CalWave Power Technologies UG

Characterization and Load Management Experimental Demonstration for a submerged WEC

CALM

Project Testing ID 1166

Deep Ocean Basin (DOB); Lir National Ocean Test Facility

Infrastructure Access Reports

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MaRINET2

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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1 Introduction & Background

1.1 Introduction

CalWave Power Technologies UG (CalWave) is developing the CalWEC, a submerged pressure-differential Wave Energy Converter (WEC) leveraging a fully submerged wave absorption mechanism which leads to higher survivability in extreme weather conditions. Extensive testing at 1:50 scale was completed in 2016, and limited testing at 1:20 scale was completed in late 2016. The results of both experiments validate CalWave's numerical calculations and economic modelling, but more extensive testing was required to increase confidence in critical design measurements and system identification. CalWave sought support from the MaRINET2 program to continue medium scaled (1:20 – 1:30) tank testing.

Two elements of the testing supported by the MaRINET2 program were particularly beneficial. First, testing at a relatively large scale reduced scaling errors due to viscous effects. CalWave preferred testing at 1:20 scale, though a smaller scale, such as 1:30 was used for certain tests assessing the device behaviour in extreme seas. Second, a testing campaign of several weeks amortized setup costs over more experimental hours, thus allowing full system characterization in-situ for reduced uncertainty and a richer data set for further design iteration.

1.2 Development So Far

1.2.1 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	➲

STAGE GATE CRITERIA	Status
• 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]	
• 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	

1.2.2 Plan for this Access

1.2.2.1 *Provide the empirical hydrodynamic coefficient associated with the device (for mathematical modelling tuning)*

- Anticipated Scale: 1:20 Scale
- For experimental identification of wave excitation and hydrodynamic characteristics of the device, forced oscillation experiments with and without the 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 behaviour and hull pressure fur further system identification.
- System identification for experimental derivation of hydrodynamic coefficients are performed using pink noise wave excitation and/or pink noise PTO excitation, see [1][2].

1.2.2.2 *Investigate physical process governing device response. May not be well defined theoretically or numerically solvable*

- Anticipated Scale: 1:20 Scale
- For identification of physical processing governing the response to wave and/or PTO excitation of the device, forced oscillation experiments with and without the presence of waves will be conducted. PTO forces and response, absorber velocities/displacement, and wave elevation are measured to derive a correlation between different excitation of the device and its kinematic response.
- Wave/PTO excitation can be achieved by monochromatic/single sine excitation or noise/multi-sine excitation.

1.2.2.3 *Initial indication of the full system load regimes & Survival loading and extreme motion behaviour*

- Anticipated Scale: 1:30 Scale
- To assess the device behaviour 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, USA 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.

1.2.2.4 *Performance in real seaways (long and short crested)*

- Anticipated Scale: 1:20 Scale
- Six irregular wave cases are tested to compare the device performance with the Wave Energy Prize - and ACE metric, as well as to determine baseline performance. The six wave cases follow the assessment for the ACE metric and results obtained from these tests can be directly used to compare performance against concepts assessed 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.

2 Outline of Work Carried Out

2.1 Setup

1.1.1 Deep Ocean Basin – 35m x 12m x 3m deep

The DOB 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, T_p = 2.7s and H_{max} = 1.1m

Figure 1: LIR Deep Ocean Basin

Figure 2: 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 prototypes.

1.1.2 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* used an independent NI DAQ system coupled to the LiR DAQ with a trigger signal for data recording synchronization.

1.1.3 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 and with the CalWave DAQ system.

1.1.4 Basin Setup

Figure 3 shows the basic DOB anchoring point pattern. The anchoring points were used to moor the prototype at certain locations to the basin floor. These anchoring points were pre-calculated representing CalWaves anticipated setup.

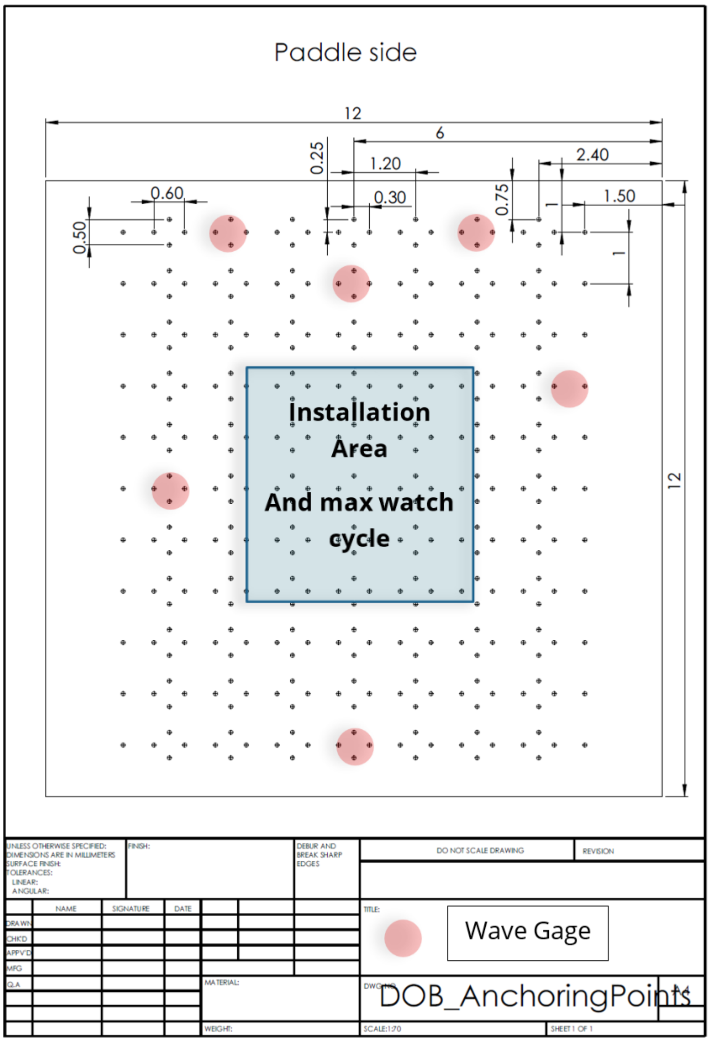


Figure 3: LiR Deep Ocean Basin - Tank Floor bolt pattern, max watch cycle area and wave gages setup.

Figure 4 shows the device installed in the basin including the tanks wave sensor setup. Here, the device response and loads on the device during a severe sea irregular wave case was assessed. Equivalent wave heights of up to 22m occurred during the full length of the test.

Figure 4: CalWave Device installed in the basin including the tanks wave sensor setup. Here, the device response and loads on the device during a severe sea irregular wave case was assessed. Equivalent wave heights of up to 22m occurred during the full length of the test.

2.2 Tests

Over 100 wave cases/tests were recorded during the entire testing period of 15 testing days.

2.2.1 Test Plan

The following categories summarize the performed tests matching the proposed testing categories. For each testing objective a larger amount of specific wave cases was run.

PTO Integration and Controllability

- 1:20 Scale
- Test PTO behaviour and stability for a static WEC setup in the basin. The capability of the PTO to submerge the absorber body and bring and hold it at its static equilibrium position is tested.
- For a static setup the behaviour in case of a power loss/PTO software failure was tested to minimize risks/threads of malfunctions during 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. PTO behaviour is observed potential tuning of software settings accommodated these tests.

Basic Working Principle Verification

- 1:20 Scale
- For hydrostatic tests and validation of total device buoyancy 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 behaviour is checked and it is ensured that all PTO units work in the same way.
- 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.

System Identification Tests (SID)

- 1:20 Scale
- Estimation of WEC system characteristics using oscillation tests
- Forced oscillation experiments are run in calm water as intrinsic device impedance tests. A pink noise is used to excite the device with different uncorrelated pink noise signals depending on the amounts of DOF, see [1][2].
- For identification of wave excitation characteristics of the device, forced oscillation experiments in presence of waves were conducted. PTO forces, absorber velocities and wave elevation were measured. Additionally, hull pressure on the absorber body was measured, allowing for further system identification information.

Performance Evaluation

- 1:20 Scale
- To compare the device performance in the ACE metric, for baseline performance evaluation 6 irregular, 0 Degree incident wave cases were tested. The wave cases can be used to compare performance against other devices. Tests were 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 the device's performance in energy extraction was assessed for specific additional irregular sea states.

WEC Survivability Testing

- 1:30 Scale

- To assess the device behaviour in severe sea and in extreme wave cases, the 1:30 scale device was used with specific survival strategies engaged.
- To define upper limits of survival cases, 100-year return wave contour plots for different test side were used. Multiple cases were defined on that 100-year return contour (e.g. Peak, resonance, longest period …) and wave cases in the basin are tuned to reproduce these sea states until limits of the wave maker/basin were reached.
- During extreme seas testing scaled waves of H > 20m full scale equivalent were tested

2.3 Results

2.3.1 Wave Tank Calibration

Example power spectrum plots of the wave tank calibration performed are shown below. In general, a good fit between the theoretically defined, irregular wave cases and the actual measured wave tank spectrum was achieved as shown in Figure 5 and Figure 6.

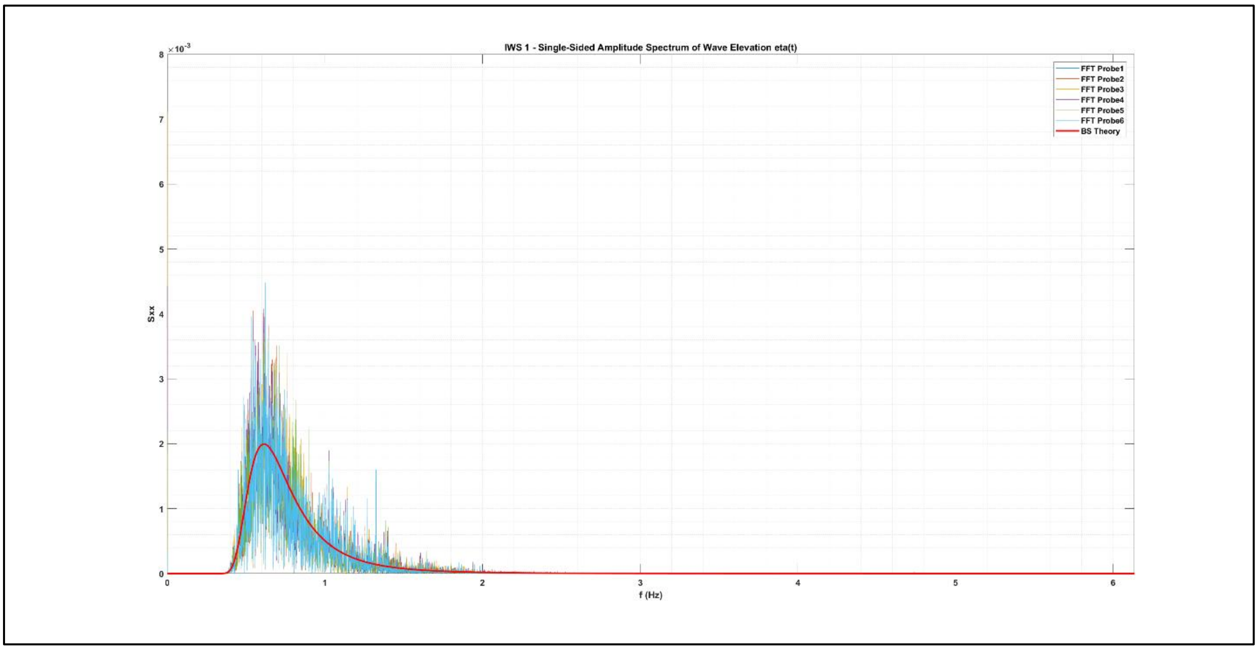


Figure 5: IWS 1 Single Sided Power Spectrum; Comparison of actual basin spectrum vs. Theory

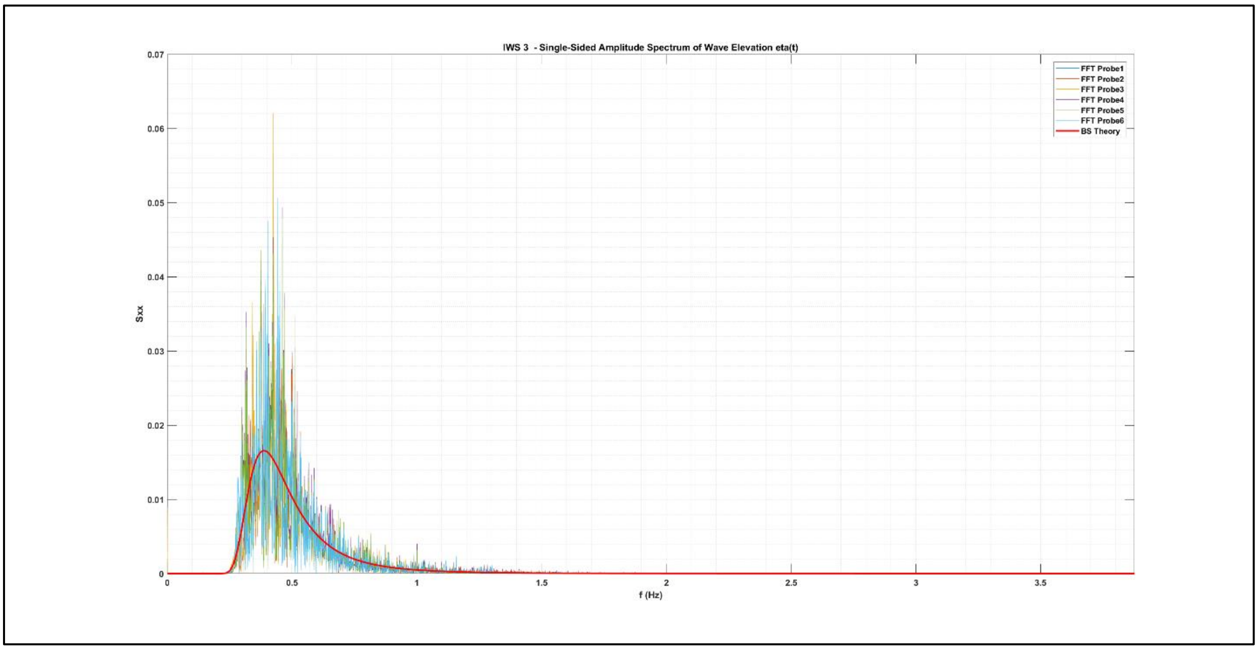


Figure 6: IWS 3: Single-sided Power Spectrum; Comparison of actual basin spectrum vs. Theory.

2.3.2 PTO Tracking Capabilities

The achieved force set point tracking capabilities shows an overall very good behaviour. For a random irregular excitation (displacement) of the PTO the force set point and actual tracking signal is compared in Figure 7.

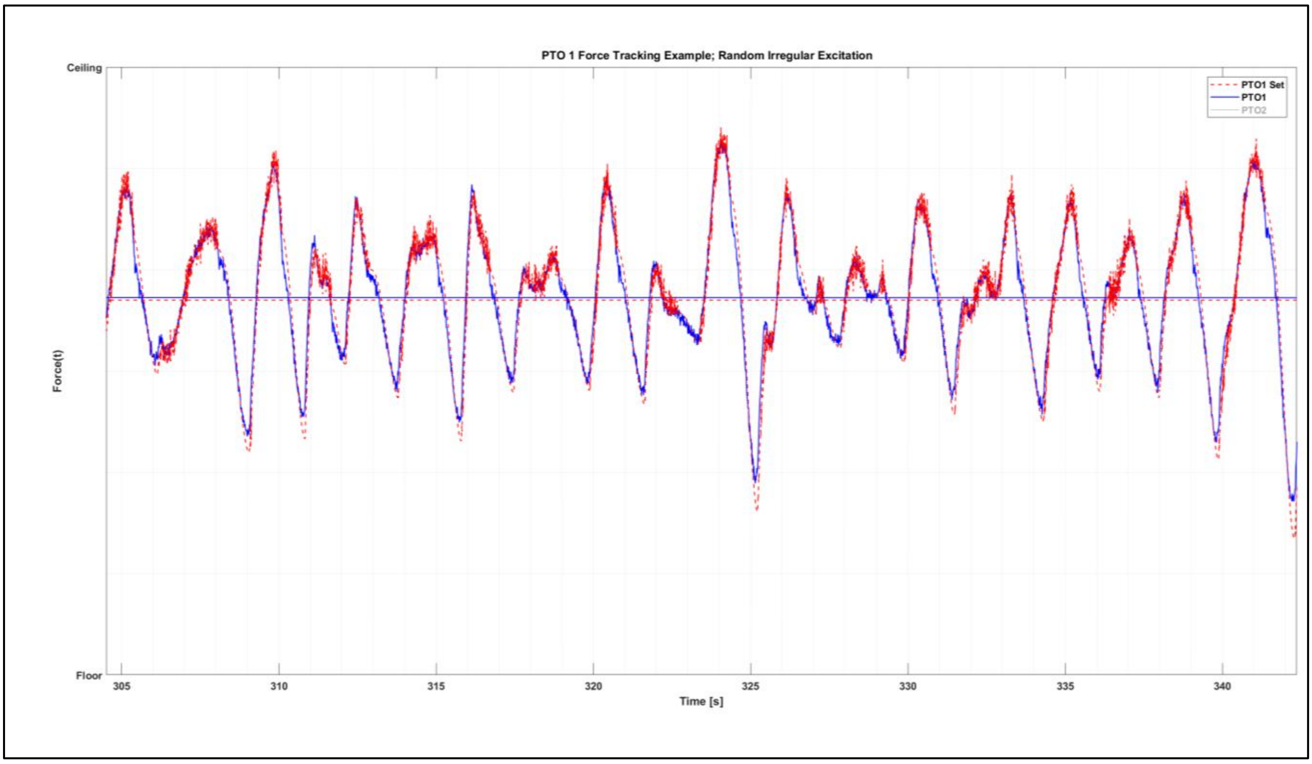


Figure 7: Exemplary Force set point and tracking signal showing a good set point tracking capability of the PTO units. Here, the PTO unit was randomly excited with an irregular signal with a common period and magnitude

2.3.3 Max Mooring Tension Reduction

Two runs of irregular wave cases are compared representing the design load case for a wave test site (e.g., the JPD case with the highest annual energy contribution). Input parameters for the two cases are shown below; to the extent possible given the experimental setup, the only difference in these experiments was the LabView-controller-imposed maximum and minimum tensions settings.

Run ID	Time	Dir. (°**)**	Hs (m) 1:30 scale	Tp (s) 1:30 scale	Damping (% of Peak)	Spring (% of Peak)	Max. Line Tension (% from allowed max Tension)
#69	1/30/18 5:12 pm	0°	0.175	1.92	25% of Max	75% of Max	100%
#91	2/1/18 1:34pm	0°	0.175	1.92	25% of Max	75% of Max	31.25 %

2.4 Analysis & Conclusions

2.4.1 PTO Controllability

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. Friction is thus directly compensated, allowing to strictly achieve the desired PTO behavior right at the PTO connection point on the absorber body.

Figure 8 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.

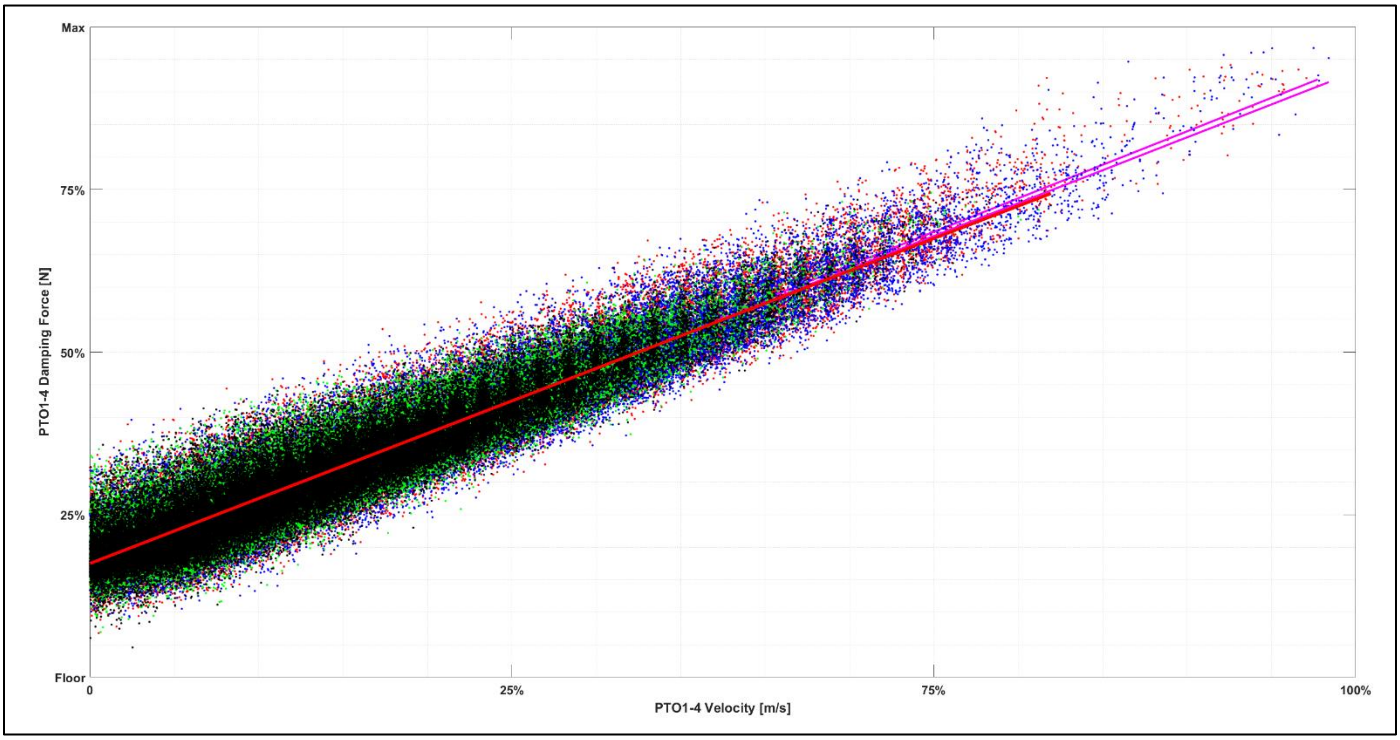


Figure 8: PTO damper force over PTO velocity (damping correlation) plotted for one PTO units which was randomly excited with an irregular pattern of common period and magnitude. The desired force-velocity correlation (damping coefficient of 1000 Ns/m) in red can very well be tracked with the PTO control /system.

2.4.2 Mooring Tension Reduction

Qualitatively, the controller and load reduction control “trade” higher velocities for lower forces at times when the force command is saturated. Note that the measured force occasionally exceeds the nominal limit. This can be due to inertia in the physical system and/or lag the commanded force response from the controller. Tuning the controller for the equivalent full-scale scenario will be crucial, to avoid the oscillations around the force limit, which would accelerate fatigue of mechanical components.

Run ID	Effectively recorded Forces	
	# 69 (Unconstrained)	# 91 (Constrained)
Mean Max Force	100%	44.68%

2.4.3 Load Reduction Control Performance Effect

"Trading" velocity for force effectively changes the damping behaviour from the setpoint, which is presumably the optimal setting for the given sea state. This move away from the optimal setpoint should decrease the captured power. The more often the force saturates in each sea state, the lower the energy capture. In this experiment, in which the largest force was reduced by nearly ¼ the average power decrease was below 10%.

Run ID	Maximum Upwards Force (% of Max)	Maximum Downwards Force (% of Max)	Normalized Average Power (%)
#69 (Unconstrained)	100%	94.89%	100%
#91 (Constrained)	77%	59.09%	91.01%

The tradeoff of lowering the PTO load requirement in exchange for decrease power capture are evident. However, the exact level at which the force limit should be set is subject to techno-economic optimization. This decision is usually made before the construction of upscaled PTO concepts, to realize the savings in all the PTO components.

In the instants where a force limit is encountered, the device behavior will suddenly change. Care should be taken to analyze the behavior in these areas and minimize oscillations around any maximum load set point caused by the controller.

3 Main Learning Outcomes

3.1 Progress Made

3.1.1 Progress Made: For This User-Group or Technology

For all the anticipated experimental tests / the plan derived from the Stage Gate table sufficient and satisfying results were obtained. The described test plan in section 2.2.1 allowed to checkmark all stages that were subject to the conducted tank test. More specifically, the following progresses were made in each of the previous listed tests/categories:

3.1.1.1 Provide the empirical hydrodynamic coefficient associated with the device (for mathematical modelling tuning)

System identification tests using noise PTO and wave excitation delivered a rich set of force, displacement, velocity, acceleration, pressure and wave elevation data. This data can conveniently be used to derive device characteristics / hydrodynamic coefficients associated to the device topology/design from the experiments, validating the numerical assessment of hydrodynamic properties such as added mass, added damping, viscous drag etc.

3.1.1.2 Investigate physical process governing device response. May not be well defined theoretically or numerically solvable

Similar to the tests described in section 3.1.1.1., system identification tests including noise excitation of PTO and noise wave excitation was successfully conducted. The experiments delivered a large dataset of PTO forces and more important, device displacement, accelerations and velocities. The direct correlation between PTO kinetics, wave elevation, and device kinematics can be made using these results to fully resolve influences/physical processes leading to characteristic device responses.

3.1.1.3 Initial indication of the full system load regimes & Survival loading and extreme motion behaviour

To assess the device behaviour in severe sea and in extreme wave cases, the 1:30 scale device was used with survival mode enabled. Using survival cases with a 100-year return wave contour plot the upper bounds of subsystem and overall device loads were inspected. Moreover, maximum displacements, velocities and accelerations in the PTO system as well as maximum watch-cycles of the WEC device were derived. The indication of the full system load regime subsequently helps to derive first principle specifications for subsystems and for the hull design, accompanying numerical results.

3.1.1.4 Performance in real seaways (long and short crested)

To compare the new device performance in the Wave Energy Prize Metric using the ACE metric, for baseline performance evaluation six irregular wave cases were tested. All irregular waves of common test sites were included in the assessment and results of performance and device behaviour were to great satisfactory with first estimates showing that the ACE factor, respectively performance compared to device costs was significantly improved beyond experimental results/assessments/estimates from the WEP in 2016/17.

2.4.4 Next Steps for Research or Staged Development Plan – Exit/Change & Retest/Proceed?

Tank testing results from the MARINET 2 testing in January 2018 showed very good results in terms of load reduction, performance in various irregular sea states and controllability of the device/PTO.

CalWave seeks to proceed with the development of their WEC technology and will build up onto recent findings from the MARINET 2 tank test. Moreover, found results and data from system identification tests can now efficiently be used to further develop the device strategy and improve PTO controls.

In terms of the stage gate criteria the following steps will be taken for further development:

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.		➲

3.1.2 Progress Made: For Marine Renewable Energy Industry

- System Characterization/Identification of submerged pressure differential devices
- Introduction of effective load management/reduction device control schemes for effective load reduction of PTOs, mooring tether, and hull localized loads while maintaining performance in power absorption
- Implementation of wave noise generation in wave tanks for system identification purposes, see [1][2]

3.2 Key Lessons Learned

- Motion tracking of submerged WECs require either an underwater motion tracking system or an extension of the device with markers to reach above water for the cameras to track. While adding such an extension for the tracking markers on a device it is important to ensure rigidity of the extension while minimizing additional weight or biasing the device motion in any other way. Otherwise additional vibrations might bias the motion tracking data captured or, in the worst case, influence the device behaviour during tests.
- Running monochromatic waves for system characterization is a very tedious process. Other system identification methods should be used which can reduce the length of this process by an order of magnitude.
- Amortizing the device setup time over a longer testing period is more convenient and effective for both, tank staff and facility as well as the customer/technology developer.

4 Further Information

4.1 Scientific Publications

List of any scientific publications made (already or planned) as a result of this work:

- Collaborative publications/conference contributions on numerical (Full CFD) and experimental system characterization with Maynooth University. Comparison of device hull pressure with CFD calculations.
- Experimental System Identification of Submerged Pressure Differential WEC Devices.

4.2 Website & Social Media

Website:	http://calwave.org/
YouTube Link(s):	-
LinkedIn/Twitter/Facebook Links:	CalWave Twitter
Online Photographs Link:	-

5 References

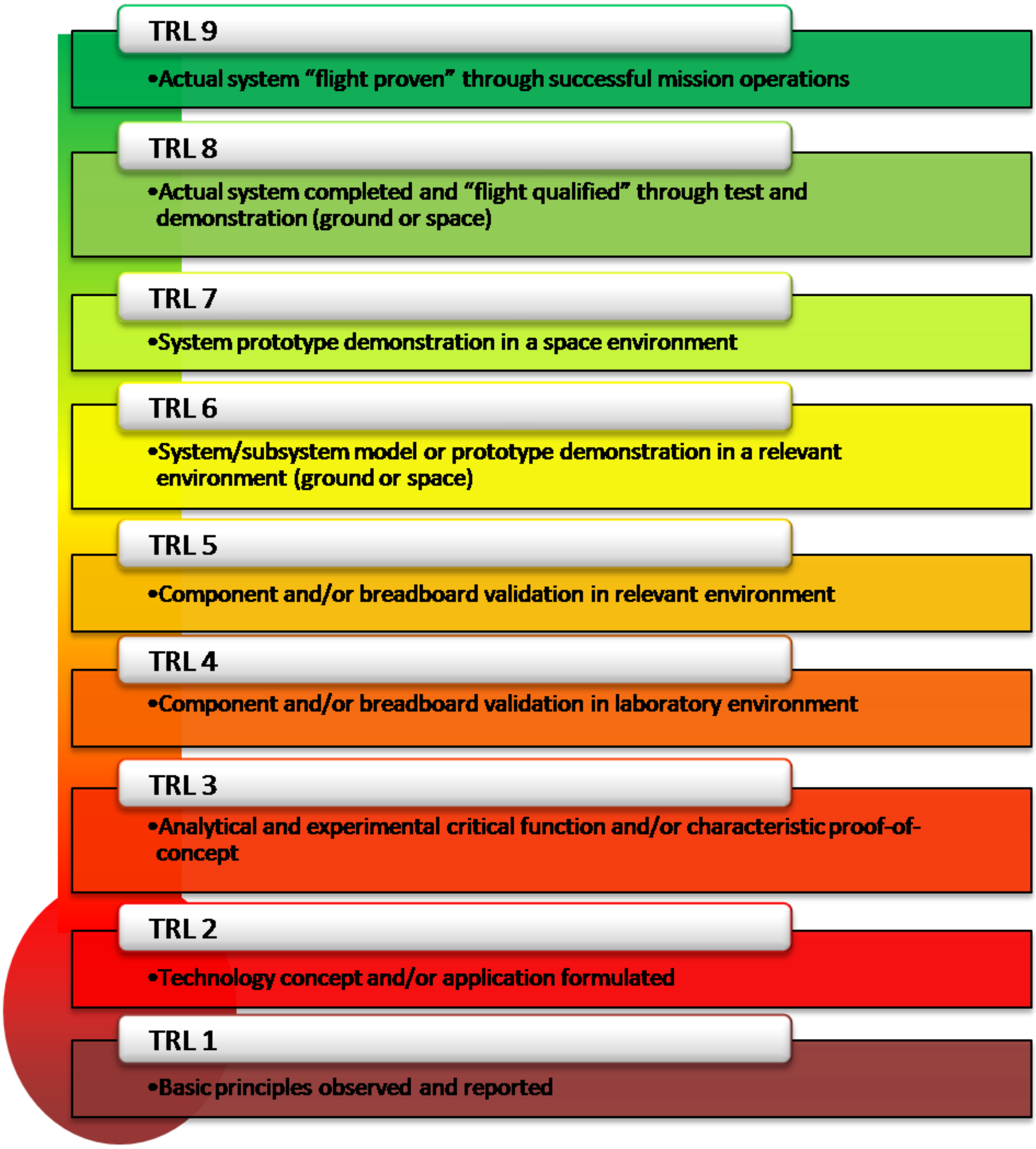
[1] G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, “System identification of a heaving point absorber: Design of experiment and device modeling,” Energies, vol. 10, no. 10, p. 472, 2017.

[2] G. Bacelli and R. G. Coe, “WEC system identification and model validation,” in Marine Energy Technology Symposium (METS2017), Washington, D.C., 2017.

6 Appendices

6.1 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[1]

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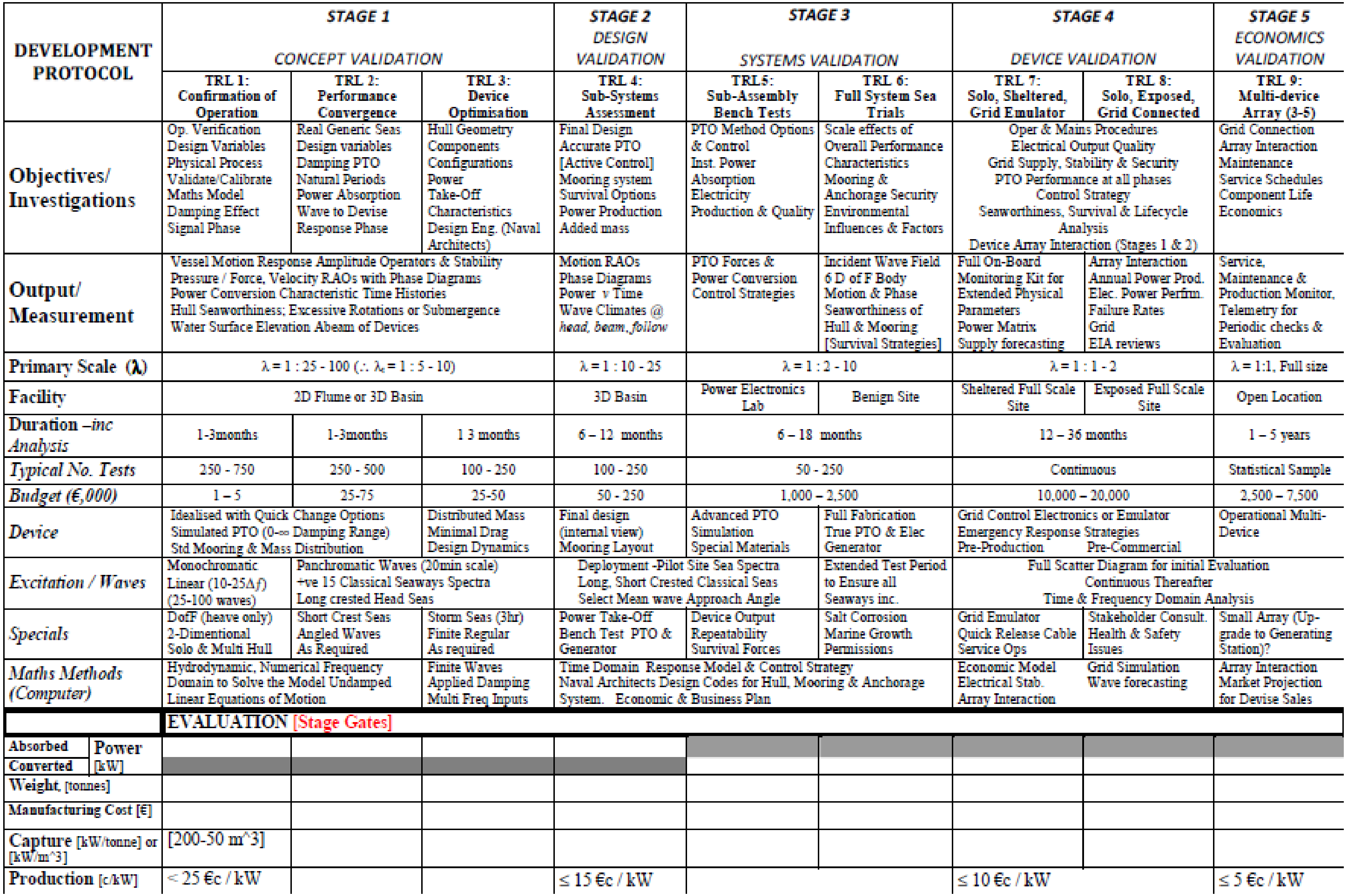
[1] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

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 Perfm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	λ = 1 : 25 - 100 (∴ λ_e = 1 : 5 - 10)			λ = 1 : 10 - 25	λ = 1 : 2 - 10		λ = 1 : 1 - 2		λ = 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 Power [kW]									
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