User Organisation (Insert Organisation)

User Project: Validation of Power & Stability outputs from CFX modelling

Project Acronym: POSTCFX

Project Reference Number: 1192

Infrastructure Accessed Oceanide - BGO FIRST Basin

ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

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Table of Contents

1 Acknowledgements

The work undertaken below could not have been achieved without the support of the Marinet2 program.

This effort was also facilitated, with exceptional enthusiasm, by the staff at the Oceanide-BGO First testing facility who were incredibly helpful in every regard, and with whom we would count ourselves very lucky to work with again in the future.

2 Introduction & Background

2.1 Introduction

The Waveram is a spar type heaving point absorber with adjustable mass, spring[CS1], and PTO damping intended to operate effectively in a changing environment using autonomous control. It is a single rigid structure reacting against the sea surface, a configuration not previously considered. Being a single body removes engineering challenges such as hinges, alignment and end-stops. The concept has been tested at scale previously and this data used for initial calibration of simulation models. This test series seeks to assert the efficacy of the simulation models by providing a second data set away from the calibration point.

2.2 Development so far

The Waveram has undergone extensive preliminary testing at lab scale[1] (~1:75) at Omey Labs in Ireland prior to its first deployment at small scale (~1:42) at École Central de Nantes in June of 2015 facilitated by Marinet access and SEAI OCN-00023. This testing set prompted revisions to the central column and tanks of the model before it was tested again, at the same facility, in November of the same year.

In parallel with this empirical testing, the model has been characterised using WAMIT, WEC-sim, and Ansys CFX. To date the WEC-sim and CFX models have been calibrated against the existing test data sets. This set of tests is required in order to refine these simulation model’s capabilities, and to assert confidence in the results.

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[1] Scale is referenced to full-scale for the North Atlantic wave climate as recorded at AMETS Berth B

2.2.1 Stage gate progress

Previously completed: ✓

Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)	➲
• Finite monochromatic waves to include higher order effects (25 –100 waves)	✓
• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)	✓
• Restricted degrees of freedom (DofF) if required by the early mathematical models	✓
• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)	➲
• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable	
• Real seaway productivity (scaled duration at 20-30 minutes)	➲
• Initially 2-D (flume) test programme	✓
• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them	
• Evidence of the device seaworthiness	✓
• Initial indication of the full system load regimes	➲
Stage 2 – Design Validation	
• Accurately simulated PTO characteristics	✓
• Performance in real seaways (long and short crested)	➲
• Survival loading and extreme motion behaviour.	
• Active damping control (may be deferred to Stage 3)	
• Device design changes and modifications	➲
• Mooring arrangements and effects on motion	➲
• Data for proposed PTO design and bench testing (Stage 3)	
• Engineering Design (Prototype), feasibility and costing	
• Site Review for Stage 3 and Stage 4 deployments	
• Over topping rates	
Stage 3 – Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	
• To employ a realistic/actual PTO and generating system & develop control strategies	
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	
• To validate electrical supply quality and power electronic requirements.	
• To quantify survival conditions, mooring behaviour and hull seaworthiness	
• Manufacturing, deployment, recovery and O&M (component reliability)	
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality (absorbed/pneumatic power-converted/electrical power)	
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	

STAGE GATE CRITERIA	Status
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	
• Device array interactions	
• Power supply interaction & quality	
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

2.2.2 Plan for this access

The primary purpose of this access request is to verify the device design decisions based on empirical results to date, and subsequent CFD analyses. This is in preparation for an extended Stage 3 programme that will also incorporate an active PTO to investigate control strategy options.

The objectives for this access are, therefore:

1. To validate the CFD simulation models as they presently stand by comparing predicted model performance and behaviour characteristics against the empirical model.
2. Failing CFD results convergence, to use this dataset to further advance the simulation models.
3. To confirm that model revisions made since the previous testing have achieved their desired effects without impacting on the ability to avoid parametric response.
4. To measure loads and stresses in advance of FEA calculations and structural design validation.

3 Outline of work carried out

3.1 Efforts at Oceanide

Here follows a summary of the nature of the work conducted at the Oceanide Facilty. In depth technical detail is provided in the facility produced report 'D40.1.R.SWIRL.WaveramModelTests.docx' and is not repeated here.

	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9	D 10	D 11	D 12	D 13	D 14	D 15
Equipment setup & Basin setup	■	■													
Sea states for CFD Validation			■	■											
Internal wave guage calibration				■											
Free decay tests				■	■										
Mooring characterisation tests					■	■									
Performance tests (Mono & BS)						■	■	■	■	■	■	■	■	■	
Recovery and packing															■

Table 1 Testing Gantt chart

3.1.1 Equipment setup & Basin setup

The initial days of access were used to unpack the model, assemble, install and function test the onboard instrumentation, interface the instruments to the facility's DAQ system and ready the model for deployment to the basin.

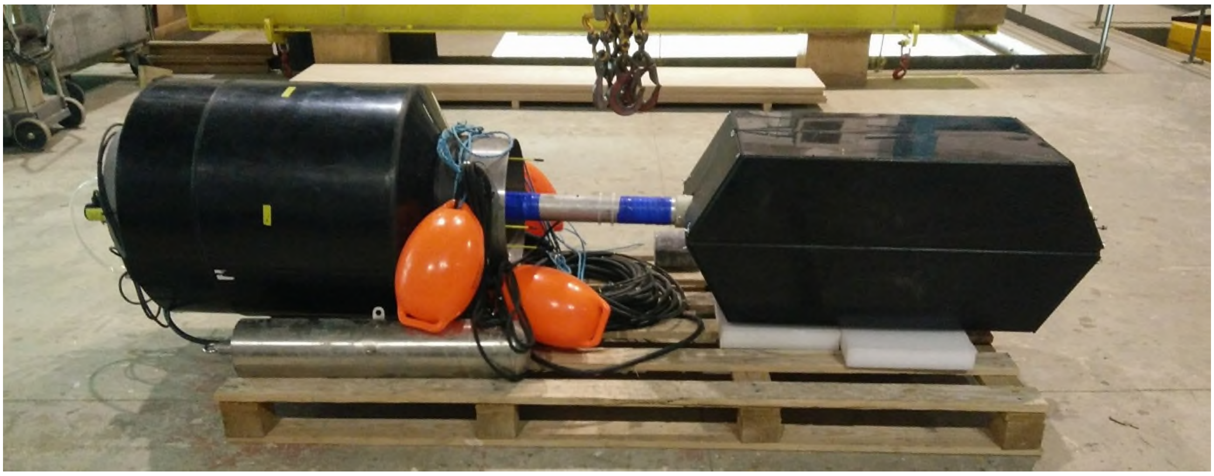

Figure 1 - Waveram awaiting deployment

In parallel with this effort, the basin was readied to run the calibration sea states. This involved the installation of wave probes in accordance with industry standards[WD2][WD3][SO4] for free surface measurement and characterisation, and the readying of the motion capture camera.

3.1.2 Sea states for CFD Validation

In this task, a spectrum of BS sea states which reflect the scaled annual scatter diagram for the AMETS testing site off the west coast of Ireland, was run without the model in place and was measured so as to provide a verification of the sea state being produced, as well as a baseline to permit calculation of the radiated wave field from the device.

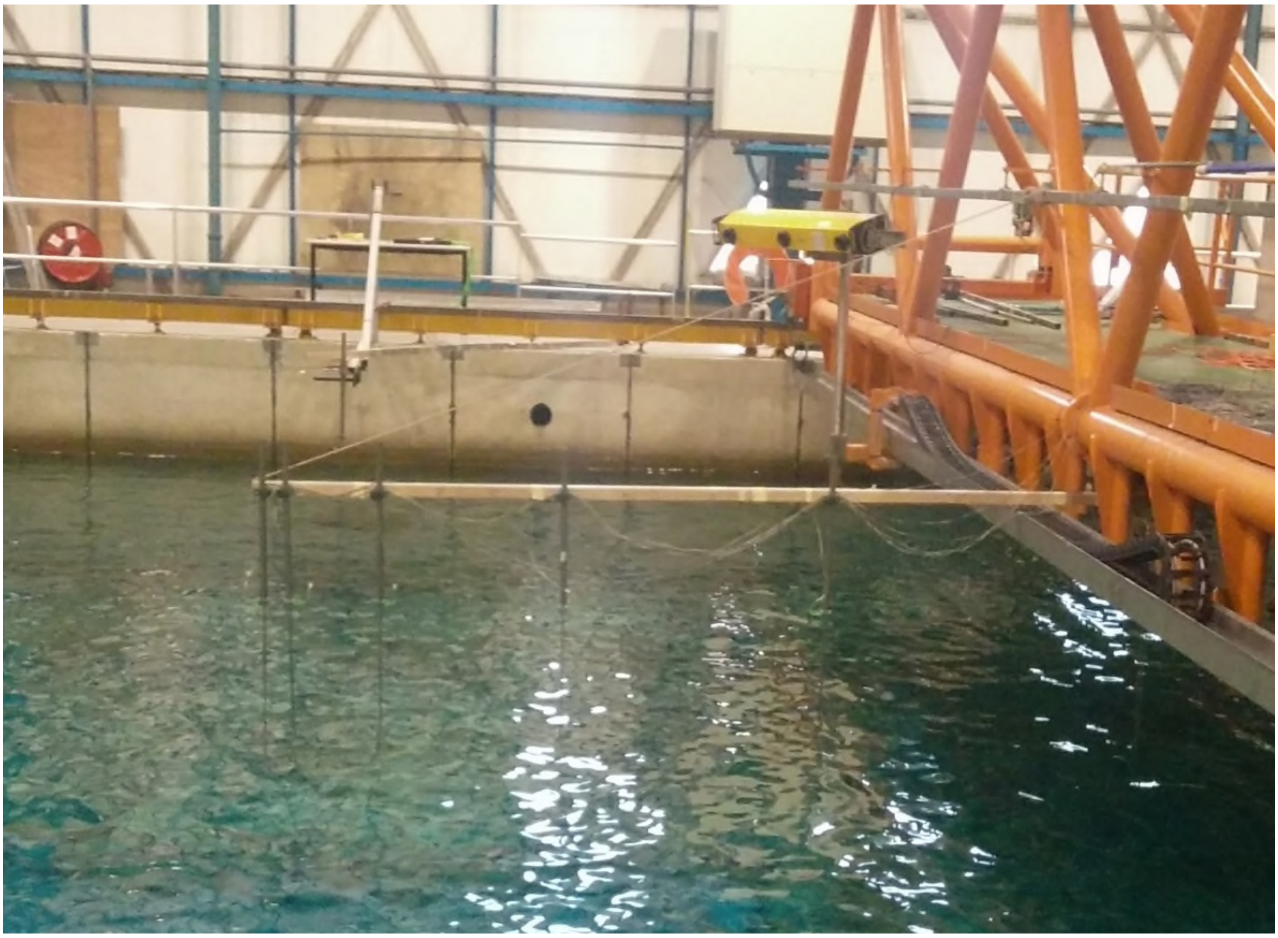

Figure 2 - Free surface characterisation wave probe array

3.1.3 Internal wave gauge calibration

The Waveram has three internal capacitive type wave probes. These were calibrated prior to fitment but a verification of the span response is conducted at the onset of testing as a matter of principle.

Figure 3 - Waveram 'Wavestaff' internal free surface monitoring gauges

3.1.4 Free decay tests

With the model deployed to the basin, in advance of sea state testing of any individual configuration, the model was displaced in each of the Heave, Pitch and Surge modes, and permitted to return to rest. The entire process from starting at rest, to being displaced, to returning to rest, was recorded and the results may be used as a basis for comparison in simulations and as a check of the related hydrodynamic coefficients.

3.1.5 Mooring characterisation tests

A single mooring line and load cell combination was subjected to a force in the horizontal plane through the displacement of the model. The displacement was recorded in conjunction with the load experienced by the line at the point where it coupled to the model through the load cell. This analysis is used in simulation as a basis for the assertion of a linear approximation to the lateral restoring force of the mooring arrangement – this approximation avoids the need to fully model the mooring lines which reduces the computational effort required.

3.1.6 Performance tests

The model was tested in a variety of tuned states and with a variety of PTO orifice plates, in a broad range of both monochromatic and Bretschneider sea states, the latter being those states which were verified at the onset of testing in the absence of the model. During testing the following parameters are recorded:

- Model motions were recorded using the facility Krypton Rodym motion capture system
- Free surface condition was monitored at 8 points using the facility wave gauges
- Mooring loads were recorded on each line at the interface to the model using the facility load cells
- Chamber pressures on the model were recorded using onboard Honeywell differential pressure sensors
- The interior free surface elevation was monitored using three capacitive type OSSI Wavestaff units
- Test video footage was captured using a facility provided camera

All data was synchronously captured by the facility DAQ system.

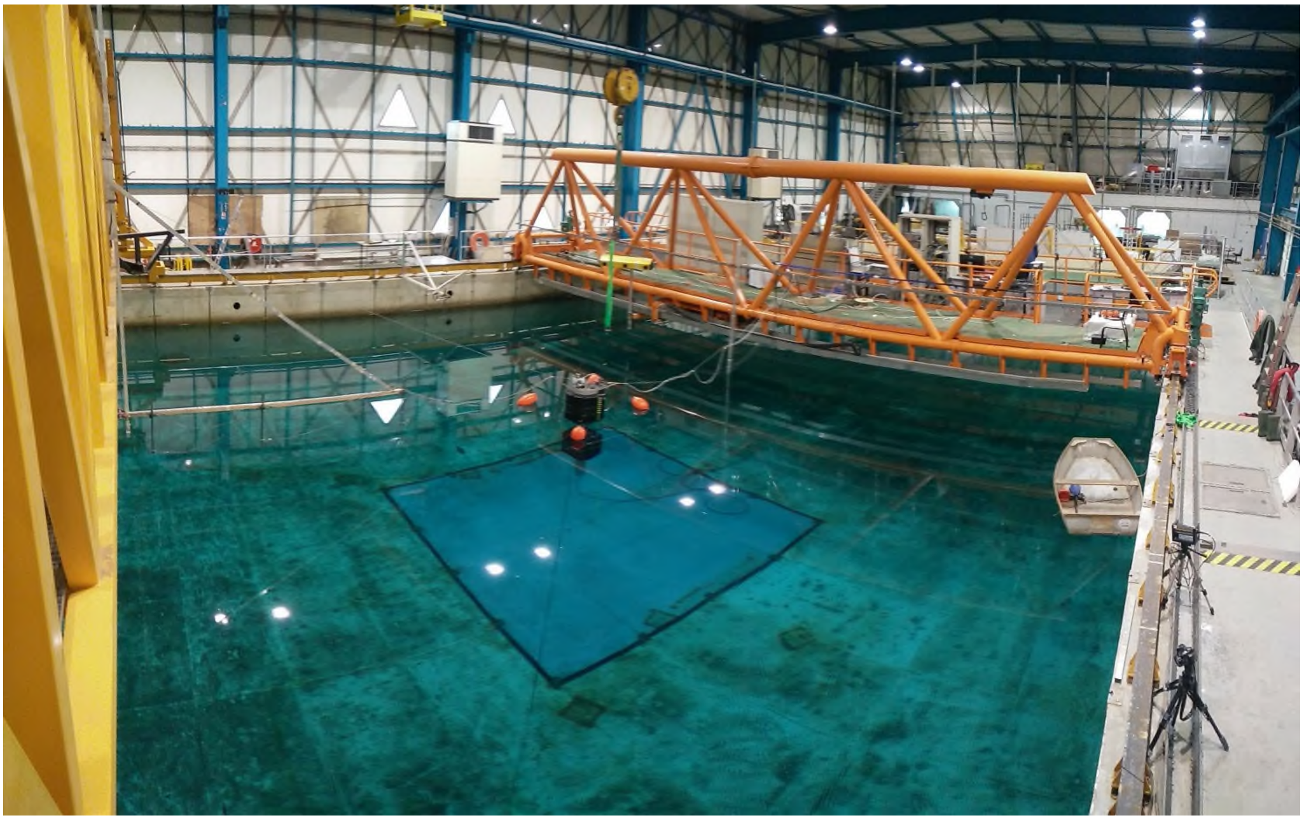

Figure 4 - Waveram deployed in the basin. The blue square closes off a 5mx5mx5m pit in the center of the basin.

3.1.7 Recovery and packing

The model was removed from the tank, mooring lines were recovered and all equipment was repacked for transport. All tests data was copied to SGL. This removal process, and indeed all hardware installation or removal operations in the tank are greatly facilitated by the moving floor, which is raised when access is required for such tasks, meaning that boat operations are unnecessary and the whole workflow is improved significantly.

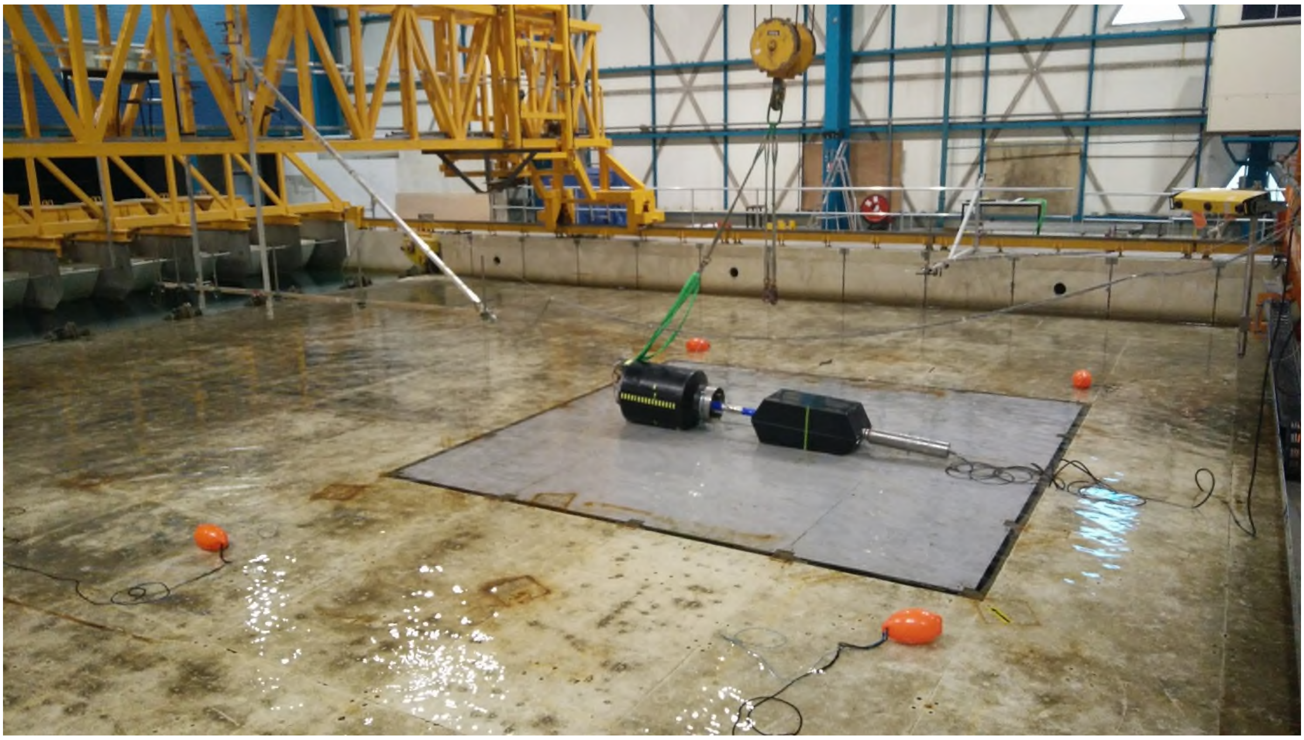

Figure 5 - Basin floor raised for model and mooring recovery

3.2 Data post-processing

3.2.1 Eigenperiods

Heave and pitch eigenperiods were calculated from decay tests, both in the time domain (by Oceanide) and frequency domain (by SGL). Negligible differences were found between the two methods. All eigenvalues are tabulated in Table 2, and as expected, significant heave eigenperiod differences can be seen for each of the tank settings. The differences in pitch eigenperiod were negligible across the various configurations, hence why only one value is shown.

Mode	Configuration	Eigenperiod (s) Model Scale	Eigenperiod (s) AMETS Scale
Heave	Vented Tank	1.719	10.46
Heave	Half Tank	2.129	12.95
Heave	Full Tank	2.514	15.29
Pitch	All Tanks	4.220	25.67

Table 2 - Eigenperiods

3.2.2 RAOs

Figure 6 shows the motion RAOs that have been produced from the regular sea state tests, overlaid with the eigenperiods. Firstly, it can be seen that venting or partial venting significantly varies the response motion. This indicates the benefits of using tank venting as a mechanism for controlling the motion of the device in different sea states.

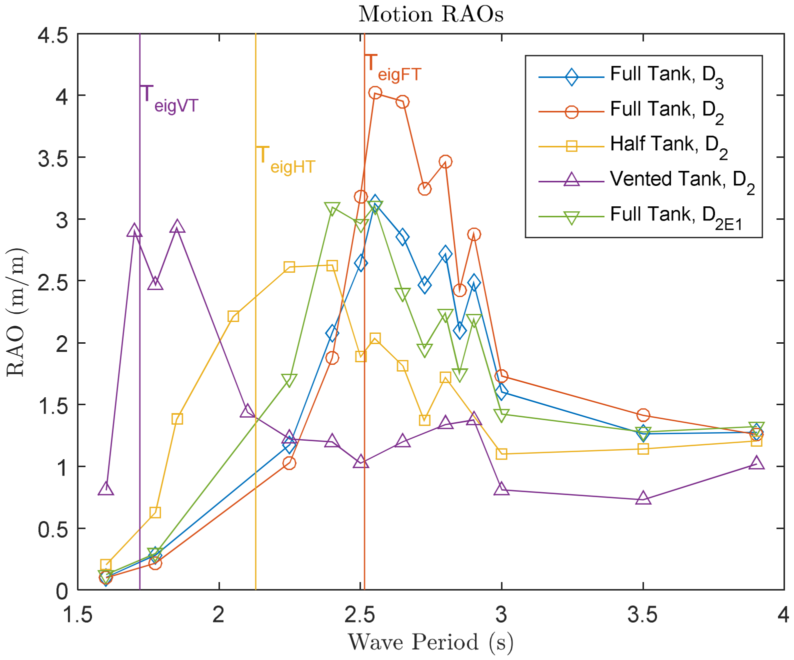

Figure 6 - Motion RAOs

For the Full Tank configuration, a comparison of the damping values shows that higher damping coefficients result in smaller motion. Note that higher damping coefficients result in higher pressures. This indicates that designing the WEC for high motion RAOs does not necessarily translate to increased power capture, since power is dependent on both pressure and flow rate (motion).

It was observed during the analysis that the heave oscillations did not reach a uniform steady-state for some of the tests. Future regular test durations should be increased, perhaps doubled, for the longer period waves.

Figure 7 shows the power RAO profiles. It can be seen that the full tank and correctly tuned damping configuration produces power that envelopes the other configurations. This suggests that while tank venting can shift the motion response with respect to frequency, thereby helping with survivability, it appears that venting does not necessarily help increase power capture.

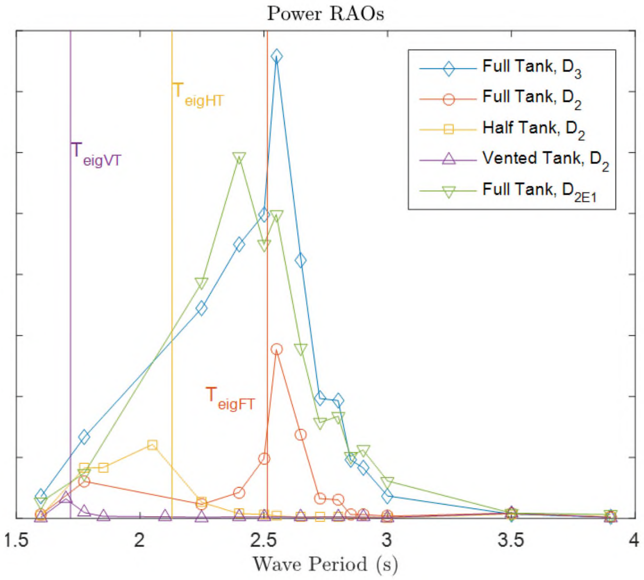

Figure 7 - Power RAOs

3.2.3 Selected Irregular Sea States from AMETS Scatter

The nineteen sea states in Table 3 were selected for the irregular tests, intended to encapsulate the 2016 AMETS scatter, such that most other untested scatter cells could be interpolated rather than extrapolated. For the larger sea states the H_s value was limited by the capabilities of the wave maker, so some cell values had to be obtained through extrapolation. The sea states tested in the tank are highlighted in Figure 8 with a black border.

Sea State #	Hs	Tp	Te
1	0.020	1.486	1.233
2	0.020	1.882	1.562
3	0.034	1.089	0.904
4	0.047	2.278	1.891
5	0.061	1.089	0.904
6	0.061	1.486	1.233
7	0.088	1.882	1.562
8	0.101	1.486	1.233
9	0.101	2.674	2.219
10	0.115	3.070	2.548
11	0.128	2.278	1.891
12	0.155	1.882	1.562
13	0.182	2.674	2.219
14	0.182	3.070	2.548
15	0.196	3.268	2.713
16	0.223	2.278	1.891
17	0.236	2.674	2.219
18	0.250	3.070	2.548
19	0.291	3.070	2.548

Table 3 - Irregular Sea States

	Full Scale	**Scaled Down**																				
Hs (m)	15.75	0.426	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	15.25	0.412	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14.75	0.399	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14.25	0.385	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
	13.75	0.372	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
	13.25	0.358	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
	12.75	0.345	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
	12.25	0.331	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0
	11.75	0.318	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0
	11.25	0.304	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	1	1	1	0	0
	10.75	**0.291**	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5	3	0	0	0	0
	10.25	0.277	0	0	0	0	0	0	0	0	0	0	0	0	1	10	0	4	0	0	0	0
	9.75	**0.264**	0	0	0	0	0	0	0	0	0	0	0	0	4	22	10	4	0	0	0	0
	9.25	**0.250**	0	0	0	0	0	0	0	0	0	0	0	0	7	29	6	2	0	0	0	0
	8.75	**0.236**	0	0	0	0	0	0	0	0	0	0	0	0	16	29	6	1	0	0	0	0
	8.25	**0.223**	0	0	0	0	0	0	0	0	0	0	0	1	33	16	3	0	0	0	0	0
	7.75	0.209	0	0	0	0	0	0	0	0	0	0	0	10	68	11	0	0	0	0	0	0
	7.25	**0.196**	0	0	0	0	0	0	0	0	0	0	0	37	87	17	2	3	1	0	0	0
	6.75	**0.182**	0	0	0	0	0	0	0	0	0	0	11	77	70	33	7	5	0	0	0	0
	6.25	0.169	0	0	0	0	0	0	0	0	0	0	46	68	64	21	4	6	0	0	0	0
	5.75	**0.155**	0	0	0	0	0	0	0	0	0	4	83	73	90	13	9	4	0	0	0	0
	5.25	0.142	0	0	0	0	0	0	0	0	0	31	167	68	71	27	3	0	0	0	0	0
	4.75	**0.128**	0	0	0	0	0	0	0	0	0	100	154	87	68	43	0	0	0	0	0	0
	4.25	**0.115**	0	0	0	0	0	0	0	0	25	177	155	85	63	10	1	1	0	0	0	0
	3.75	**0.101**	0	0	0	0	0	0	0	2	108	199	173	95	31	9	0	0	0	0	0	0
	3.25	**0.088**	0	0	0	0	0	0	0	26	209	243	157	53	15	0	0	0	0	0	0	0
	2.75	0.074	0	0	0	0	0	0	7	99	210	116	153	34	9	0	0	0	0	0	0	0
	2.25	**0.061**	0	0	0	0	0	1	68	189	156	127	101	18	9	0	0	0	0	0	0	0
	1.75	**0.047**	0	0	0	0	0	12	93	150	101	72	29	10	11	0	0	0	0	0	0	0
	1.25	**0.034**	0	0	0	0	0	29	106	64	36	21	3	0	0	0	0	0	0	0	0	0
	0.75	**0.020**	0	0	0	0	0	0	1	5	15	11	0	0	0	0	0	0	0	0	0	0
	0.25	0.007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Full Scale	**Te (s)**	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
		Tp (s)	0.602	1.807	3.012	4.217	5.422	6.627	7.831	9.036	10.241	11.446	12.651	13.855	15.060	16.265	17.470	18.675	19.880	21.084	22.289	23.494
	Scaled Down	**Te (s)**	0.082	0.247	0.411	0.575	0.740	**0.904**	1.069	**1.233**	1.397	**1.562**	1.726	**1.891**	2.055	**2.219**	2.384	**2.548**	**2.713**	2.877	3.041	3.206
		Tp (s)	0.099	0.297	0.495	0.693	0.891	**1.089**	1.287	**1.486**	1.684	**1.882**	2.080	**2.278**	2.476	**2.674**	2.872	**3.070**	**3.268**	3.466	3.664	3.862

Figure 8 - Selected AMETS Scatter Sea States

3.2.4 Determination of the Orifice Plate Damping through System Identification

The damping coefficient for each damping plate has been calculated using Greybox System Identification, where an iterative process is used to select a coefficient that best matches the measured data with the underlying physics of compressible air in an open chamber. This effort was undertaken because the usual formula for orifice damping plates did not produce simulated pressures that matched the measured values. The causes of this discrepancy are unknown exactly, but it is considered that it may be due to the fact that orifice plates are usually calibrated in steady uniform flow, as opposed to the oscillating irregular conditions here. This should definitely be further studied in subsequent research. The following range of irregular sea states were used in the system ID process, using the full tank configuration:

Hs	Tp
0.182	3.070
0.196	3.268
0.223	2.278
0.236	2.674
0.250	3.070
0.291	3.070

Figure 9 to Figure 12 show plots of measured pressure and simulated pressure. As can be seen the converged damping coefficients led to a very good fit between the measured and simulated data, providing a high level of confidence in the coefficients.

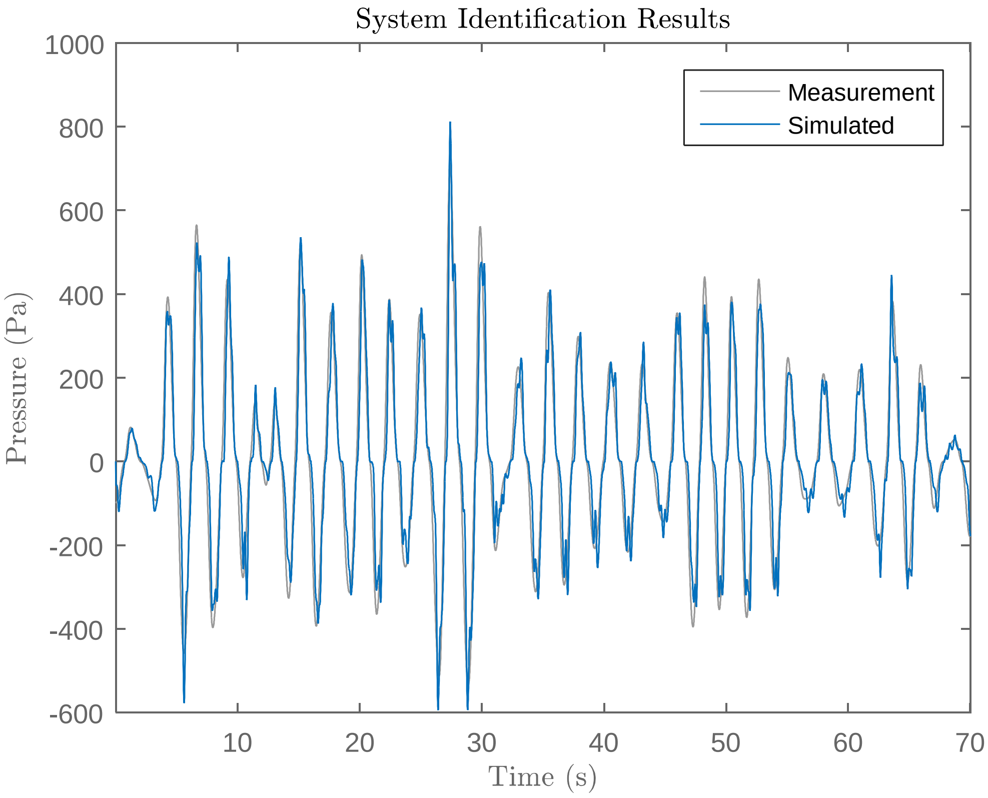

Figure 9 - System ID Results for S3_T2_D3_BS1_H0p196_T3p268

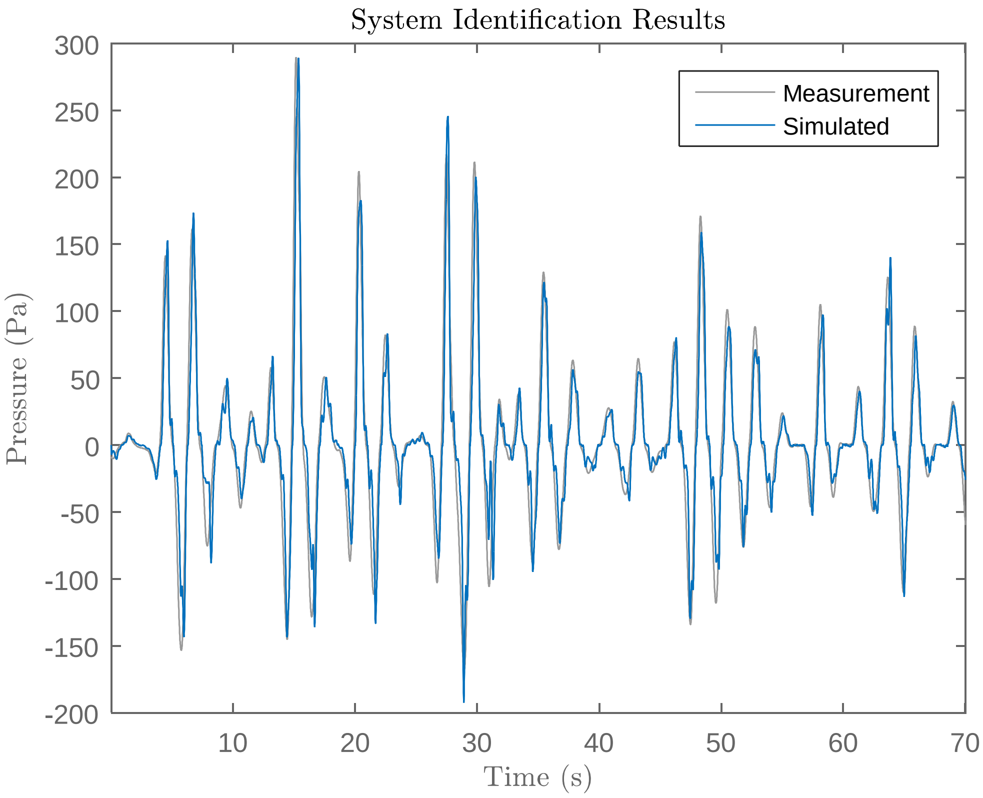

Figure 10 - System ID Results for S3_T2_D2_BS1_H0p223_T2p278

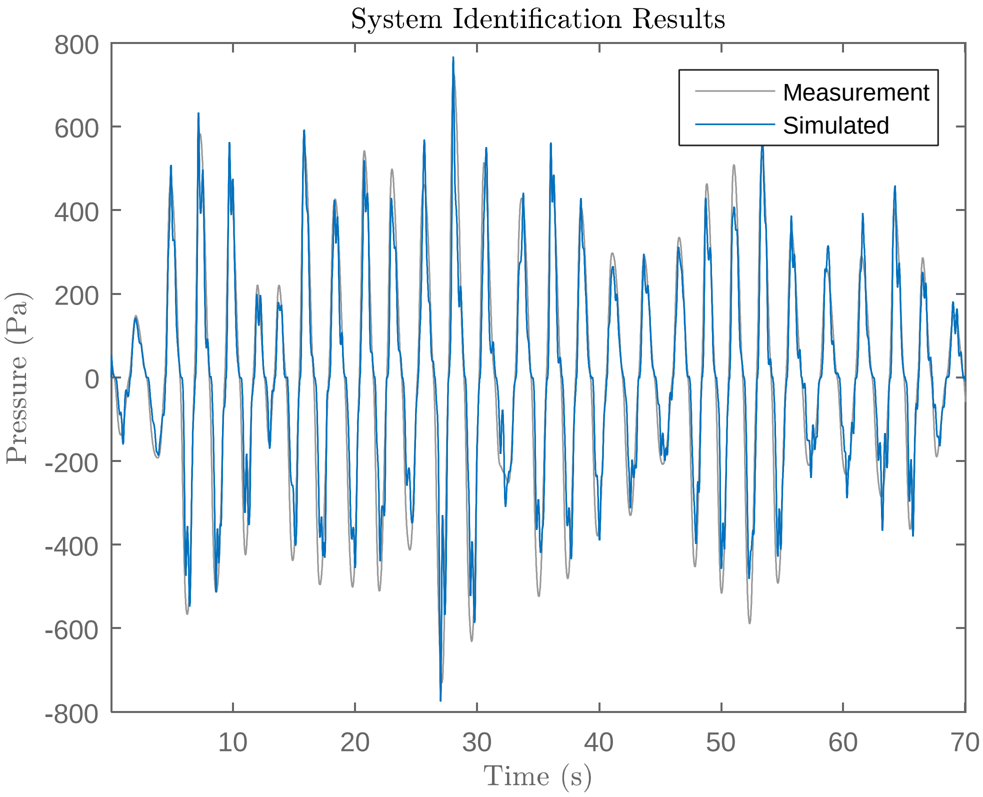

Figure 11 - System ID Results for S3_T2_D2E1_BS1_H0p182_T3p070

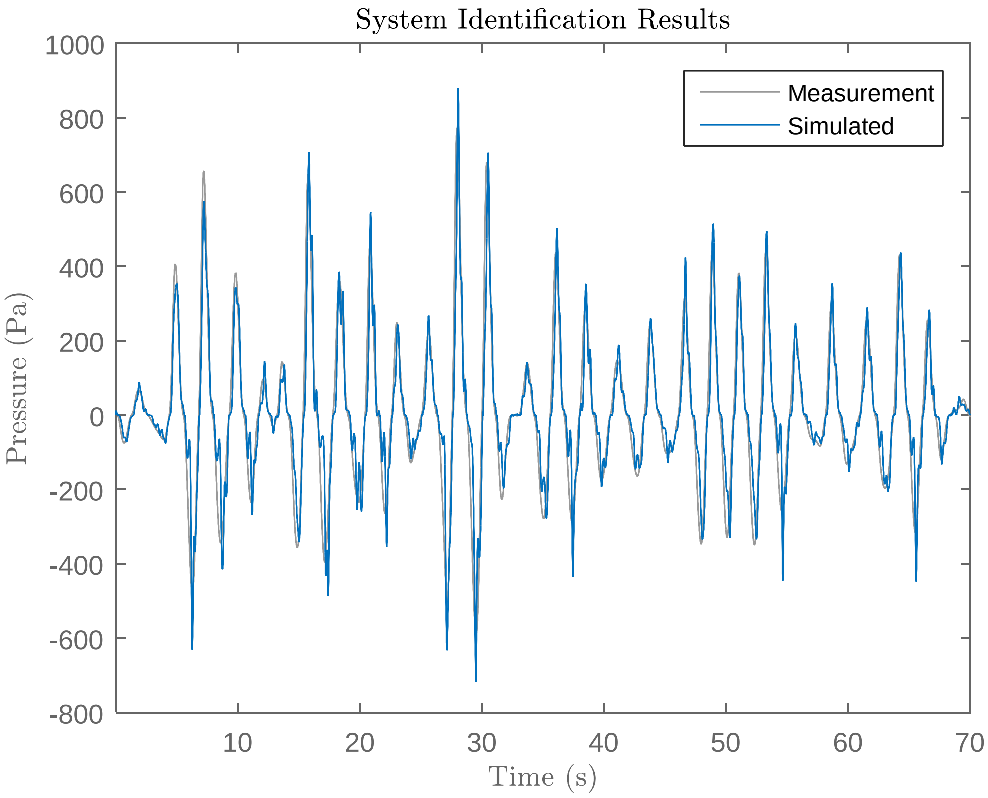

Figure 12 - S3_T2_D2E4_BS1_H0p250_T3p070

3.2.5 Mooring Stiffness Characterisation

The mooring stiffness was characterised by applying an arbitrary series of forces to displace the WEC model in pitch. The model was pulled with one mooring line, reacting against the diametrically opposite mooring. Note, the line of action was oriented at approximately 45 degrees with respect to the X and Y directions in the tank's global coordinate system. Consequently, the mooring displacement was computed by projecting the X and Y displacements onto the mooring line's direction. Since the line of action was aligned visually, the force projections were slightly different. They were then averaged to produce the values used in the characterisation. Note that Oceanide performed an independent analysis, achieving the same results. The mooring stiffness was calculated to be 160 $N.m^{-1}$.

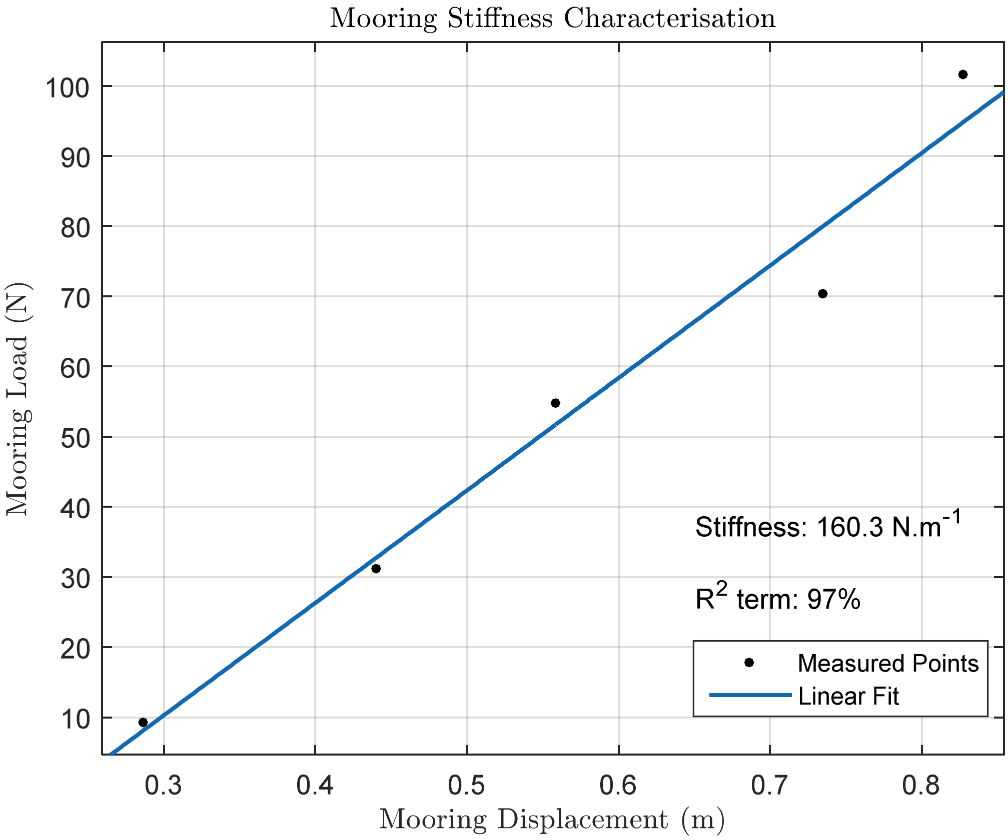

Figure 13 - Mooring stiffness characterisation

3.2.6 Power Capture

3.2.6.1 *Relative Performance for Different WEC Configurations*

The relative performance for five WEC configurations is shown in Figure 14. The best performing configuration was a full tank with damping plate D3. Note that all full tank configurations performed the best.

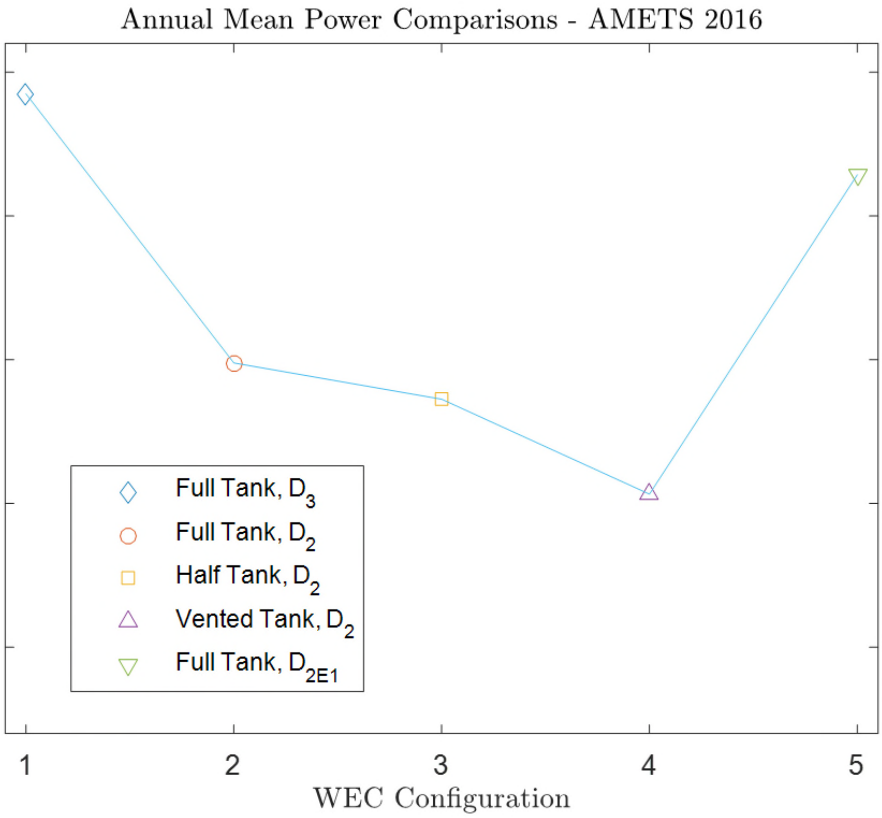

Figure 14 - Relative Performance of each WEC Configuration

3.2.6.2 *Power vs. Damping*

Figure 15 and Figure 16 show the approximate location of the damping value for the highest power capture for two different sea states. In both cases this corresponds to D3, which has an orifice diameter of 45mm. Note, the exact peak is likely to be further along the damping axis, meaning the optimal orifice diameter is somewhere between 27.8 and 45mm. It can be seen that the power is highly sensitive for orifice variations with larger diameters, noted by the sharp dropoff between D2E4 (4x 27.8mm dia) and D2 (93mm). This characteristic can also be seen in the Power RAO above where for the full tank configuration with D2 results in significantly less power than for D3 and D2E1.

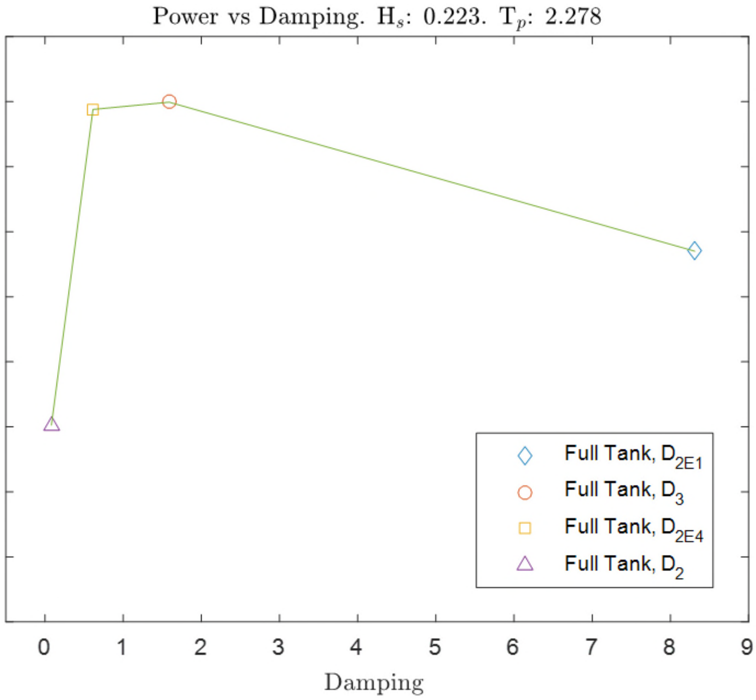

Figure 15 - Power vs Damping Hs 0.223

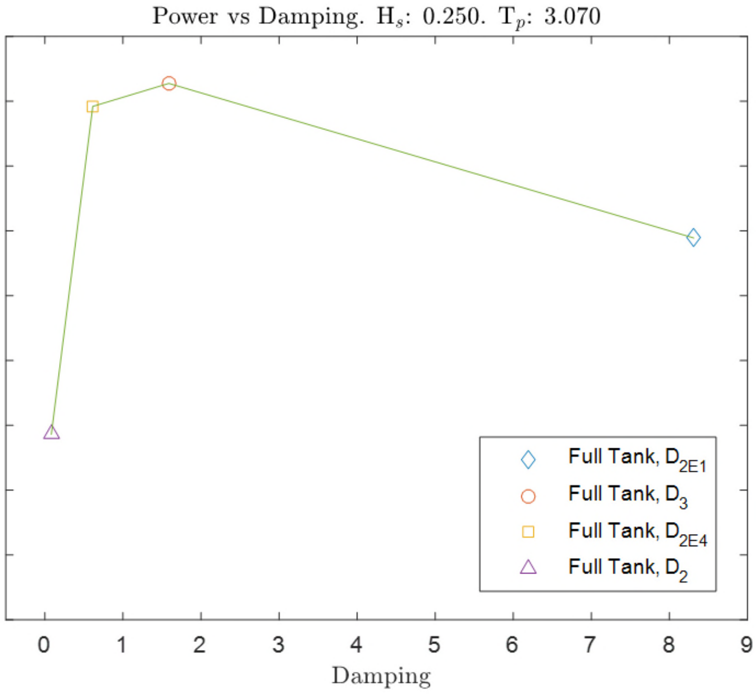

Figure 16 - Power vs Damping Hs 0.25

3.3 Tests

A copy of the schedule of tests performed is included as Appendix.1 to this report.

3.4 Results

In parallel to the Oceanide effort, CADFEM Ireland were contracted for the simulation modelling of the platform using Ansys CFX. CADFEM were provided with the Oceanide tank specifics, a copy of the free surface elevations at the intended model location from one of the calibration sea states, the geometric and mass properties of the model, the diameter of the PTO orifice in use, and a constant linear stiffness in the water plane derived from the mooring response data from the tests. The figures presented here are first pass results with no fine tuning employed beyond the addition of a time delay to the CFX results in order to bring them into phase with the empirical data.

3.6.1 Comparison with predicted performance

Here the data captured during testing at Oceanide is overlaid on data generated by CADFEM Ireland using Ansys CFX and the test specifics.

3.6.1.1 *Measure free surface vs CFX simulation*

In this instance, CADFEM were provided with the free surface elevation time series recorded at the intended model location during sea state calibration. This information is important as it permits assertion of the exciting conditions in the simulation tank relative to the experimental tank; differences between the two are expected and it is important to be able to quantify this difference.

Figure 177 [CS5][SO6]presents a graph of the CFX simulation data for the free surface measured in the virtual tank at the intended model location, overlaid on the Oceanide data recorded for the same location in the tank. It is notable that the CFX free surface elevation are generally less than the experimental record; accordingly, a relative reduction in platform excitation should be expected in the tests which follow.

3.6.1.2 *Structural heave comparison*

Figure 188 illustrates the heave data for the model from the Oceanide tests overlaid by the CFX simulation data. Good agreement is achieved, with the CFX model heave excursions proportionatly less than the emprical data as a consquence of the underestimation of the exciting wave field.

3.6.1.3 *Pitch response comparison*

Figure 199 illustrates the Pitching data from the respective sources. Here we see significantly less correlation between the curves with the CFX simulation overestimating the pitching of the platform by quite a margin. This could be indicative of the CoG in the simulation model being incorrect and located too high; more likely though the mooring in the experimental model is having a damping effect on the pitching mode which is not being adequately accounted for. This damping could easily come from the act of pulling the mooring buoys across the water surface, a factor which is not accounted for in the CFX parameters.

The point will require further investigation and the integration of far more comprehensive mooring approximations is planned for the future in any case, so this mismatch is not of significant concern.

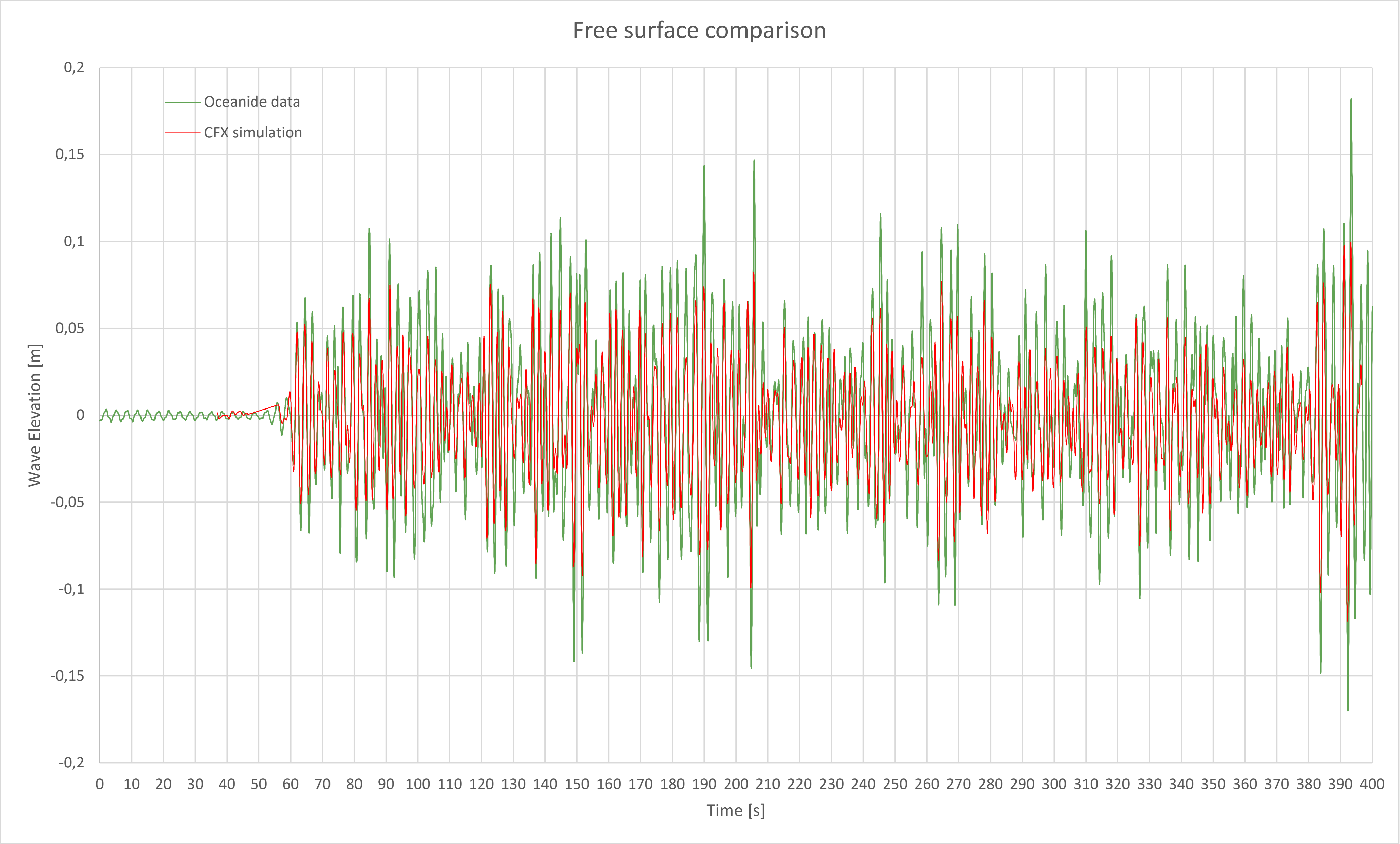

Figure 17 - Oceanide experimental data vs CFX simulation data for free surface elevation

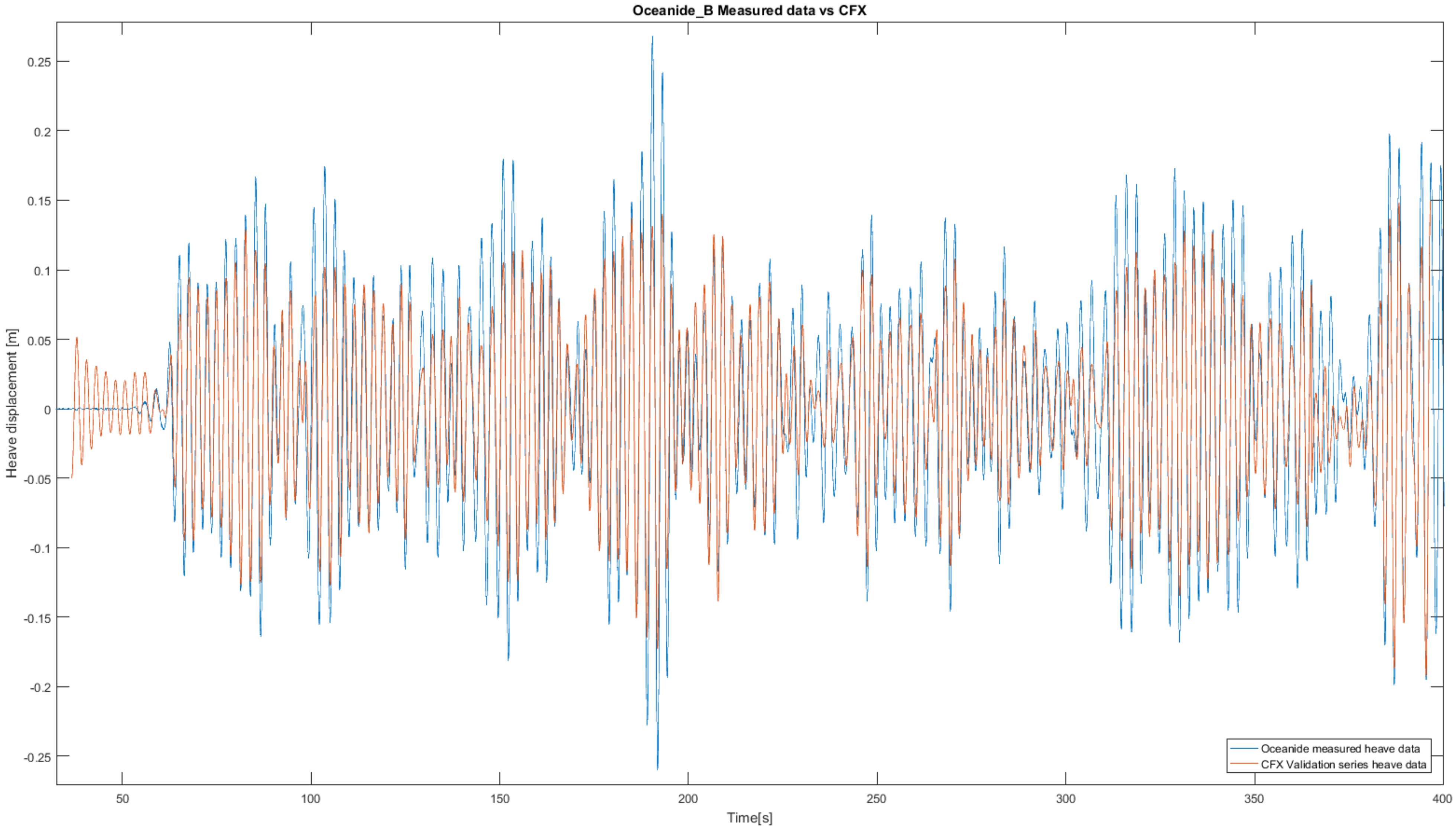

Figure 18 - Experimental vs CFX Heave response plot

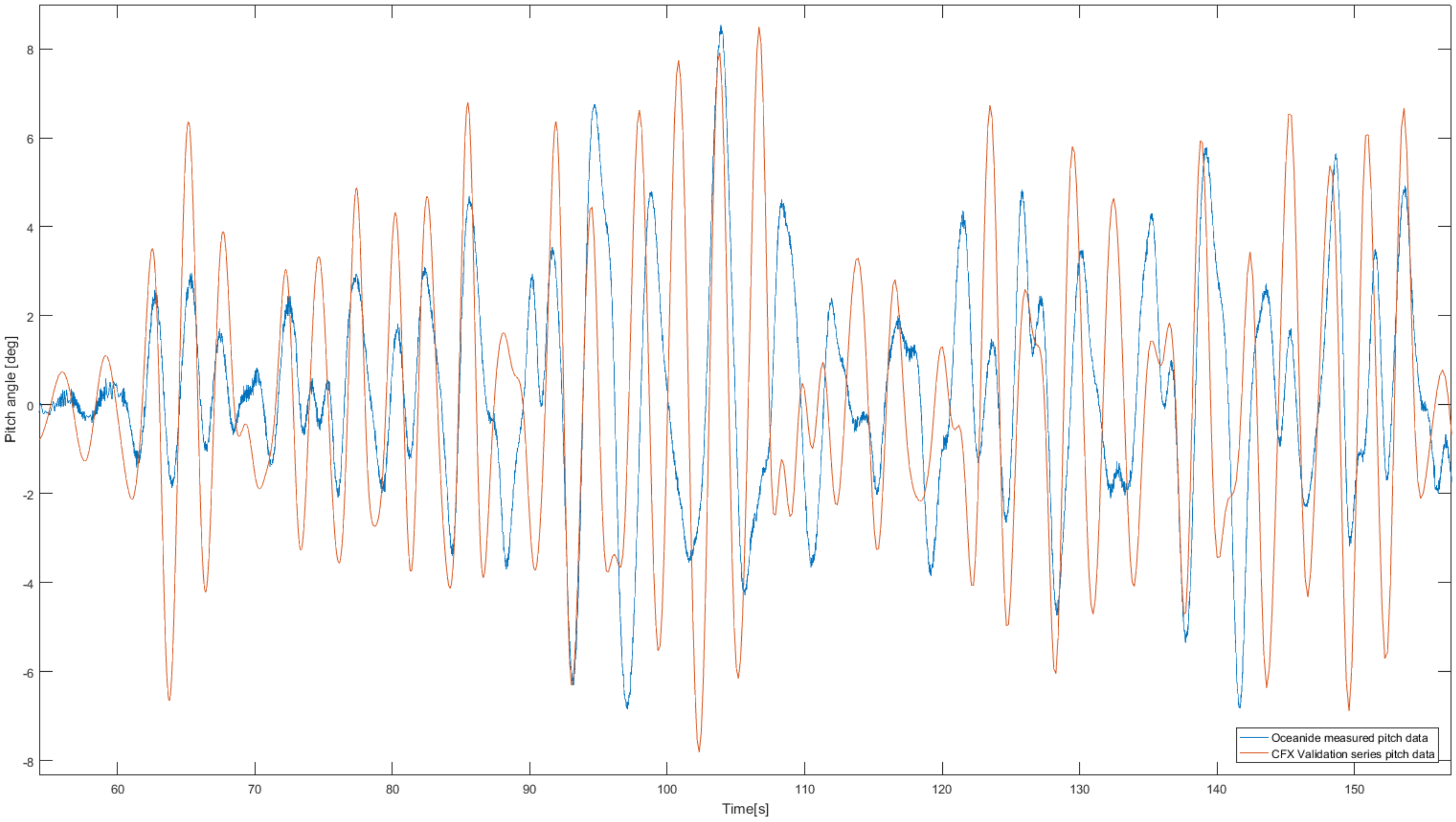

Figure 19 - Pitch data comparison

3.6.1.4 *Air chamber pressure comparison*

Figure 20 shows the respective air chamber pressure curves. Here we see pressure underestimation on the low side of the chart, followed by overestimation on the high side. This could be on account of a cross coupling between the overestimated pitching behaviour, and certainly warrants investigation. However as the overall pressure range exhibited is broadly in-line with experimental recordings, the result is satisfactory for the moment.

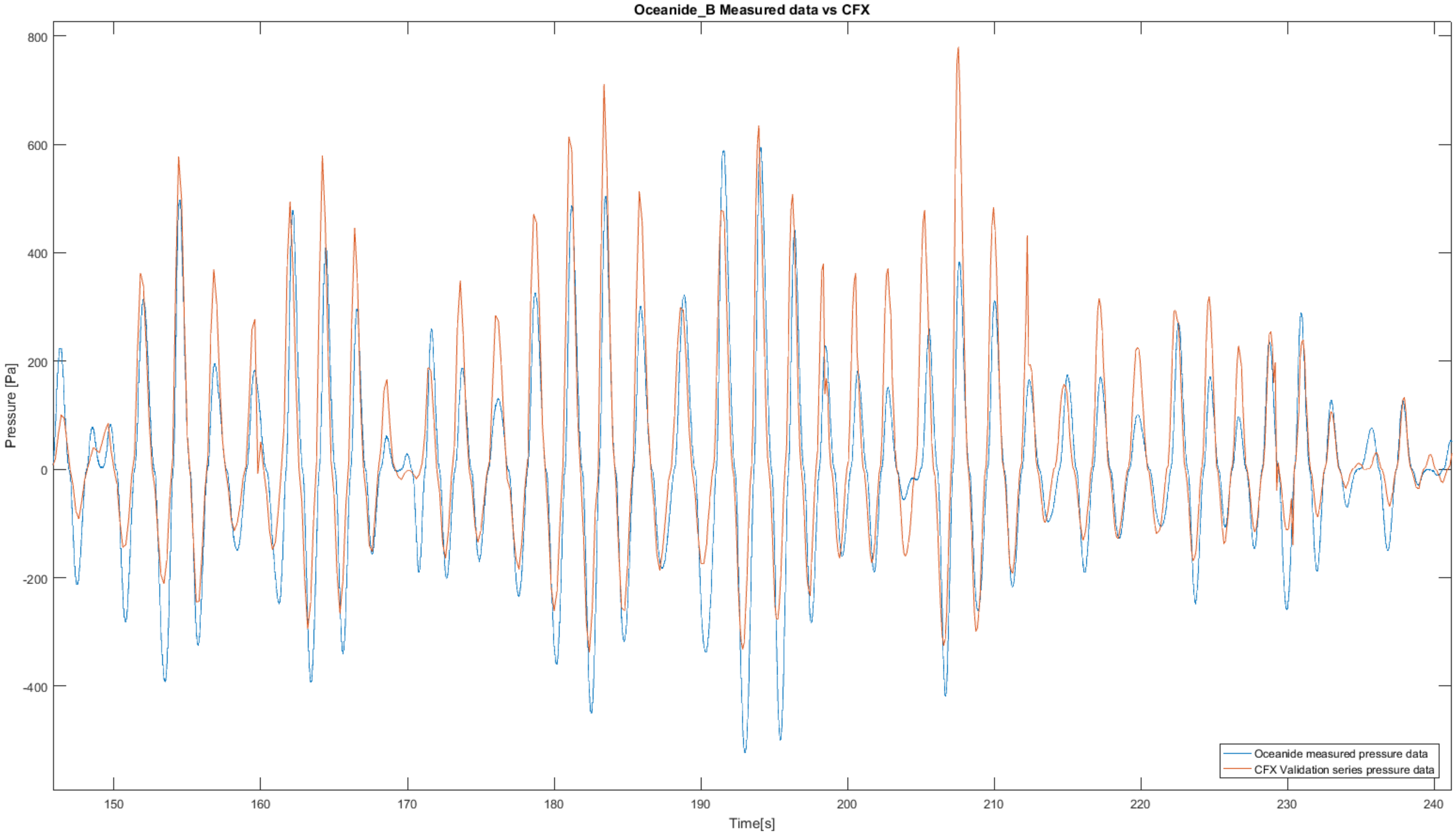

Figure 20 – Air chamber pressure comparison data

3.6.2 Further developments to CFD models

The disparity between anticipated and measured pitching response suggests that there are mooring interactions which are not being effectively captured in the CFX model. The pitch reports arising are not of any particular concern, however the disparity in the chamber air pressures, which is believed to be a coupled effect, is of interest. Detailed modelling and integration of the moorings has always been a development goal for the model and this observation merely serves to illustrate the requirement.

The difference between the free surface elevation time series measured at Oceanide, and that reproduced in CFX is another point which warrants further attention. It is known that CFX is sensitive to the nature of the free surface boundary simulation conditions, and that this can lead to wave amplitude dissipation with distance from the paddle. A scalar factor could be employed here but the difference between the respective time series is not simply a scaled one.

3.6.3 Impact of model revisions

A number of revisions were made to the model based on the learning from the previous testing campaigns at École Central de Nantes in July[2] and again in November of 2015.

3.6.3.1 *Nature of model revisions*

After previous testing, is was concluded that the mass of the water retention tanks was insufficient for optimal power capture in typical sea conditions off the west coast of Ireland. It was also noted that the circular tank cross section employed at the time could be difficult to fabricate. As a result, the tanks were redesigned to a square cross section and increased in volume by ~60%.

It was also decided to move away from the four-orifice PTO simulation plates previously used, and to instead employ conventional single orifice alternatives. The reason for this decision is that no agent could be found who could provide a calibration of the former, whereas the latter are well known. Hence the majority of testing in this instance is conducted with conventional single orifice plates, save for one series where a four-orifice plate, D_{2E4}, is employed so as to obtain a direct performance comparison between the two types.

3.6.3.2 *Concerns anticipated*

Owing to the larger reference mass, an increase in the heave RAO of the model was expected in instances where it was insufficiently damped. This could lead to a critical buoyancy loss and the onset of parametric behaviour. Accordingly, it was deemed important that the model should still exhibit the ability to avoid entering, or resolve, a parametric condition through detuning (tank venting).

3.6.3.3 *Impact of revisions*

The platform was found to exhibit similar RAO’s to the previous version, however the platform stability in pitch appears to have improved markedly being now, in itself, sufficient to avoid parametric behaviour in irregular sea states regardless of tuning. This improvement is attributed to the heavier mass lower down leading to an increase in metacentric height and hence greater pitching/rolling resistance. Parametric behaviour could, unsurprisingly, still be provoked in monochromatic conditions. In such cases, detuning was reaffirmed as being effective at preventing any unwanted modes of motion from becoming established.

3.6.4 Measurement of structural loads & stresses

The single structural element which ties everything together is the central column of the model. It is desirable to obtain an indication of the loads being experienced by this component under normal operational conditions to begin with, and under extreme condition in the future. It is also important to obtain an indication of the forces being exerted on the mooring lines so as to facilitate the costing and design of appropriate full-scale equivalents.

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[2] Access supported by MaRINET, User-project WramMkII (Doc.ref:MARINET-TA1-WRAM MkII)

3.6.4.1 *Measurement methods*

The mooring loads were measured using in-line load cells provided by Oceanide. These were simply coupled to the mooring attachment points on the model, and the mooring lines themselves were then attached to the other end of the load cells.

The stresses on the central column were to be measured by way of surface annealed strain gauge bridges provided, installed on model and waterproofed by SWIRL at two locations. These locations were just above the water tanks, and just below the lower bracing attaching the float to the column. This provides a separating distance of ~250mm between the bridges and is considered to be the most stressed point on the structure.

3.6.4.2 *Measurement results*

The mooring load cells performed perfectly and very good data was obtained from their application.

The strain gauges provided by SWIRL however were insufficiently watertight and no useful data was recovered from them. Since the conclusion of testing a revised method of installation and waterproofing has been developed, tested, and repeated with perfect results. A series of structural loading tests is to follow under OCEANERA-NET project CAPTOW, using the same model and the FIHAC CCOB facility in Santander.

3.3 Analysis & Conclusions

3.7.1 ANSYS CFX

The CFX results have proved very promising, confidence in the output of the package can now positively be asserted as being 'high'. Even with this relatively basic model, the unrefined results present a very good approximation of the experimental equivalent. It is believed that with the integration of an appropriate mooring representation that these results can be further improved.

3.7.2 Geometry revisions

The model is more stable now than it ever has been, which is good news for a heaving spar type structure. It is generally considered at this point that the focus will shift to making the pump more productive in order to optimise energy absorption.

3.7.3 Structural stress measurement

The mooring load cells have provided good data which will be used, in the near term, to create a meaningful model of the mooring lines in simulation; and in the longer term, as a point of reference for the design of full scale equivalents.

The strain bridges provided by SWIRL on the other hand, were a total loss on this occasion and a revised procedure has since been perfected and will be employed in their installation going forward.

4 Main Learning Outcomes

4.1 Progress Made

Confidence in the CFX simulation model had been improved dramatically – this will permit confident assessment of future revisions of the platform using numerical techniques, dramatically reducing development costs.

The modifications to the reference mass tank, in both proportions and relative size, have been well justified in terms of stability and heave response amplitudes.

The failure of the strain gauges provided by SWIRL has prompted the development of a new installation method which has been bench tested, repeated, and is set to be employed at CCOB in the near future.

4.2 Next Steps for Research or Staged Development Plan

Following on the success of the initial CFX simulations, further developments are now progressing with CADFEM Ireland, the first object being to determine geometry that will maximise energy absorption. CFX however is a very slow means of calculation, and it would be unreasonable to attempt development solely using this approach. For this reason, a wecSim model is also in the advanced stages of development.

Given the results seen here, once this faster numerical modelling approach is fully developed, it will be reasonable to use CFX to assert a single co-witness simulation of any given geometry whilst using wecSim to perform the bulk of the characterisation. Convergence of the two simulations engines should be expected and the resulting confidence in the geometry, in advance of any empirical testing, may be reasonably asserted as being very high.

Structural load and stresses will be studied at CCOB during Q2-18 under OCEANERA-NET project CAPTOW in partnership with FIHAC (Fundación Instituto de Hidráulica AMBIENTAL de Cantabria), Spain.

A RANSE solver is being developed by Cruz-Atcheson Engineering Consultants Lda, to be validated against empirical results from the FIHAC structural loading tests, a key output being indicative Design Load Cases for real sea tests of a prototype.

The School of Engineering, Trinity College Dublin is assisting in the development of control algorithms and in the thermodynamics of alternative PTO arrangements.

The OCEANERA-NET project will also see a PTO and control system designed and tested at IDMEC (Instituto de Engenharia Mecânica, part of IST, Instituto Superior Técnico), Portugal.

The economic models and LCOE predictions are continuously up-dated as the R&D advances.

4.3 Progress Made: For Marine Renewable Energy Industry

Confirmation that given even a modestly well described model and test scenario, CFD engines such as Ansys CFX can provide very good structural motion, and dual fluid interaction, behavioural approximations with account taken for air compressibility.

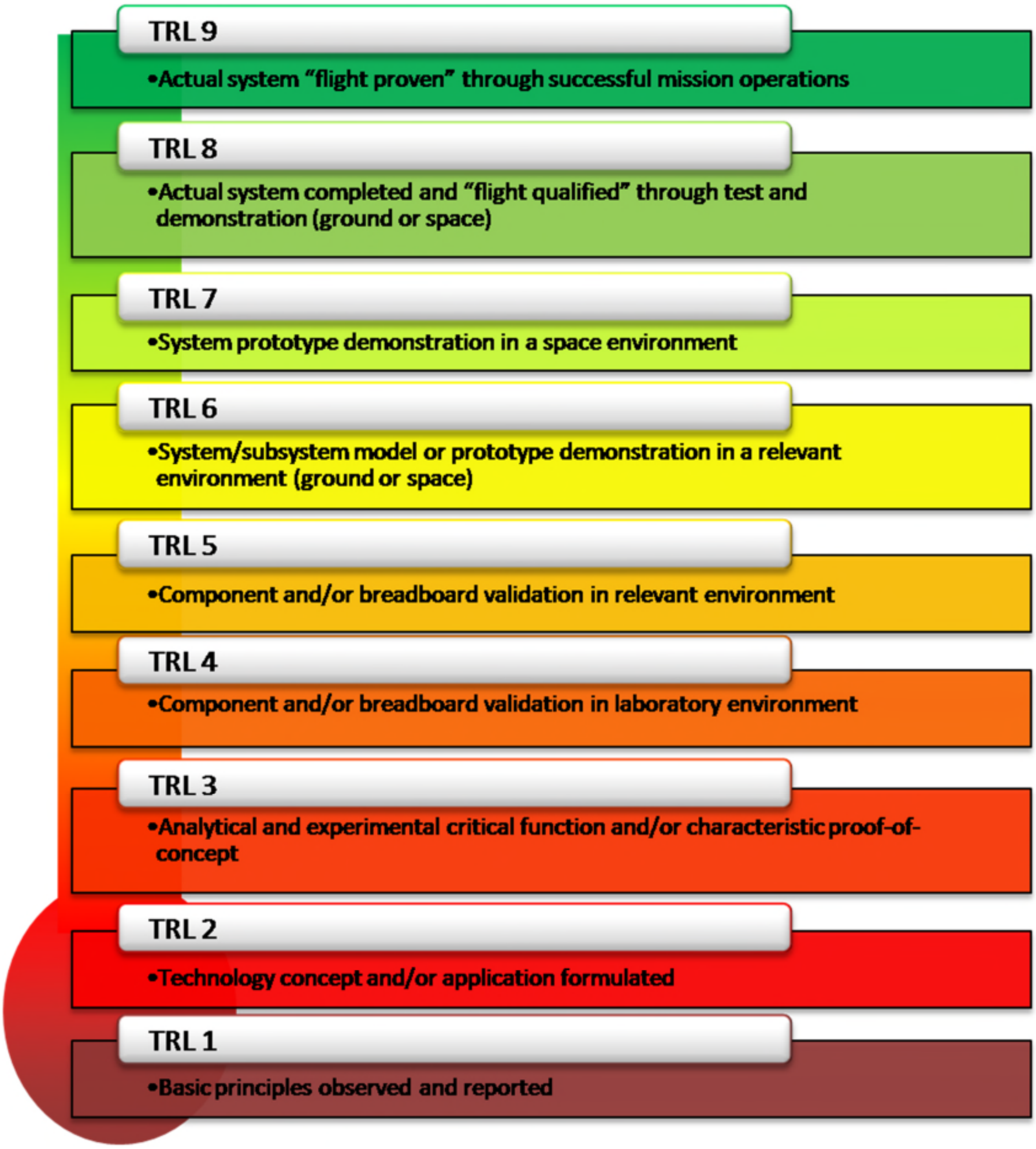
4.4 Key Lessons Learned

- Strain gauges require substantial effort to permit effective operation in a wet environment.
- Ansys CFX, though slow, can produce credible results from very simple models – historically the computational resources required for its application would have been prohibitive, however the availability of configurable cloud-based computing systems is a game changer in this regard.
- Even in simple models, some attempt to account for damping interactions with mooring arrangements, rather than just restorative forces, is advised.
- CFX has difficultly in preserving wave amplitudes as they propagate down a tank – the baseline comparison test at a minimum is an absolute must; however time could be considered well spent in developing an approach which would compensate for this amplitude degradation.
- System identification techniques provide more appropriate orifice damping coefficient values in this application than standard orifice equations which are based on empirical data in steady and uniform flow.

5 Appendices

5.1 Stage Development Summary Table

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.



TRL 9
- Actual system "flight proven" through successful mission operations

TRL 8
- Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
- System prototype demonstration in a space environment

TRL 6
- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
- Component and/or breadboard validation in relevant environment

TRL 4
- Component and/or breadboard validation in laboratory environment

TRL 3
- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
- Technology concept and/or application formulated

TRL 1
- Basic principles observed and reported

NASA Technology Readiness Levels[3]

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[3] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

NASA TRL Definition Hardware Description Software Description Exit Criteria

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modelling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test Performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test Performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results

DEVELOPMENT PROTOCOL	***STAGE 1*** *CONCEPT VALIDATION*			***STAGE 2*** *DESIGN VALIDATION*	***STAGE 3*** *SYSTEMS VALIDATION*		***STAGE 4*** *DEVICE VALIDATION*		***STAGE 5*** *ECONOMICS VALIDATION*
	TRL 1: Confirmation of Operation	**TRL 2: Performance Convergence**	**TRL 3: Device Optimisation**	**TRL 4: Sub-Systems Assessment**	**TRL5: Sub-Assembly Bench Tests**	**TRL 6: Full System Sea Trials**	**TRL 7: Solo, Sheltered, Grid Emulator**	**TRL 8: Solo, Exposed, Grid Connected**	**TRL 9: Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power *v* Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfrm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_e = 1 : 5 - 10$)			$\lambda = 1 : 10 - 25$	$\lambda = 1 : 2 - 10$		$\lambda = 1 : 1 - 2$		$\lambda = 1{:}1$, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration –*inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production	Pre-Commercial	Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δf) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed Power [kW]									
Converted									
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW

5.2 Appendix.1 – Schedule of tests performed

Test N°	Result file	Wave name	Test type	Tank configuration	Damping configuration	Waves			Sea State Duration
[-]			[-]	[-]	[-]	Hs/H [m]	Tp/T [s]	γ [-]	[s]
Sea States for CFD Validation (no model)									
Basin mobilisation for environmental conditions calibration									
1	06111514.a17	irr1	Bretschneider Long Crested	-	-	0.020	1.486	-	493
2	06111556.a17	irr2	Bretschneider Long Crested	-	-	0.020	1.882	-	625
3	06111624.a17	irr3	Bretschneider Long Crested	-	-	0.034	1.089	-	362
4	06111651.a17	irr4	Bretschneider Long Crested	-	-	0.047	2.278	-	756
5	06111717.a17	irr5	Bretschneider Long Crested	-	-	0.061	1.089	-	362
6	06111739.a17	irr6	Bretschneider Long Crested	-	-	0.061	1.486	-	493
7	07110910.a17	irr7	Bretschneider Long Crested	-	-	0.088	1.882	-	625
8	07110936.a17	irr8	Bretschneider Long Crested	-	-	0.101	1.486	-	493
9	07111036.a17	irr9	Bretschneider Long Crested	-	-	0.101	2.674	-	888
10	07111138.a17	irr10	Bretschneider Long Crested	-	-	0.115	3.070	-	900
11	07111212.a17	irr11	Bretschneider Long Crested	-	-	0.128	2.278	-	756
12	07111428.a17	irr12	Bretschneider Long Crested	-	-	0.155	1.882	-	625
13	07111240.a17	irr13	Bretschneider Long Crested	-	-	0.182	2.674	-	888
14	07111523.a17	irr14	Bretschneider Long Crested	-	-	0.182	3.070	-	900
15	07111553.a17	irr15	Bretschneider Long Crested	-	-	0.196	3.268	-	900
16	07111621.a17	irr16	Bretschneider Long Crested	-	-	0.223	2.278	-	756
17	07111710.a17	irr17	Bretschneider Long Crested	-	-	0.236	2.674	-	888
18	07111759.a17	irr18	Bretschneider Long Crested	-	-	0.250	3.070	-	900
19	08110928.a17	irr19	Bretschneider Long Crested	-	-	0.291	3.070	-	900
20	08110956.a17	irr7	Bretschneider Long Crested	-	-	0.088	1.882	-	625
Internal Wave Gauge Calibration									
Model mobilisation									
21		-	-	Full Tank	D0	-	-	-	-

Decay Tests										
Setup	**Pitch**	**Heave**								
22	09111004.a17	09111014.a17	-	Full Tank	D0	-	-	-	-
Change damping										
23	09111043.a17	09111041.a17	-	Full Tank	D2	-	-	-	-
Change damping										
24	09111020.a17	09111032.a17	-	Full Tank	D4	-	-	-	-
Change tank										
25	15111621.a17	15111608.a17	-	Half Tank	D4	-	-	-	-
Change damping										
26	15111641.a17	15111639.a17	-	Half Tank	D2	-	-	-	-
Change damping										
27	15111631.a17	15111635.a17	-	Half Tank	D0	-	-	-	-
Change tank										
28	1711452.a17	17111447.a17	-	Vented Tank	D0	-	-	-	-
Change damping										
29	17111504.a17	17111456.a17	-	Vented Tank	D2	-	-	-	-
Change damping										
30	17111443.a17	17111436.a17	-	Vented Tank	D4	-	-	-	-
Mooring Tests										
Mooring stiffness	**test31a**	**test31b**								
31	23111652.a17	23111713.a17	-	Vented Tank	-	-	-	-	-
	Surge									
32	17111513.a17	-	-	Vented Tank	-	-	-	-	-
	Surge									
33	15111655.a17	-	-	Half Tank	-	-	-	-	-

	Surge								
34	09111505.a17	-	-	Full Tank	-	-	-	-	-
				Performance Tests					
Change damping		**Wave name**							
35	10111008.a17	reg1	Regular	Full Tank	D3	0.060	1.600	-	240
36	10111036.a17	reg2	Regular	Full Tank	D3	0.060	1.775	-	266
37	10111056.a17	reg3	Regular	Full Tank	D3	0.060	2.250	-	338
38	10111119.a17	reg4	Regular	Full Tank	D3	0.060	2.400	-	360
39	10111138.a17	reg5	Regular	Full Tank	D3	0.060	2.500	-	375
40	10111157.a17	reg6	Regular	Full Tank	D3	0.060	2.550	-	383
41	10111216.a17	reg7	Regular	Full Tank	D3	0.060	2.650	-	398
42	10111236.a17	reg8	Regular	Full Tank	D3	0.060	2.725	-	409
43	10111325.a17	reg9	Regular	Full Tank	D3	0.060	2.800	-	420
44	10111348.a17	reg10	Regular	Full Tank	D3	0.060	2.850	-	428
45	10111405.a17	reg11	Regular	Full Tank	D3	0.060	2.900	-	435
46	10111427.a17	reg12	Regular	Full Tank	D3	0.060	3.000	-	450
47	10111459.a17	reg13	Regular	Full Tank	D3	0.060	3.500	-	525
48	10111458.a17	reg14	Regular	Full Tank	D3	0.060	3.900	-	585
49	10111540.a17	irr1	Bretschneider Long Crested	Full Tank	D3	0.020	1.486	-	493
50	10111602.a17	irr2	Bretschneider Long Crested	Full Tank	D3	0.020	1.882	-	625
51	10111622.a17	irr3	Bretschneider Long Crested	Full Tank	D3	0.034	1.089	-	362
52	10111640.a17	irr4	Bretschneider Long Crested	Full Tank	D3	0.047	2.278	-	756
53	10111704.a17	irr5	Bretschneider Long Crested	Full Tank	D3	0.061	1.089	-	362
54	10111721.a17	irr6	Bretschneider Long Crested	Full Tank	D3	0.061	1.486	-	493
55	13111338.a17	irr7	Bretschneider Long Crested	Full Tank	D3	0.088	1.882	-	625
56	13111401.a17	irr8	Bretschneider Long Crested	Full Tank	D3	0.101	1.486	-	493
57	13111422.a17	irr9	Bretschneider Long Crested	Full Tank	D3	0.101	2.674	-	888
58	13111448.a17	irr10	Bretschneider Long Crested	Full Tank	D3	0.115	3.070	-	900
59	13111512.a17	irr11	Bretschneider Long Crested	Full Tank	D3	0.128	2.278	-	756
60	13111540.a17	irr12	Bretschneider Long Crested	Full Tank	D3	0.155	1.882	-	625

61	13111601.a17	irr13	Bretschneider Long Crested	Full Tank	D3	0.182	2.674	-	888
62	13111628.a17	irr14	Bretschneider Long Crested	Full Tank	D3	0.182	3.070	-	900
63	13111657.a17	irr15	Bretschneider Long Crested	Full Tank	D3	0.196	3.268	-	900
64	13111724.a17	irr16	Bretschneider Long Crested	Full Tank	D3	0.223	2.278	-	756
65	14110910.a17	irr17	Bretschneider Long Crested	Full Tank	D3	0.236	2.674	-	888
66	14110942.a17	irr18	Bretschneider Long Crested	Full Tank	D3	0.250	3.070	-	900
67	14111013.a17	irr19	Bretschneider Long Crested	Full Tank	D3	0.291	3.070	-	900
Change damping									
68	14111044.a17	reg1	Regular	Full Tank	D2	0.060	1.600	-	240
69	14111100.a17	reg2	Regular	Full Tank	D2	0.060	1.775	-	266
70	14111112.a17	reg3	Regular	Full Tank	D2	0.060	2.250	-	338
71	14111130.a17	reg4	Regular	Full Tank	D2	0.060	2.400	-	360
72	14111148.a17	reg5	Regular	Full Tank	D2	0.060	2.500	-	375
73	14111203.a17	reg6	Regular	Full Tank	D2	0.060	2.550	-	383
74	14111219.a17	reg7	Regular	Full Tank	D2	0.060	2.650	-	398
75	14111307.a17	reg8	Regular	Full Tank	D2	0.060	2.725	-	409
76	14111325.a17	reg9	Regular	Full Tank	D2	0.060	2.800	-	420
77	14111343.a17	reg10	Regular	Full Tank	D2	0.060	2.850	-	428
78	14111357.a17	reg11	Regular	Full Tank	D2	0.060	2.900	-	435
79	14111413.a17	reg12	Regular	Full Tank	D2	0.060	3.000	-	450
80	14111433.a17	reg13	Regular	Full Tank	D2	0.060	3.500	-	525
81	14111455.a17	reg14	Regular	Full Tank	D2	0.060	3.900	-	585
82	14111516.a17	irr1	Bretschneider Long Crested	Full Tank	D2	0.020	1.486	-	493
83	14111539.a17	irr2	Bretschneider Long Crested	Full Tank	D2	0.020	1.882	-	625
84	14111607.a17	irr3	Bretschneider Long Crested	Full Tank	D2	0.034	1.089	-	362
85	14111629.a17	irr4	Bretschneider Long Crested	Full Tank	D2	0.047	2.278	-	756
86	14111656.a17	irr5	Bretschneider Long Crested	Full Tank	D2	0.061	1.089	-	362
87	14111715.a17	irr6	Bretschneider Long Crested	Full Tank	D2	0.061	1.486	-	493
88	14111734.a17	irr7	Bretschneider Long Crested	Full Tank	D2	0.088	1.882	-	625
89	15110924.a17	irr8	Bretschneider Long Crested	Full Tank	D2	0.101	1.486	-	493

90	15110948.a17	irr9	Bretschneider Long Crested	Full Tank	D2	0.101	2.674	-	888
91	15111014.a17	irr10	Bretschneider Long Crested	Full Tank	D2	0.115	3.070	-	900
92	15111039.a17	irr11	Bretschneider Long Crested	Full Tank	D2	0.128	2.278	-	756
93	15111104.a17	irr12	Bretschneider Long Crested	Full Tank	D2	0.155	1.882	-	625
94	15111131.a17	irr13	Bretschneider Long Crested	Full Tank	D2	0.182	2.674	-	888
95	15111200.a17	irr14	Bretschneider Long Crested	Full Tank	D2	0.182	3.070	-	900
96	15111335.a17	irr15	Bretschneider Long Crested	Full Tank	D2	0.196	3.268	-	900
97	15111400.a17	irr16	Bretschneider Long Crested	Full Tank	D2	0.223	2.278	-	756
98	15111432.a17	irr17	Bretschneider Long Crested	Full Tank	D2	0.236	2.674	-	888
99	15111505.a17	irr18	Bretschneider Long Crested	Full Tank	D2	0.250	3.070	-	900
100	15111536.a17	irr19	Bretschneider Long Crested	Full Tank	D2	0.291	3.070	-	900

Test N°	Result file	Wave name	Test type	Tank configuration	Damping configuration	Waves			Sea State Duration
[-]			[-]	[-]	[-]	Hs/H [m]	Tp/T [s]	γ [-]	[s]
Change tank									
101	16110920.a17	reg1	Regular	Half Tank	D2	0.060	1.600	-	240
102	16110936.a17	reg2	Regular	Half Tank	D2	0.060	1.775	-	266
103	16110950.a17	reg3	Regular	Half Tank	D2	0.060	2.250	-	338
104	16111008.a17	reg4	Regular	Half Tank	D2	0.060	2.400	-	360
105	16111024.a17	reg5	Regular	Half Tank	D2	0.060	2.500	-	375
106	16111040.a17	reg6	Regular	Half Tank	D2	0.060	2.550	-	383
107	16111059.a17	reg7	Regular	Half Tank	D2	0.060	2.650	-	398
108	16111115.a17	reg8	Regular	Half Tank	D2	0.060	2.725	-	409
109	16111157.a17	reg9	Regular	Half Tank	D2	0.060	2.800	-	420
110	16111215.a17	reg10	Regular	Half Tank	D2	0.060	1.850	-	428
111	16111304.a17	reg11	Regular	Half Tank	D2	0.060	2.050	-	435
112	16111329.a17	reg12	Regular	Half Tank	D2	0.060	3.000	-	450
113	16111348.a17	reg13	Regular	Half Tank	D2	0.060	3.500	-	525
114	16111407.a17	reg14	Regular	Half Tank	D2	0.060	3.900	-	585
115	16111434.a17	irr1	Bretschneider Long Crested	Half Tank	D2	0.020	1.486	-	493

116	16111458.a17	irr2	Bretschneider Long Crested	Half Tank	D2	0.020	1.882	-	625
117	16111519.a17	irr3	Bretschneider Long Crested	Half Tank	D2	0.034	1.089	-	362
118	16111535.a17	irr4	Bretschneider Long Crested	Half Tank	D2	0.047	2.278	-	756
119	16111600.a17	irr5	Bretschneider Long Crested	Half Tank	D2	0.061	1.089	-	362
120	16111618.a17	irr6	Bretschneider Long Crested	Half Tank	D2	0.061	1.486	-	493
121	16111638.a17	irr7	Bretschneider Long Crested	Half Tank	D2	0.088	1.882	-	625
122	16111704.a17	irr8	Bretschneider Long Crested	Half Tank	D2	0.101	1.486	-	493
123	16111730.a17	irr9	Bretschneider Long Crested	Half Tank	D2	0.101	2.674	-	888
124	17110906.a17	irr10	Bretschneider Long Crested	Half Tank	D2	0.115	3.070	-	900
125	17110935.a17	irr11	Bretschneider Long Crested	Half Tank	D2	0.128	2.278	-	756
126	17111003.a17	irr12	Bretschneider Long Crested	Half Tank	D2	0.155	1.882	-	625
127	17111032.a17	irr13	Bretschneider Long Crested	Half Tank	D2	0.182	2.674	-	888
128	17111101.a17	irr14	Bretschneider Long Crested	Half Tank	D2	0.182	3.070	-	900
129	17111128.a17	irr15	Bretschneider Long Crested	Half Tank	D2	0.196	3.268	-	900
130	17111155.a17	irr16	Bretschneider Long Crested	Half Tank	D2	0.223	2.278	-	756
131	17111305.a17	irr17	Bretschneider Long Crested	Half Tank	D2	0.236	2.674	-	888
132	17111335.a17	irr18	Bretschneider Long Crested	Half Tank	D2	0.250	3.070	-	900
133	17111404.a17	irr19	Bretschneider Long Crested	Half Tank	D2	0.291	3.070	-	900
Change tank									
134	17111535.a17	reg1	Regular	Vented Tank	D2	0.060	1.600	-	240
135	17111553.a17	reg2	Regular	Vented Tank	D2	0.060	1.775	-	266
136	17111610.a17	reg3	Regular	Vented Tank	D2	0.060	2.250	-	338
137	17111625.a17	reg4	Regular	Vented Tank	D2	0.060	2.400	-	360
138	17111642.a17	reg5	Regular	Vented Tank	D2	0.060	2.500	-	375
139	17111658.a17	reg6	Regular	Vented Tank	D2	0.060	2.100	-	383
140	20110921.a17	reg7	Regular	Vented Tank	D2	0.060	2.650	-	398
141	20110940.a17	reg8	Regular	Vented Tank	D2	0.060	1.700	-	409
142	20110954.a17	reg9	Regular	Vented Tank	D2	0.060	2.800	-	420
143	20111012.a17	reg10	Regular	Vented Tank	D2	0.060	1.850	-	428
144	20111030.a17	reg11	Regular	Vented Tank	D2	0.060	2.900	-	435

145	20111047.a17	reg12	Regular	Vented Tank	D2	0.060	3.000	-	450
146	20111115.a17	reg13	Regular	Vented Tank	D2	0.060	3.500	-	525
147	20111135.a17	reg14	Regular	Vented Tank	D2	0.060	3.900	-	585
148	20111157.a17	irr1	Bretschneider Long Crested	Vented Tank	D2	0.020	1.486	-	493
149	20111220.a17	irr2	Bretschneider Long Crested	Vented Tank	D2	0.020	1.882	-	625
150	20111242.a17	irr3	Bretschneider Long Crested	Vented Tank	D2	0.034	1.089	-	362
151	20111259.a17	irr4	Bretschneider Long Crested	Vented Tank	D2	0.047	2.278	-	756
152	20111330.a17	irr5	Bretschneider Long Crested	Vented Tank	D2	0.061	1.089	-	362
153	20111351.a17	irr6	Bretschneider Long Crested	Vented Tank	D2	0.061	1.486	-	493
154	20111414.a17	irr7	Bretschneider Long Crested	Vented Tank	D2	0.088	1.882	-	625
155	20111437.a17	irr8	Bretschneider Long Crested	Vented Tank	D2	0.101	1.486	-	493
156	20111458.a17	irr9	Bretschneider Long Crested	Vented Tank	D2	0.101	2.674	-	888
157	20111525.a17	irr10	Bretschneider Long Crested	Vented Tank	D2	0.115	3.070	-	900
158	20111553.a17	irr11	Bretschneider Long Crested	Vented Tank	D2	0.128	2.278	-	756
159	20111620.a17	irr12	Bretschneider Long Crested	Vented Tank	D2	0.155	1.882	-	625
160	20111649.a17	irr13	Bretschneider Long Crested	Vented Tank	D2	0.182	2.674	-	888
161	20111716.a17	irr14	Bretschneider Long Crested	Vented Tank	D2	0.182	3.070	-	900
162	21110913.a17	irr15	Bretschneider Long Crested	Vented Tank	D2	0.196	3.268	-	900
163	21110937.a17	irr16	Bretschneider Long Crested	Vented Tank	D2	0.223	2.278	-	756
164	21111002.a17	irr17	Bretschneider Long Crested	Vented Tank	D2	0.236	2.674	-	888
165	21111032.a17	irr18	Bretschneider Long Crested	Vented Tank	D2	0.250	3.070	-	900
166	21111104.a17	irr19	Bretschneider Long Crested	Vented Tank	D2	0.291	3.070	-	900
Change tank									
167	21111158.a17	-	Bretschneider Long Crested	3/4 Vented Tank	D2	0.088	1.882	-	625
168	21111228.a17	-	Bretschneider Long Crested	3/4 Vented Tank	D2	0.128	2.278	-	756
169	21111332.a17	-	Bretschneider Long Crested	3/4 Vented Tank	D2	0.182	2.674	-	888
Change tank									
170	21111422.a17	-	Bretschneider Long Crested	3/4 Full Tank	D2	0.088	1.882	-	625
171	21111445.a17	-	Bretschneider Long Crested	3/4 Full Tank	D2	0.128	2.278	-	756
172	21111518.a17	-	Bretschneider Long Crested	3/4 Full Tank	D2	0.182	2.674	-	888

Test N°	Result file	Wave name	Test type	Tank configuration	Damping configuration	Hs/H(m)	Tp/T(s)	γ	
173	21111601.a17	reg1	Regular	Full Tank	D2_ECNx1	0.060	1.600	-	240
174	21111618.a17	reg2	Regular	Full Tank	D2_ECNx1	0.060	1.775	-	266
175	21111635.a17	reg3	Regular	Full Tank	D2_ECNx1	0.060	2.250	-	338
176	21111653.a17	reg4	Regular	Full Tank	D2_ECNx1	0.060	2.400	-	360
177	21111711.a17	reg5	Regular	Full Tank	D2_ECNx1	0.060	2.500	-	375
178	21111729.a17	reg6	Regular	Full Tank	D2_ECNx1	0.060	2.550	-	383
179	21111744.a17	reg7	Regular	Full Tank	D2_ECNx1	0.060	2.650	-	398
180	22110905.a17	reg8	Regular	Full Tank	D2_ECNx1	0.060	2.725	-	409
181	22110922.a17	reg9	Regular	Full Tank	D2_ECNx1	0.060	2.800	-	420
182	22110938.a17	reg10	Regular	Full Tank	D2_ECNx1	0.060	2.850	-	428
183	22110956.a17	reg11	Regular	Full Tank	D2_ECNx1	0.060	2.900	-	435
184	22111018.a17	reg12	Regular	Full Tank	D2_ECNx1	0.060	3.000	-	450
185	22111039.a17	reg13	Regular	Full Tank	D2_ECNx1	0.060	3.500	-	525
186	22111057.a17	reg14	Regular	Full Tank	D2_ECNx1	0.060	3.900	-	585
187	22111115.a17	irr1	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.020	1.486	1	493
188	22111136.a17	irr2	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.020	1.882	1	625
189	22111220.a17	irr3	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.034	1.089	1	362
190	22111236.a17	irr4	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.047	2.278	1	756
191	22111333.a17	irr5	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.061	1.089	1	362
192	22111353.a17	irr8	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.101	1.486	1	493
193	22111413.a17	irr9	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.101	2.674	1	625
194	22111440.a17	irr10	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.115	3.070	1	493
195	22111508.a17	irr12	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.155	1.882	1	888
196	22111532.a17	irr16	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.223	2.278	1	900
197	22111603.a17	irr17	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.236	2.674	1	756
198	22111638.a17	irr19	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.291	3.070	1	625
199	22111712.a17	irr18_BS	Bretschneider Short Crested	Full Tank	D2-ECNx1	0.250	3.070	1	888
200	22111740.a17	irr13_BS	Bretschneider Short Crested	Full Tank	D2-ECNx1	0.182	2.674	1	900
201	23110910.a17	irr6	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.061	1.486	1	888

202	23110929.a17	irr7	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.088	1.882	1	900
203	23110949.a17	irr11	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.128	2.278	1	900
204	23111013.a17	irr13	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.182	2.674	1	756
205	23111038.a17	irr14	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.182	3.070	1	888
206	23111104.a17	irr15	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.196	3.268	1	900
207	23111129.a17	irr18	Bretschneider Long Crested	Full Tank	D2-ECNx1	0.250	3.070	1	900
208	23111445.a17	irr11_BS	Bretschneider Short Crested	Full Tank	D2-ECNx1	0.128	2.278	1	900
Change damping	**Result file**	**Wave name**	**Test type**	**Tank configuration**	**Damping configuration**	**Hs/H(m)**	**Tp/T(s)**	γ	
209	23111203.a17	irr16	Bretschneider Long Crested	Full Tank	D2-ECNx4	0.223	2.278	1	
210	23111408.a17	irr18	Bretschneider Long Crested	Full Tank	D2-ECNx4	0.250	3.070	1	