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User Project: Experimental validation of a floating OWC for wave energy conversion

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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, In Experimental validation of a floating OWC for wave energy conversion novation 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 Introduction & Background

1.1 Introduction

IDOM is an international company offering professional integrated services in Consulting, Engineering and Architecture. In September 2018, IDOM motivated by an interest in increasing their know-how in marine renewable energies, absorbed the company OCEANTEC Energias Marinas S.L.

OCEANTEC was founded in Spain in 2008 from the joint venture of Tecnalia and Iberdrola. It was created around a wave energy converter technology based on an attenuator with a gyroscope as power take off system. After an extensive R&D effort, going through two laboratory testing campaigns and a ¼ scaled sea trials, in 2010 it was decided to stop with that technology in order to reassess the competitiveness with other WEC technologies in the market.

A full year was dedicated to this comparative study and based on the conclusions obtained it was decided to start with the development of a floating Oscillating Water Column technology-based device.

This Spar OWC project started in 2012, developing advanced numerical tools which were calibrated and validated with two testing campaigns in CEHIPAR laboratory, Madrid, Spain (in 2012 and 2014).

In 2016 Oceantec manufactured, installed, connected to the grid and operated a reduced power prototype (MARMOK-A-5) at BiMEP offshore test site.

The device has survived 3 winters in open waters on the Atlantic, connected to the grid without suffering any mishap, and generating the electricity that was initially expected. The prototype is the test platform for the innovations proposed by the EU funded OPERA project (H2020).

As the next step of the technology development path, IDOM has designed a commercial size device which has a larger diameter and similar draft to the MARMOK-A-5 prototype. Before going to a full-scale testing program at sea, it seemed highly convenient to perform a new lab testing campaign to reduce the risk and increase the confidence in the next development stage of development.

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 (DoF) 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)	➲

STAGE GATE CRITERIA	Status
• 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]	
• 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

The project objectives may be briefly enumerated as follows:

- Hydrodynamic characterization of the fixed device through forced oscillation and diffraction tests
- Full hydrodynamic characterization of the moored device
- Device motion characterization and power production assessment under irregular sea conditions
- Mooring loads assessment and device dynamics under extreme sea conditions
- Centre of gravity (CoG) sensitivity analysis to assess its influence both on device performance and extreme sea conditions
- Higher order effects on the hydrodynamic behavior and power production
- Validation and refinement of the numerical models

2 Outline of Work Carried Out

2.1 Setup

2.1.1 Physical Model

The device, presented in the sketch in Figure 1, was manufactured in aluminium with 1:28 scale factor. Special considerations were taken in the prototype design and manufacturing to respect mass, CoG position and inertia values to be coherent with full scale device.

The instrumentation applied to the device during the tests were:

- Capacitive wave probes to measure the water surface elevation, internal and external;
- Buoy motion tracking system;
- Air chamber pressure sensors;
- Servo controlled actuated cylinders to induce forced oscillations (for forced oscillation tests);
- Force transducers on the actuating systems in the forced excitation tests (for forced oscillation tests).

The model employs a movable mass to achieve 3 different mass distributions named C1, C2 and C3.

A full testing campaign was performed for C1, C2 and C3 to analyze the center of gravity position influence on the hydrodynamic behavior. Before starting the tests, the center of gravity and the inertia for the three configurations were measured and adjusted.

The mooring lines were composed of 4 catenaries lines connected to a submerged cell (See Figure 2). To accommodate mooring system model to tank dimensions, lines were truncated by using springs.

In order to measure mooring forces, six load cells were installed.

Figure 1: Physical model sketch

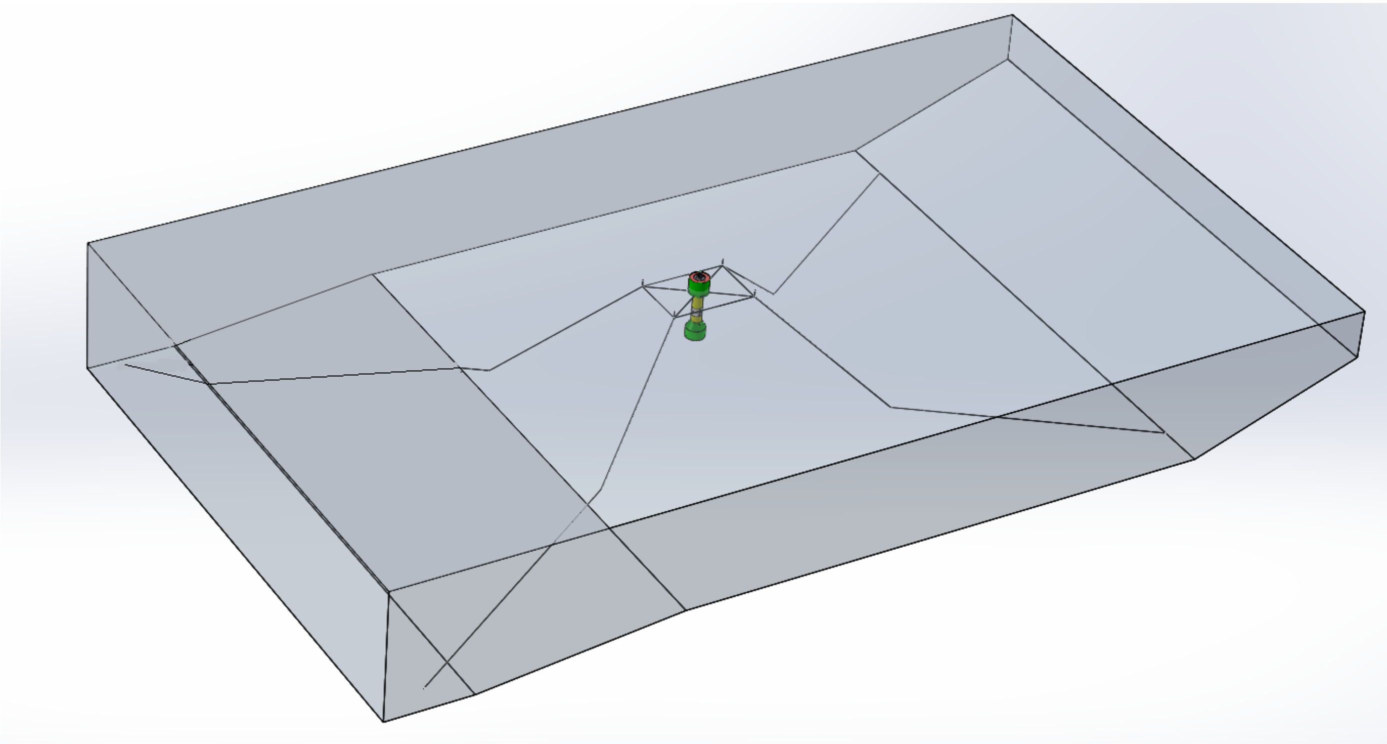


Figure 2: 3D Sketch of the moored device arrangement in the COAST Ocean Basin

2.1.2 Wave Tank

The tests were carried out at COAST Laboratory in the University of Plymouth. The Ocean Basin is 15.50m wide and 35m long, with a moveable floor that allows different depth values of up to 3m. The wave generator is composed of 24 individually controlled hinged flap absorbing paddles. It generates current through a recirculating hydraulic system up to 0.3m/s for a 2m water depth.

Figure 3 represents a picture of the moored device arrangement as was deployed in the COAST Ocean Basin.

The wave probes' position implemented during the tests can be observed in Figure 4. In total, 6 wave probes were used, 3 in front the device and 3 at the side; an additional wave probe was installed in the device position during the wave calibration stage.

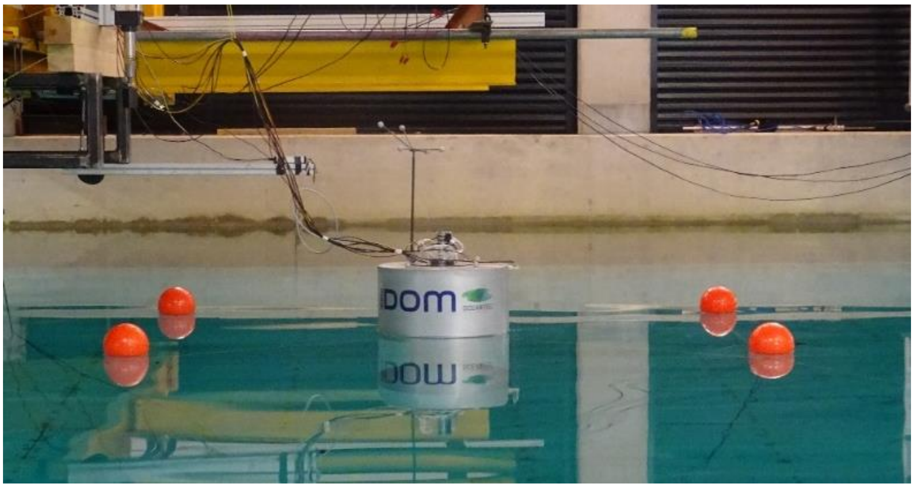


Figure 3: Picture of the moored device arrangement in the COAST Ocean Basin

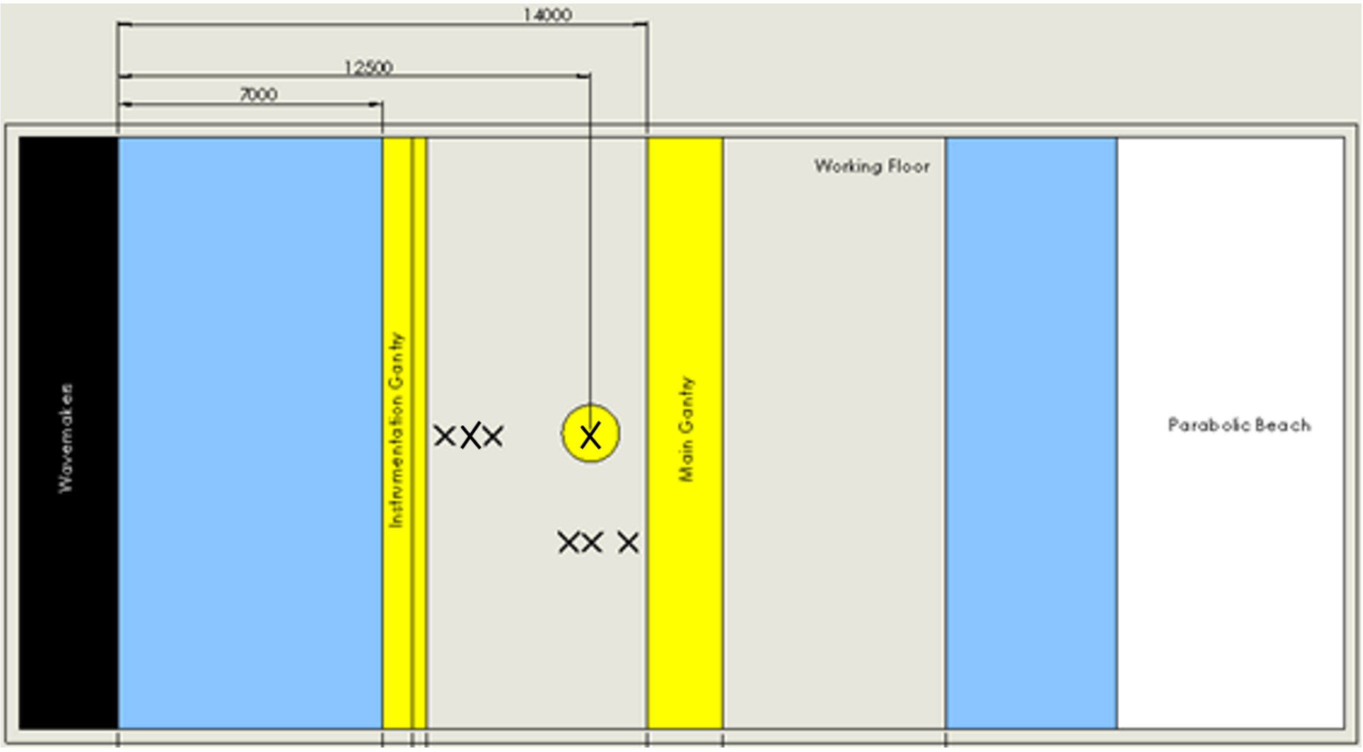


Figure 4: Wave probe position into the COAST Ocean Basin. Dimensions in mm

2.2 Tests

2.2.1 Test Plan

Test preparation (4 days)

- Mass, Inertia and CoG measurements for the 3 configurations
- Waves calibration
- Mooring Installation
- Instrumentation installation on the device, on the moorings and cabling

Hydrodynamic characterization: C1 (4.5 days)

Device fixed to the gantry

- Water current test, measuring horizontal force and moment for a set of predefined constant water velocities
- Forced oscillations in heave for 2 different wave amplitudes, with and without mooring attached
- Forced oscillations in surge for 2 different wave amplitudes
- Regular waves with fixed structure measuring forces (F_{surge}, F_{heave}) for opened chamber and a medium damping PTO

Connect mooring system

- Quasi-static characterization of mooring system.

Free Device from the gantry

- Decay tests for the surge, heave (air chamber closed and opened) and pitch of the buoy and heave of the internal water column
- Regular waves. 22 frequencies for the same amplitude + 5 repeated frequencies with another amplitude. Three different PTO configurations have been tested for each regular wave train
- Band-limited white noise wave train for the Heave-Pitch and Surge frequency range intervals

Irregular waves: C1 (1 days)

- 27 irregular sea states from BiMEP test site following the JONSWAP spectra defined by a set of Hs,Tp and γ); considering the optimum PTO configuration to maximize power generation.

Extreme sea conditions: C1 (1 days)

- 8 extreme sea states defined from the BiMEP test site environmental contours.

CoG position sensitivity: C2 and C3 (4 days)

- Decay test in pitch (C2 and C3);
- Band-limited white noise wave train (C2 and C3);
- Regular waves. 22 frequencies for the same amplitude + 3 repeated frequencies with another amplitude. A medium PTO damping configuration has been tested in each regular wave;
- Same 27 irregular sea states than in C1 considering the optimum PTO configuration to maximize power generation;
- Same 8 extreme sea states tested in C1.

Decommissioning (0.5 day)

2.3 Results

In the present section some of the main test results of the data analyzed so far are presented.

2.3.1 Wave generation

During the initial part of the testing campaign, waves were calibrated without the model in place.

In Figure 5, an example of a regular wave generated and measured in the probes in front of the device is presented. Some small difference of phase due to the different wave probe position is noticeable. Gauge 1 is the closest to the wavemaker and Gauge 3 is the closest to the device.

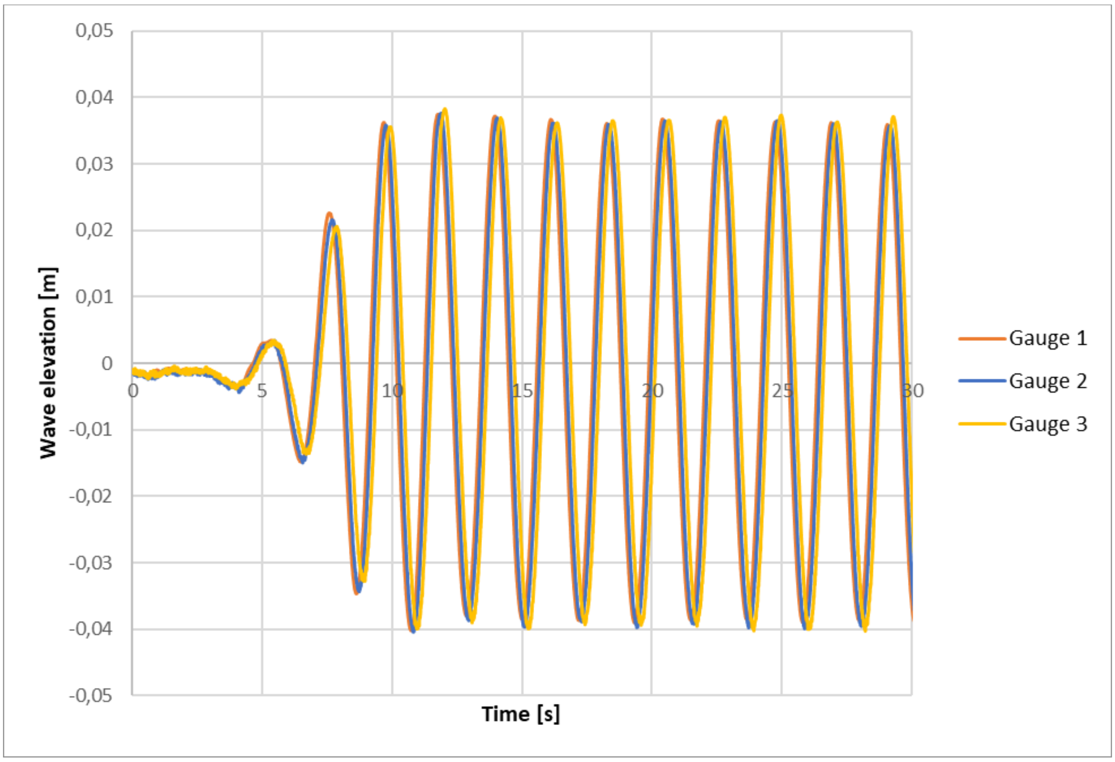


Figure 5: Wave elevations for regular wave (G1, G2 and G3). Model Scale Data

Figure 6, represents a graphical comparison between the generated and the analytical JONSWAP spectrum. The correlation obtained is satisfactory, as can be confirmed by observing the spectrum characteristics reported in the table below:

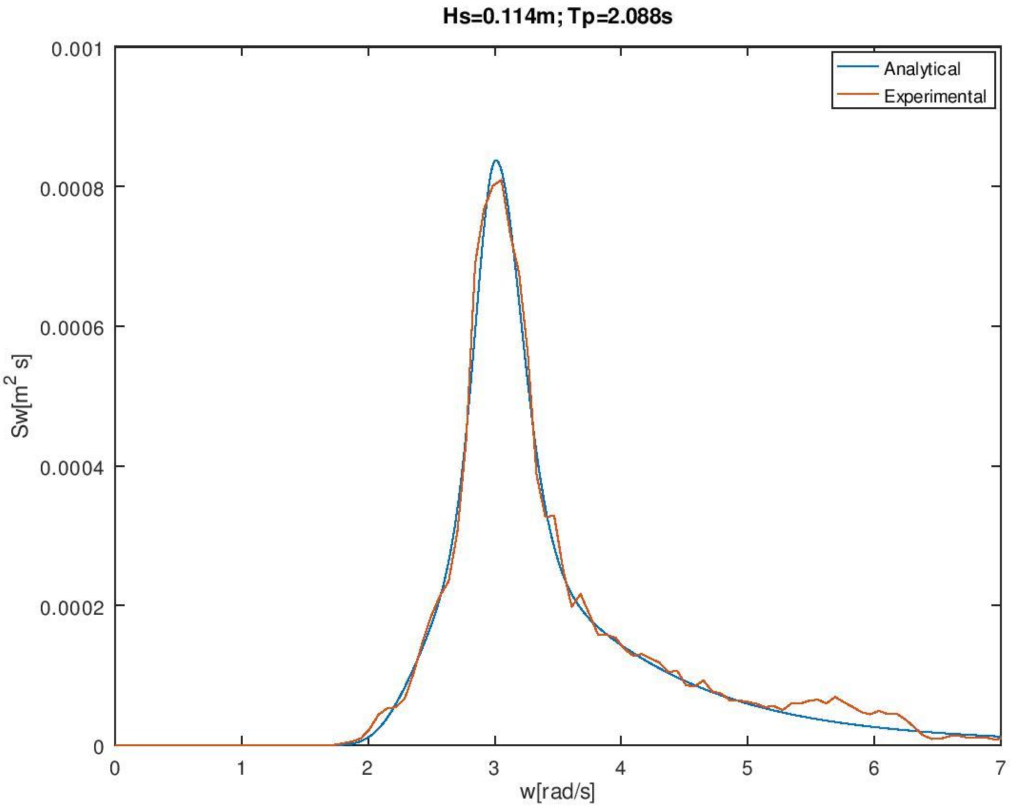


Figure 6: Analytical and experimental Irregular wave JONSWAP spectrum comparison. Model Scale Data

Table 1 Analytical and Experimental wave spectra comparison

	m0 [m^2]	**Hs [m]**	**Tp[s]**
Analytical	0.000812m^2	0.114m	2.088s
Experimental	0.000841m^2	0.116m	2.0251

To keep the good wave measurement accuracy, wave probes were calibrated daily before starting the tests.

2.3.2 Decay Test

In Figure 7 and Figure 8, an example of decay test results in the heave degree of freedom for C1 is shown for the device and the OWC, respectively. The numerical curves have been adjusted through the hydrodynamic parameters calibration (added mass, radiation damping and quadratic damping).

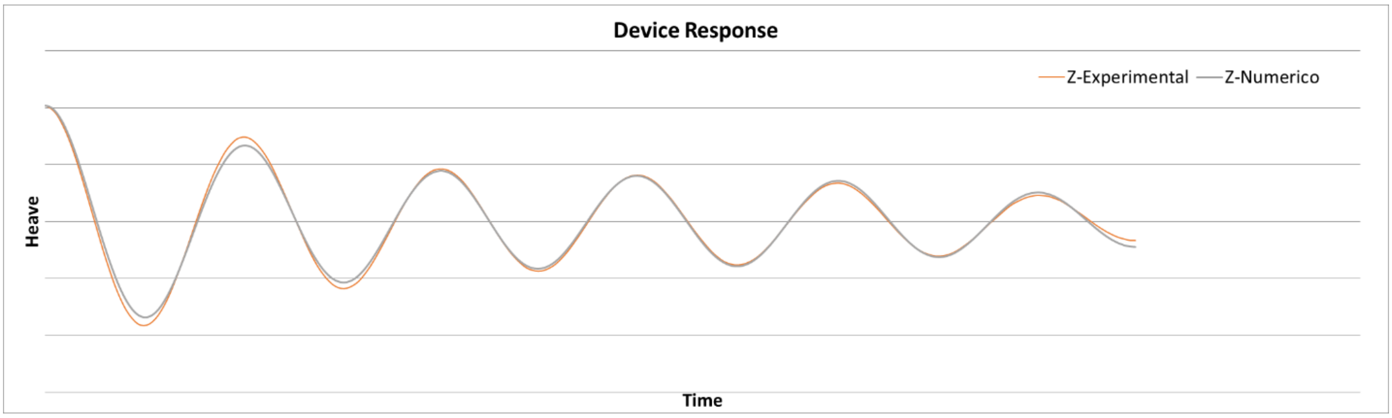


Figure 7: Device response during a decay test in heave for the C1. Experimental and numerical comparison results

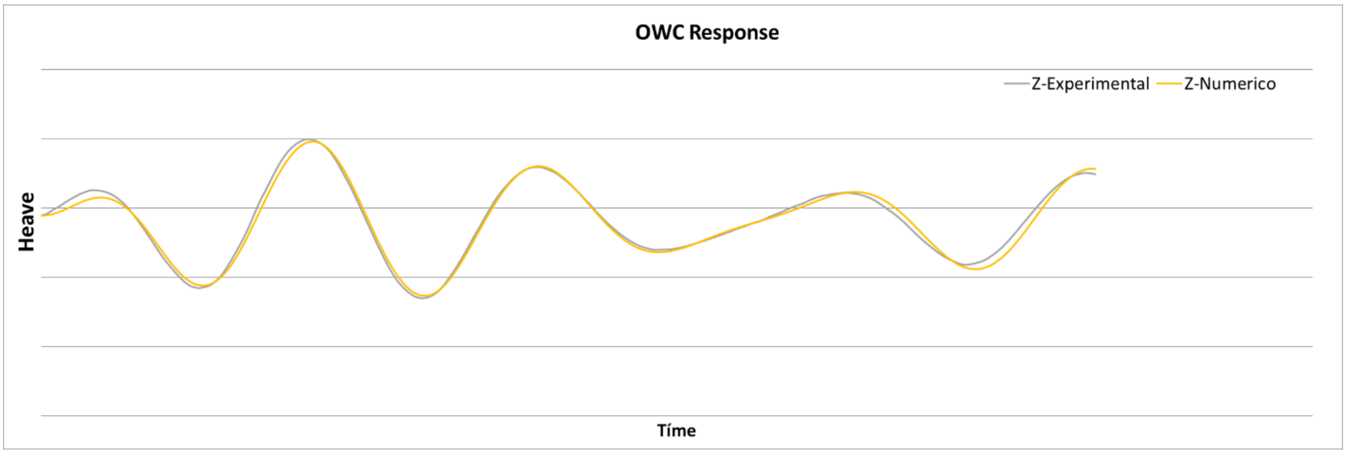


Figure 8: OWC response during a decay test in heave for the C1. Experimental and numerical comparison results

2.3.3 White Noise

The aim of these tests is to characterize the response amplitude operator (RAO) for the two bodies (device and OWC) through a single wave train. In this section some results obtained with the white noise tests post-process are reported.

Three PTO configurations, soft, medium and hard, have been considered to introduce the PTO damping between the two bodies. In Figure 9 the RAOs in heave for the device and the OWC, in C1, are reported. It is interesting to note how the damping is affecting on the body dynamics, to a point where for the hard PTO, when the PTO damping is larger, there is a remarkable similar trend for both device and OWC RAOs, with similar resonance periods (Figure 9 - Bottom); whereas for lower PTO damping values, the resonance for the two bodies tends to separate (Figure 9 – Top left). An intermediate case is represented by the medium PTO (Figure 9 – Top right).

In Figure 10 the RAO in pitch is presented which is not influenced by the PTO configuration, a result that was already predicted by the numerical models.

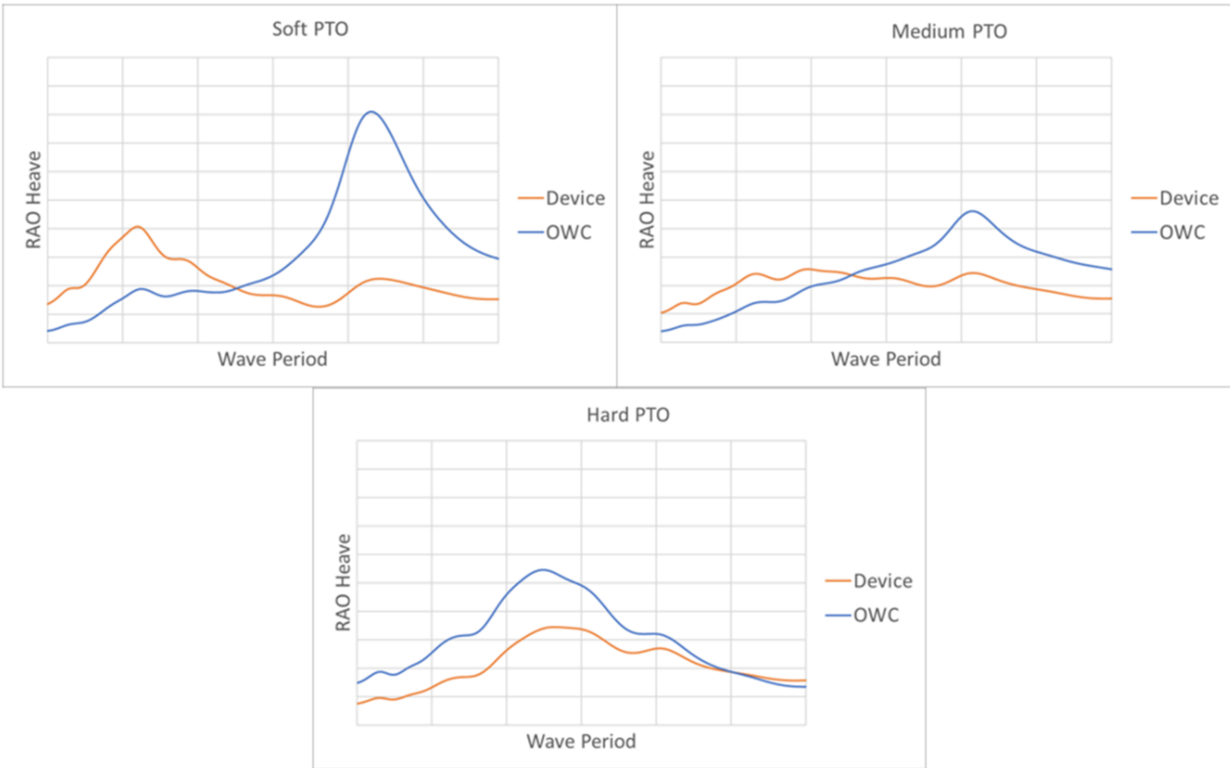


Figure 9: RAO Heave C1 for the device and OWC. Low PTO damping (Top left), Medium PTO damping (Top right), High PTO damping (Bottom)

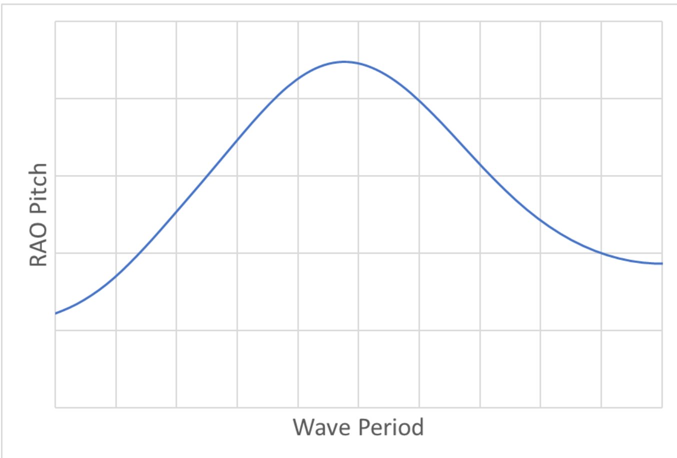


Figure 10: RAO Pitch C1 for the device

2.3.4 Irregular Waves

Apart from obtaining data of the device behavior under realistic sea conditions, this type of tests seek to provide an estimation of the power capture characteristics of the device. Consequently, an important outcome of these tests is the comparison of the pneumatic power captured for the three different mass distributions.

In Figure 11 the non-dimensional average pneumatic power available for some tested operational sea states, and for the 3 configurations (C1, C2 and C3) is reported. It is noticeable that the differences between the absorbed power for the 3 configurations increases for larger values of the energy absorbed by the device. And the lower the center of gravity position (C3 lower than C1, lower than C2) the larger amount of energy is captured.

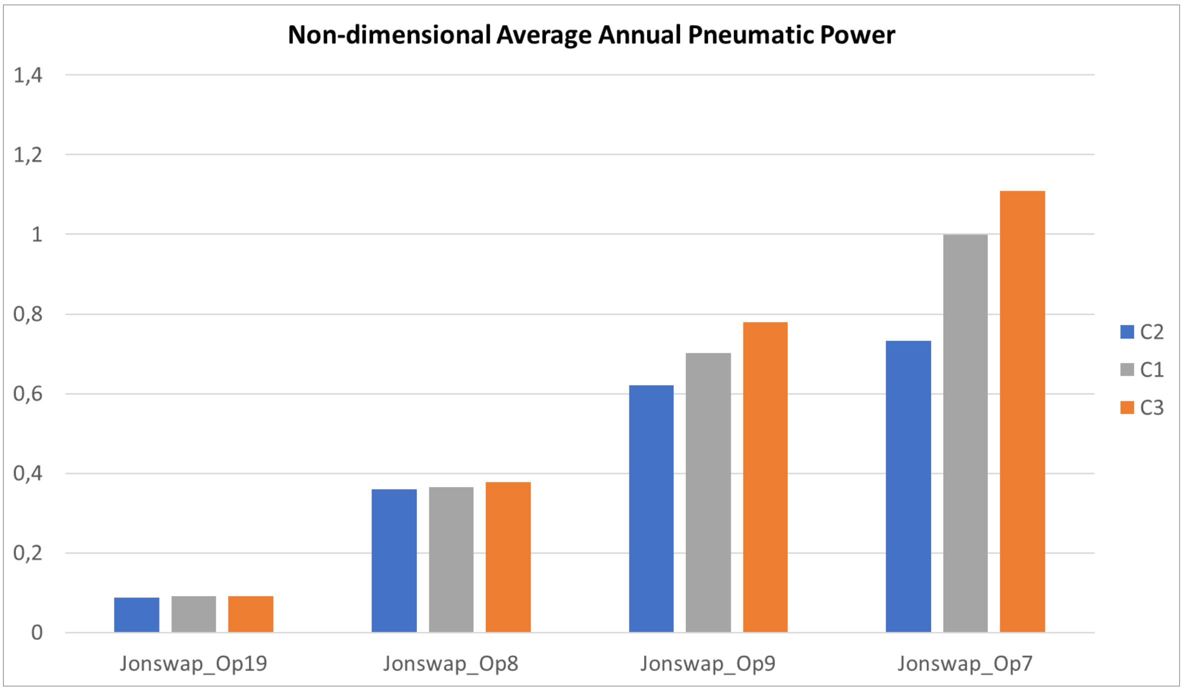


Figure 11: Non-dimensional average pneumatic power for all configurations in several operational sea states

2.3.5 Extreme Waves

Through the extreme waves tests it is possible to characterize the maximum device motions and the extreme design mooring tension values, which will be later used to calibrate numerical model used for mooring system design.

In Figure 12, results for one up-wave mooring line peak tension have been reported. As it can be observed, center of gravity position has a non-negligible influence on peak loads. However, it was not possible to identify a clear trend across all sea states, as was the case with power capture, since it is dependent on sea state period.

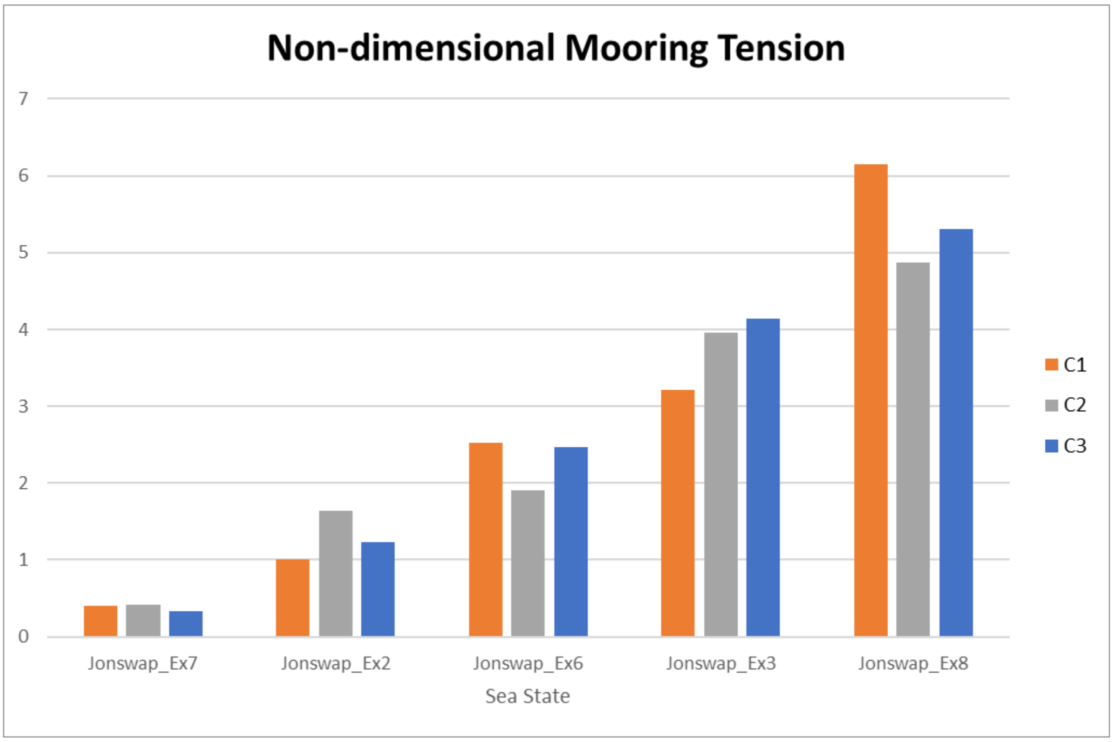


Figure 12: Non-dimensional mooring tension for all configurations in some extreme sea states

In Figure 13, a picture taken during an extreme sea state condition is presented.

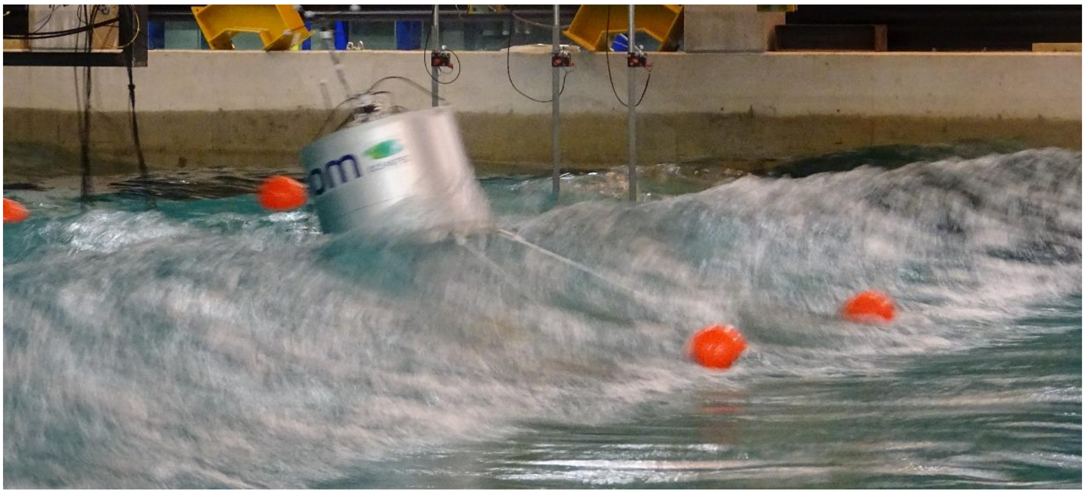


Figure 13: Waves impacting the prototype during extremal sea state condition test

2.3.6 Forced Oscillation

Forced oscillation tests seek to validate device and OWC radiation forces. By means of these tests, and after filtering the signal of the forces to eliminate high frequency noise induced by actuators, it was possible to adjust the hydrodynamic parameters and the quadratic damping coefficients of the numerical model, in order to minimize the difference with the experimental results. Figure 14 represents an example of numerical and experimental comparison of the forced oscillation test in heave motion.

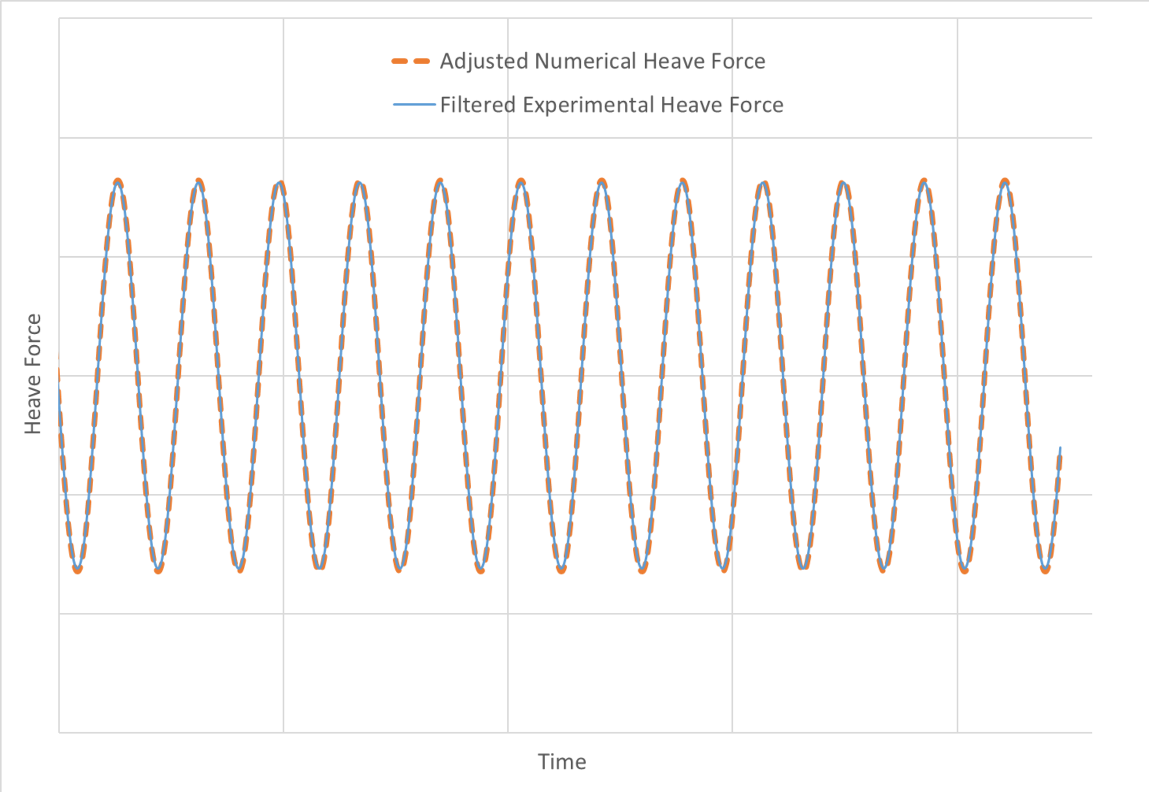


Figure 14: Comparison between experimental and adjusted numerical heave force

2.4 Analysis & Conclusions

In order to validate IDOM's commercial-size floating OWC buoy for wave energy conversion, a test campaign was undertaken to fully validate device and mooring dynamics and assess power capture performance. The experimental campaign was carried out in the COAST Laboratory at the University of Plymouth, using a 1:28 scaled model.

It was possible to characterize the hydrodynamic behavior of the system under operational and extreme conditions, the hydrodynamic parameters, the diffraction forces, the response amplitude operator through regular wave and white noise tests and stablish an upper bound to device motions and the extreme design tension for the mooring lines. In this report, some of the most important results based on the data analyzed so far have been presented and commented.

Testing objectives have been fulfilled despite a more detailed data analysis is still ongoing. As a summary, the tests can be considered extremely valuable for:

- Numerical model calibration, both in frequency and time domain with special focus on second order effects for moderate and extreme sea states
- To know the device's hydrodynamic behavior for 3 different configurations, obtained varying the center of gravity position, to understand how it changes the overall behavior and to help on defining feasible limits for manufacturing
- To better understand the higher order effects on coupled motions

3 Main Learning Outcomes

3.1 Progress Made

3.1.1 Progress Made: For This User-Group or Technology

This testing campaign has been of uttermost importance to gain confidence in the spar-type OWC technology for the next development stages. Numerical models for the prediction of device behavior and power performance as well as extreme loads, which ultimately affect technology LCOE figures have been significantly improved. Second order effects, which are difficult to predict through numerical modelling, such as drag or different DoF cross-coupling have been investigated.

Additionally, the sensitivity to the mass distribution on the device behavior and extreme loads has been investigated, which is key when feasible manufacturing restrictions have to be defined.

3.1.2 Progress Made: For Marine Renewable Energy Industry

Tests results combined with the lessons learnt of the low power device operating offshore have implied a step forward for this technology, which due to its simplicity and cost of energy figures, can be one of the first ones to reach commercial viability pushing wave energy sector forward.

Despite the large experience of the company on this technology, with several tank testing campaigns and currently operating device offshore, this tank testing campaign has demonstrated to be of great importance, with many outstanding learnings, even if the tested device is very similar to the one operating offshore. Consequently, based on our experience, having reached the offshore testing stage doesn´t mean tank testing is not necessary anymore.

On the testing side, this has been the first experience on forced oscillations for this type of *slender* (i.e., vertical dimension much larger than horizontal ones) devices in COAST lab, which has provided valuable learnings for future users. Additionally, white noise tests have demonstrated a large potential to complement regular wave tests to build RAOs which are much more time-consuming tests.

3.2 Key Lessons Learned

- Carefully plan the tests through the help of numerical model to best define instrumentation set up;
- Engage with infrastructure staff when defining test plan since each tank is different and they have the best knowledge to adjust plan timing
- Plan with flexibility to allow test order modifications to best fit daily schedule and testing incidents;
- Plan extra tests as a backup, in case of extra time
- Try to have backup of the key sensors and model instrumentation since failures tend to happen
- Test results are very sensitive to model characteristics, so manufacture your model well in advance to allow fixing any manufacturing issues and try to include a flexible mass distribution to be able to make final adjustments if required
- Analyze test results daily as produced to allow test plan adaptation.

4 Further Information

4.1 Scientific Publications

- Touzón I., De Miguel B. at al; Mooring System Design Approach: A Case Study for MARMOK-A Floating OWC Wave Energy Converter, *Proc. Of the 37th Int. Conf. on Ocean and Artic Engineering (OMAE),* Madrid (2018).

4.2 Website & Social Media

https://www.idom.com/

https://www.idom.com/ada/

http://www.oceantecenergy.com/

https://opera-h2020.eu/

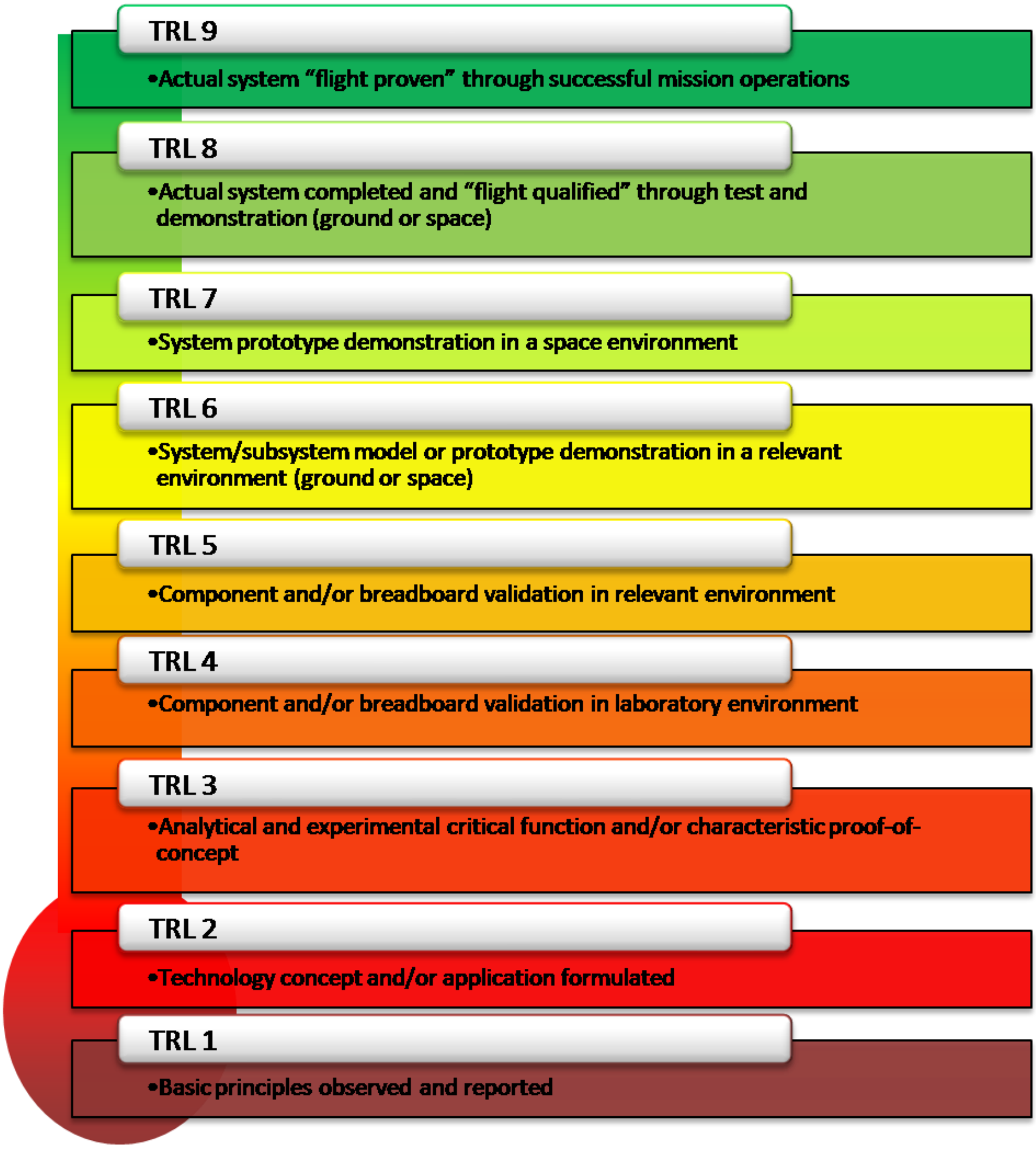
5 References

- Dong-Sheng, Qiao and Jin-Ping, Ou, "Truncated Model Tests for Mooring Lines of a Semi-Submersible Platform and its Equivalent Compensated Method", *Journal of Marine Science and Technology, Vol. 22, No. 2*, pp. 125-136 (2014).
- Climent, Molins; Pau, Trubat; Xavi Gironella and Alexis Campos, "Design Optimization for a Truncated Catenary Mooring System for Scale Model Test", *Journal of Marine Science and Engineering, No. 3*, pp. 1362-1381 (2015).

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.



NASA Technology Readiness Levels[1]

[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 Perfrm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_s = 1 : 5 - 10$)			$\lambda = 1 : 10 - 25$	$\lambda = 1 : 2 - 10$		$\lambda = 1 : 1 - 2$		$\lambda = 1:1$, 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 (10-25Δ*f*) (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