Motor 1	CTR0	Quad Encoder Position	A	DI0+	9
				DI0-	28
			B	DI4+	16
				DI4-	35
Motor 2	CTR1	Quad Encoder Position	A	DI1+	11
				DI1-	30
			B	DI5+	14
				DI5-	32
Motor 3	CTR2	Quad Encoder Position	A	DI2+	3
				DI2-	22
			B	DI6+	6
				DI6-	24
Motor 4	CTR3	Quad Encoder Position	A	DI3+	1
				DI3-	20
			B	DI7+	7
				DI7-	26
Motor 1	CTR4	Quad Encoder Velocity	A	DI0+	9
				DI0-	28
			B	DI4+	16
				DI4-	35
Motor 2	CTR5	Quad Encoder Velocity	A	DI1+	11
				DI1-	30
			B	DI5+	14
				DI5-	32
Motor 3	CTR6	Quad Encoder Velocity	A	DI2+	3
				DI2-	22
			B	DI6+	6
				DI6-	24

Motor 4	CTR7	Quad Encoder Velocity	A	DI3+	1
				DI3-	20
			B	DI7+	7
				DI7-	26

Module:	**NI 9237**		
Run on:	FPGA		
Description:	4 Analog Input Bridge - We are using this module to measure 4 load cells		
Notes:	RS is for remote sensing, T is for TEDS data, and SC for shunt calibration, all of which we are not using.		
PTO	Bridge/ Load Cell	Channel Function	Pin
PTO1	0	EX+	2
		EX-	21
		AI+	3
		AI-	22
PTO2	1	EX+	6
		EX-	25
		AI+	7
		AI-	26
PTO3	2	EX+	12
		EX-	31
		AI+	13
		AI-	32
PTO4	3	EX+	16
		EX-	35
		AI+	17
		AI-	36

Module:	**NI 9401**		
Run on:	Real Time OS		
Description:	8 Channel DIO - We are using to enable/disable the motor controllers		
Notes:			
PTO	Use	Channel	Pin
Driver 1	Digital Out	DIO0	14
		COM	13
Driver 2	Digital Out	DIO1	16

		COM	12
Driver 3	Digital Out	DIO2	17
		COM	10
Driver 4	Digital Out	DIO3	19
		COM	9

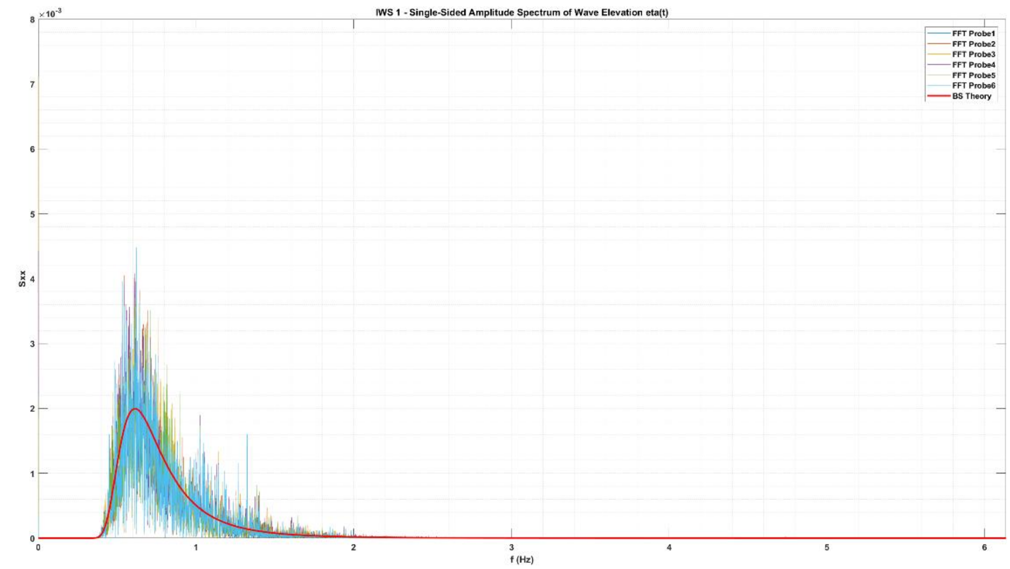
Module:	**NI 9263**	
Run on:	Real Time OS	
Description:	4 Channel AO - Used to control motor speed	
Notes:		
Use	Channel	Pin
Motor 1	AO0	0
	COM	1
Motor 2	AO1	2
	COM	3
Motor 3	AO2	4
	COM	5
Motor 4	AO3	6
	COM	7

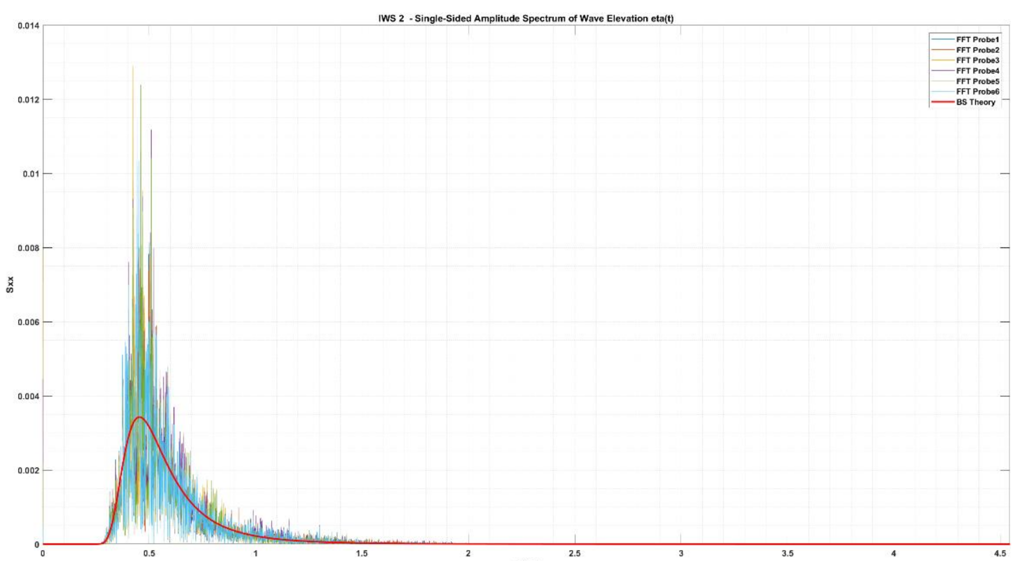
Module:	**NI 9205**	
Run on:	Real Time OS	
Description:	16 Analog Input Differential, 32 Analog input Single Ended. Used to read motor velocity from the drive contollers.	
Notes:	See gettings started guide for differential pairs, currently using in single ended mode.	
Use	Channel	Pin
Motor 1 Speed	AI0	1
Motor 2 Speed	AI1	2
Motor 3 Speed	AI2	3
Motor 4 Speed	AI3	4
Wave Gauge 1	AI4	5
Wave Gauge 2	AI5	6
Wave Gauge 3	AI6	7

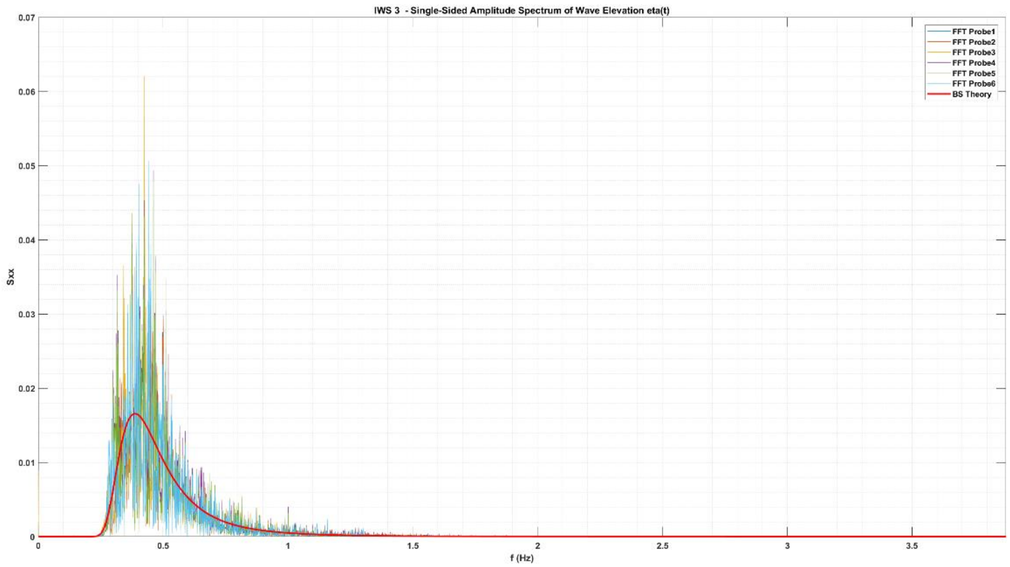
CalWave Power Technologies

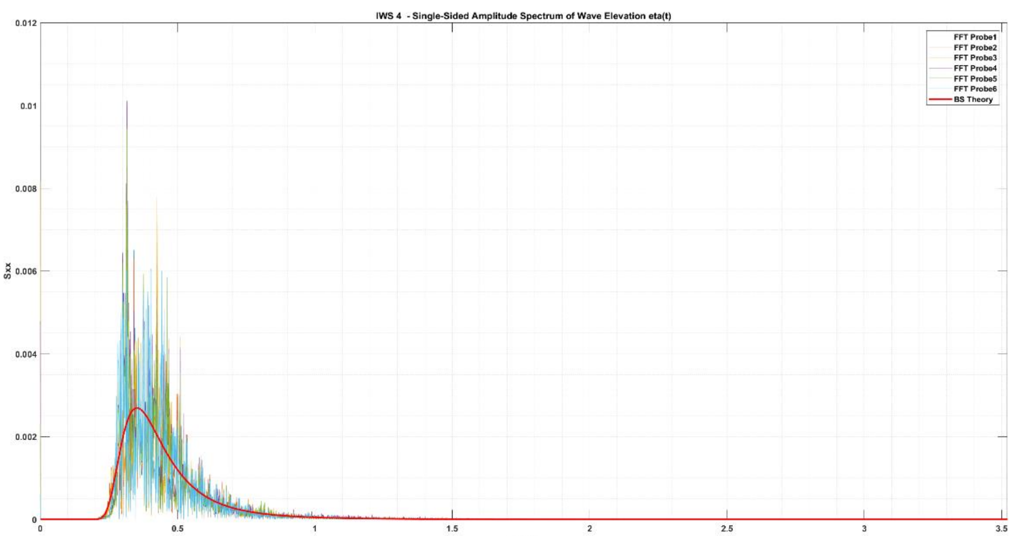
Wave Gauge 4	AI7	8
Wave Gauge 5	AI8	19
Pressure 1	AI9	20
Pressure 2	AI10	21

APPENDIX H: WAVE CALIBRATION IRREGULAR WAVES






IWS 3 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)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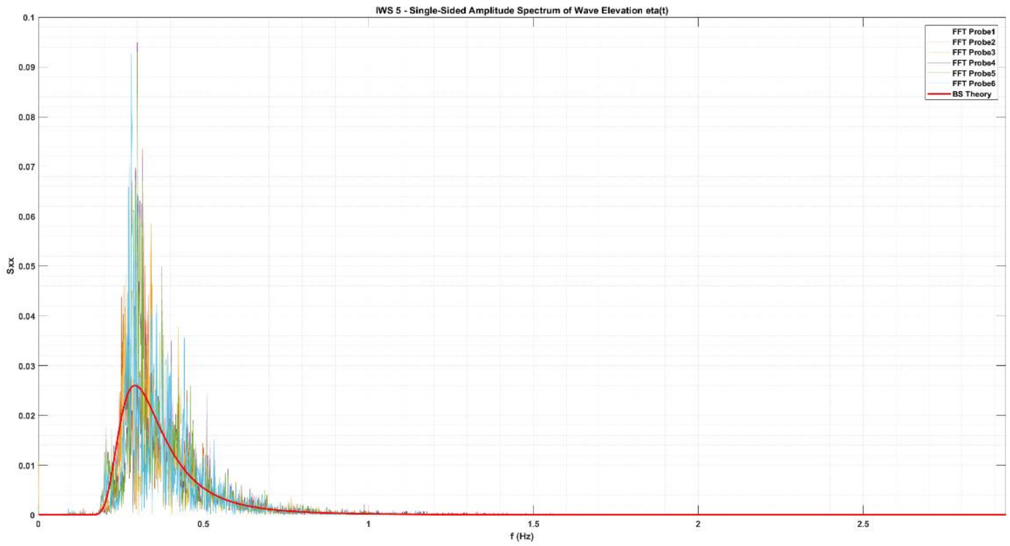
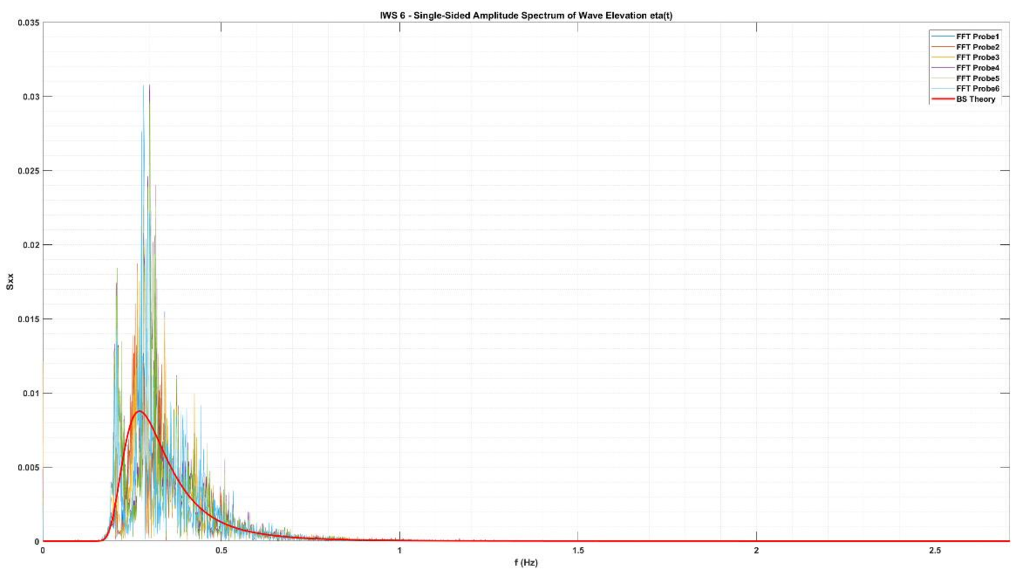
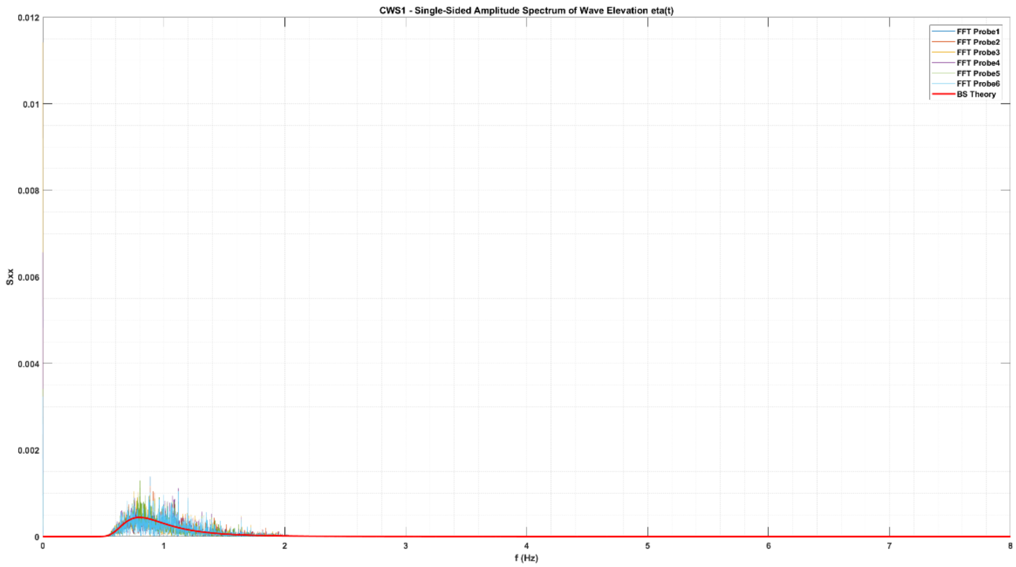
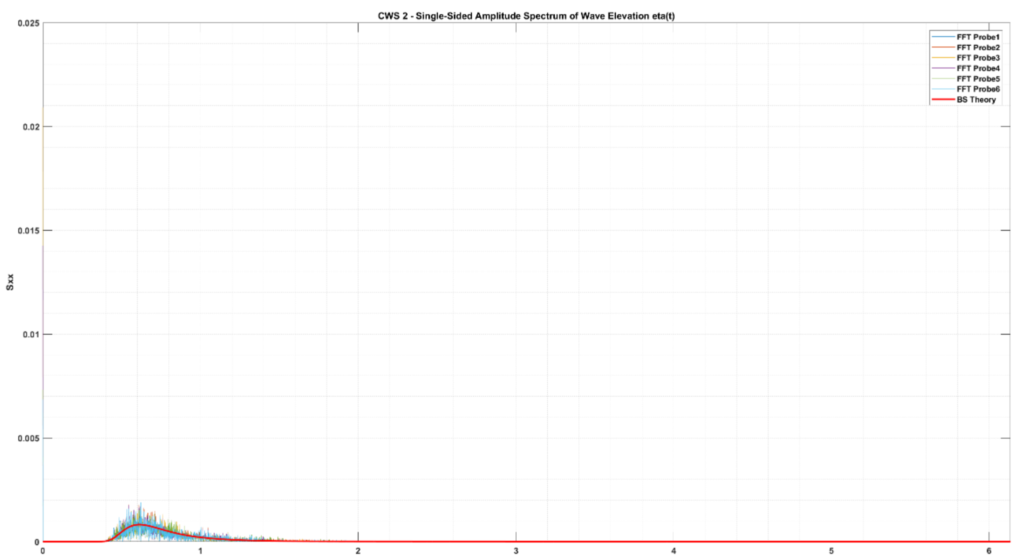
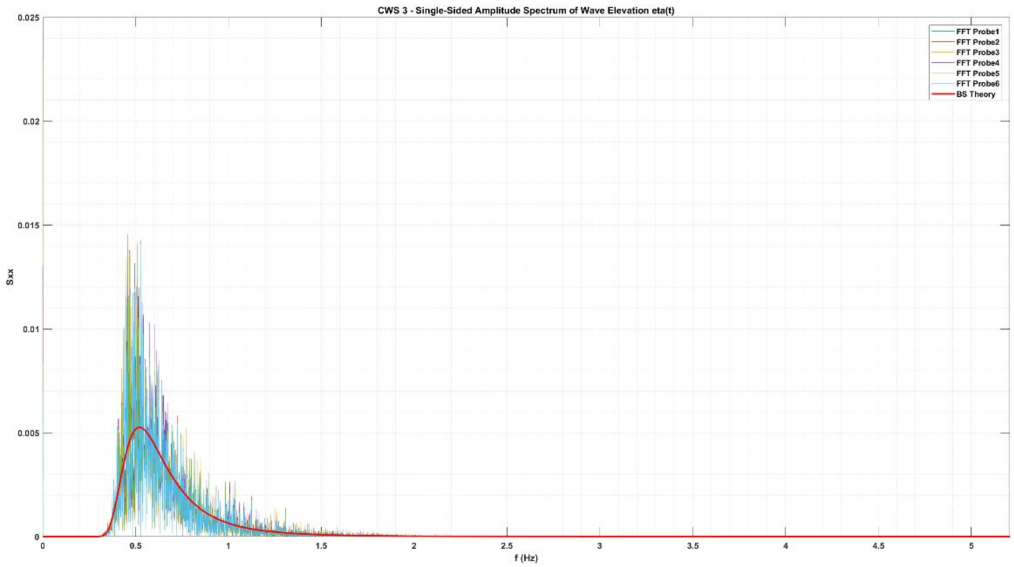
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)

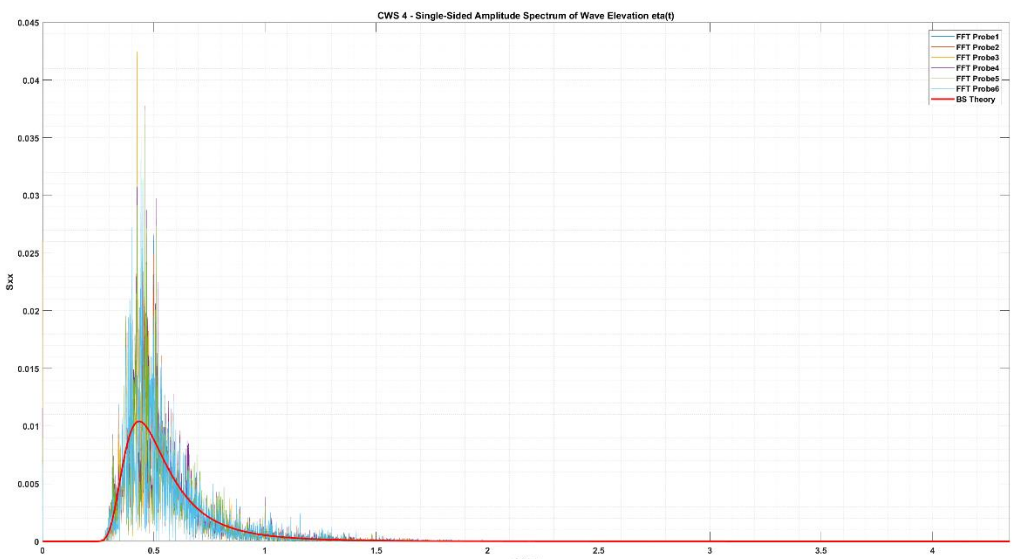

IWS 5 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


IWS 6 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS1 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS 2 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS 3 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS 4 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)

APPENDIX I: WAVE CALIBRATION PINK NOISE (EXAMPLE FOR 1 REALIZATION)