[Virginia Tech]

User Project: Simutanous Ocean Wave and Current Energy Harvesting using a Single Power Take Off System

Project Acronym: VT Wave-Current Energy Converter

Project Reference Number :(Insert Reference Number)

Infrastructure Accessed Oceanide - BGO FIRST Basin

aRINET2

Infrastructure Access Reports

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

European Commission

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1. Introduction

1.1 Introduction

Virginia Tech (VT) team has developed a prototyped device capable of simultanaously converting wave, current, and tidal energies into electricity using one single PTO. Where most developers design for a singular specific marine energy resource, the prototyped hybrid wave-current energy converter (HWCEC) aims to harvest a range of marine energy through an innovative PTO mechanism that converts bidirectionnal wave motion onto unidirectionnal generator and directly couples the rotating shaft of a marine turbine.

The WEC protion of the HWCEC prototype has already been tested at University of Maine's Wave Basin in July 2017. Testing results validated both the base structure and WEC portion of the HWCEC prototype. The turbine portion of the HWCEC was tested in towing tunnel in July 2018. Testing results validated the possibility to amalgamate the WEC structure with the turbine.

The research now requires evaluation of the WEC and turbine operating concurrently. Such validation requires a facility capable of both generating scaled ocean waves and current structure.

This evaluation has been done within MARINET2 program at BGO FIRST tests facility operated by OCEANIDE company, and located at La Seyne sur mer, France.

This present document is the Model Tests Report including the scope of testing, a description of the model, of its instrumentation and of the data that have been recorded.

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	

STAGE GATE CRITERIA	Status
• 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 objectives of the project were threefold: i) To test and validate the design of a hybrid wave-current energy converter (1/10th scale) that harvests both ocean wave and marine current energy via a single power take-off. ii) To evaluate the performances (power output, efficiency, PTO force, mooring forces) of a hybrid wave-current energy converter against the wave energy converter only baseline and marine current turbine only baseline. iii) To identify avenues for hybrid wave-current device optimization and potential concerns via comparison of the hybrid wave current converter with traditional WECs or current turbines alone.

As described in the Stage Gate Criteria above, the hybrid wave-current energy converter will be tested subject to regular and irregular waves to investigate its response and energy capability. In order to compare the performance of hybrid energy converter to the existing energy structure, the test series has been comprised of a mixed of: turbine performance test, point absorber baseline test and hybrid energy converter performance test. In addition to that, two gearbox tuning settings have been tested (also referred to as hereafter as "resistance" tuning) to compromise the velocity difference between turbine and the ball screw driven by the point absorber.

2. Outline of Work Carried Out

2.1 Setup

2.1.1 Model

The hybrid wave current energy converter consisting a floating buoy, a submerged heave plate, marine current turbine, and a hybrid PTO that couple the two-source input. As illustrated in the figure below, the buoy and the rest of body connects each other via push tube which connects a ball screw to convert linear heave motion into rotation. The system takes a commercial DC generator together with external resistive loads for different PTO damping and takes advantage of a track-roller system to constrain the relative rotation between the buoy and the second body. The tested structure is a 1:10th scaled down prototype with 0.75m diameter buoy and 1m diameter turbine. In the tank testing stage, extra features including balancing mass, force sensor, Krypton frame and Rudder was applied on the structure to make sure the structure is well balanced, correctly faced to the current direction and important data properly recorded.

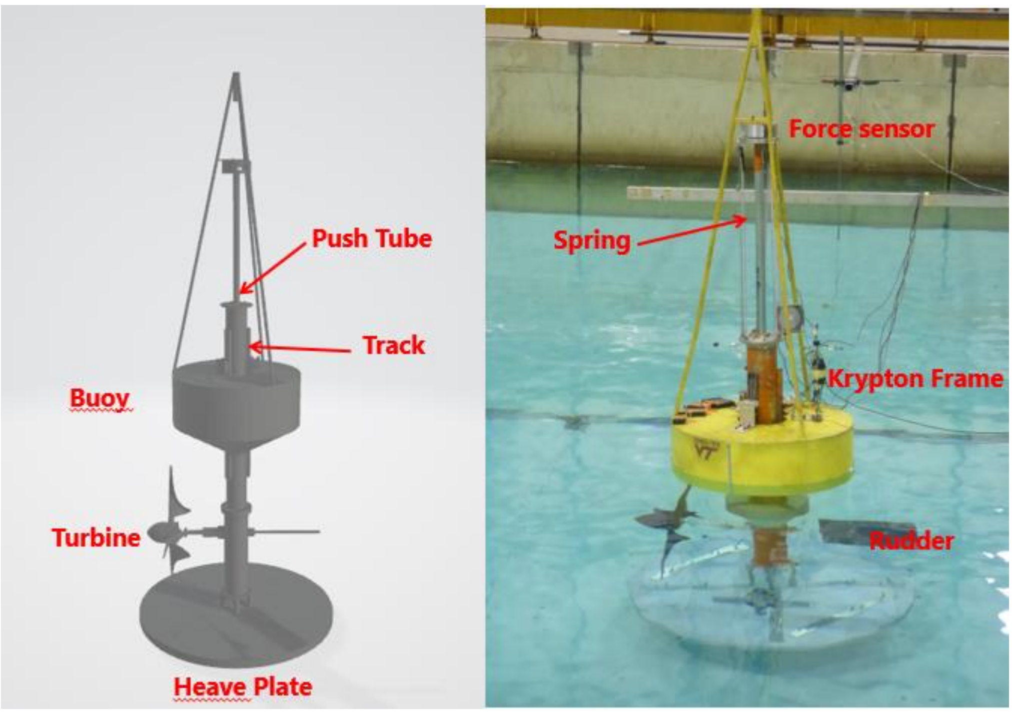


Figure 1: Model of Hybrid wave-current energy converter. 3-D model(left) and hardware for testing(right)

2.1.2 Wave Tank Setup

The tests were conducted at at BGO FIRST tests facility operated by OCEANIDE company, and located at La Seyne sur mer, France. The basin is 16m in width, 40m in length and is able to generate wave and current simutaneously. The basin is equipped with adjustable floor in depth. For all the cases tested, The water surface is kept 2m from the floor. The model was positioned approximately 15m from the wave/current maker and at the center of the basin. Details can be found in the Apendix drawings.

2.1.3 Mooring and reference frame

The mooring arrangement is illustrated in figures below. The structure took use of 4 mooring lines in total. Among them, 3 mooring lines were installed on the bottom of the column (spring reference RZ-165X, Stiffness line 90.25N/m). The mooring lines were kept horizontal using pully and was kept at 1.5m depth from free water surface. One extra mooring line was installed on the top of the column to restrict pitching and further stabilize the system (spring reference T31910, Stiffness line 50N/m). The global reference frame is built with the regulation as: x as surge; y as sway; z as heave.

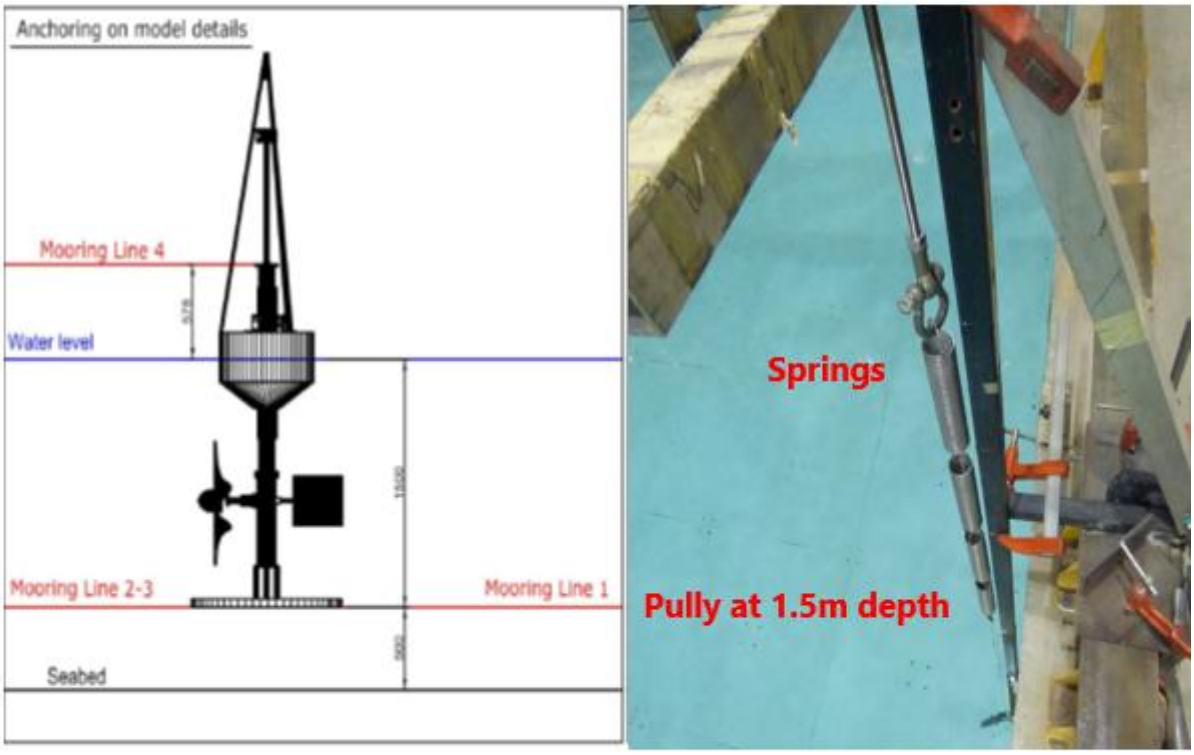


Figure 2 – Implantation of mooring lines (dimensions are given in mm model scale)

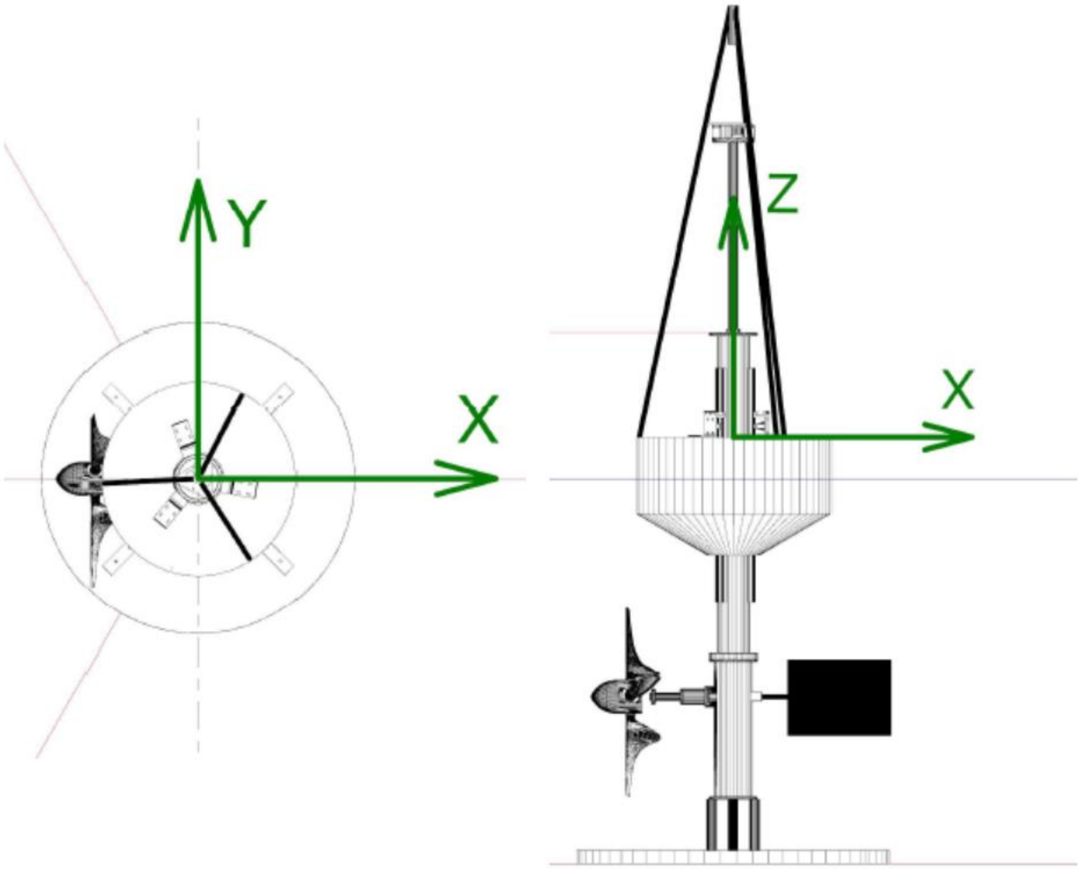


Figure 2: Reference Frame

2.2 Instrumentation

2.2.1 Acquisition

All sensors (both VT and OCD sensors) were recorded on the Oceanide DAQ system. One trigger signal for data synchronization was used at the start of data acquisition. All measurements were given to Virginia Tech in one data set, for each test. In additional to the data logging, Oceanide also recorded video of most of the tests. The video recordings were started using the trigger signal. All data are given at basin scale in one data set for each test. The sampling frequency for the Oceanide files was set to 100 Hz for all instrumentation, except for the video for which the acquisition frequency is of 25 Hz.

2.2.2 Virginia Tech sensors

Virginia Tech had its own sensors, as follows:

- 1 load cell between the buoy and the column
- 1 string actuated sensor (relative displacement of the two body)
- 1 turbine shaft encoder to measure the rotation of the pale
- 1 power output voltage to measure the produced energy

2.2.3 Oceanide sensors

Oceanide has provided the following sensors:

- 3 markers fixed on the model for the 6D buoy motions measurement

- 1 marker fixed on the column for the absorber 3D translations measurement at one location (see Figure)
- 1 current-meter to measure the current speed in basin
- 1 wave probe to measure the wave elevation in basin
- 4 force sensors to measure the axial tension in each of the 4 mooring lines
- 2 HD video cameras to witness all the tests

Motions measurement

The KRYPTON RODYM DMM System performs the motion measurements of the platform model in the 6 degrees of freedom. This contactless tracking system is based on infrared cameras aiming at infrared active markers located on the model. A fourth marker is used to measure the 3 coordinates (x,y,z) of a point on the absorber (see Figure), given in the reference frame.

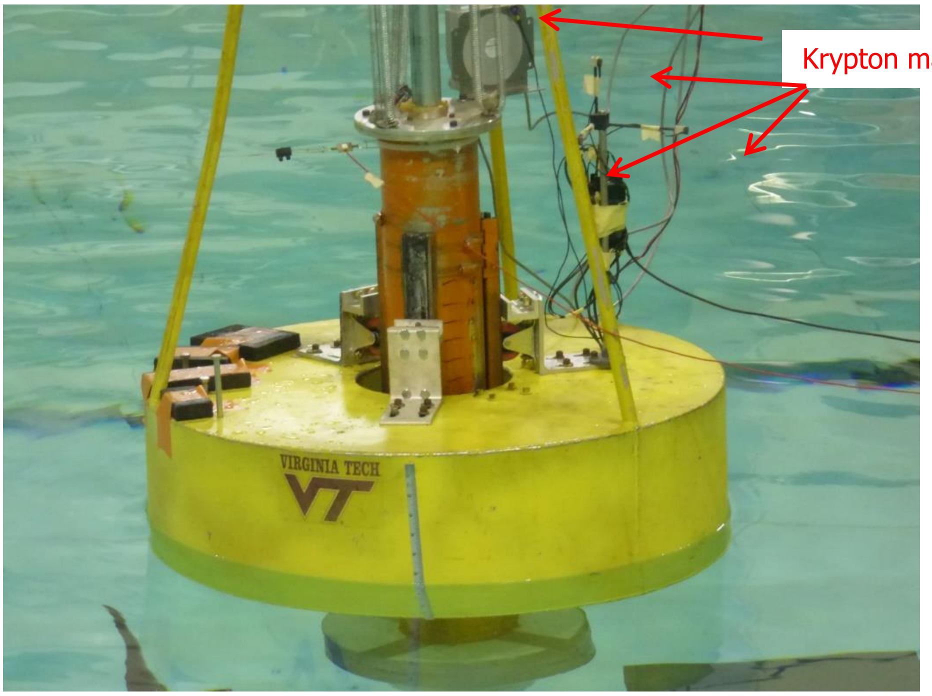


Figure 4: Markers for motion measurements

2.3 Tests

2.3.1 Point absorber baseline tests

The trial concerned performance test of point absorber under regular/ irregular wave conditions without current. The tested model is same as described in section 2.1.1 except that turbine is not applied. Since same PTO and buoy structure will be used in the hybrid energy converter, this serves as baseline for hybrid energy converter. Tested wave cases are shown in the tables below. JONSWAP spectrum was employed for all the irregular wave trials. Multiple external resistive loads are tested to tune the PTO damping to track peak output power.

Wave Type	Wave (Peak) Period [s]	(Sig.) Wave Height [m]	(Sig.) Wave Amplitude [m]	Approx. Wavelength [m]
Mono	1.57	0.048	0.024	3.83
Mono	1.79	0.063	0.0315	5

Mono	1.9	0.07	0.035	5.63
Mono	2.21	0.096	0.048	7.65
Mono	2.53	0.125	0.0625	9.99
Mono	2.85	0.158	0.079	12.65
Poly	1.3	0.0875	0.0437	N/A
Poly	3.06	0.12	0.06	N/A

Table 1: Test matrix for wave-only tests

2.3.2 Turbine baseline tests

The trial concerned performance test of marine current turbine under constant current velocity without wave. The tested turbine geometry and PTO settings will also be used in the hybrid energy converter. Thus, the test series serves as second baseline for hybrid energy converter. The tested current velocities are 0.4m/s, 0.5m/s and 0.6m/s. Different gearbox with gear ratio 1 and 3.5 are tested.

2.3.3 Hybrid wave-current energy converter performance tests

The trials concerned performance test of marine current turbine under both constant current velocity and regular/irregular wave conditions. The tests serve to verify the concept of combining 2 energy sources with one single PTO by integrating same buoy/turbine geometry and PTO setting tested in the previous section. Tested cases are shown in the tables below.

Wave Type	Current velocity [m/s]	Wave (Peak) Period [s]	(Sig.) Wave Height [m]	(Sig.) Wave Amplitude [m]	Approx. Wavelength [m]
Mono	0.5	1.57	0.048	0.024	3.83
Mono	0.5	1.79	0.063	0.0315	5
Mono	0.4	1.9	0.07	0.035	5.63
Mono	0.5	1.9	0.07	0.035	5.63
Mono	0.4	2.21	0.096	0.048	7.65
Mono	0.5	2.21	0.096	0.048	7.65
Mono	0.5	2.53	0.125	0.0625	9.99
Mono	0.5	2.85	0.158	0.079	12.65
Poly	0.5	1.3	0.0875	0.0437	N/A
Poly	0.5	3.06	0.12	0.06	N/A

Table 2: Test matrix for hybrid wave-current energy converter

Cases are also tested with a speed-up gearbox with ratio 3.5 between turbine and PTO in order to compromise velocity difference between turbine and ball screw shaft driven by the push tube.

Wave Type	Current velocity [m/s]	Wave (Peak) Period [s]	(Sig.) Wave Height [m]	(Sig.) Wave Amplitude [m]	Approx. Wavelength [m]
Mono	0.6	1.57	0.048	0.024	3.83
Mono	0.6	1.79	0.063	0.0315	5
Mono	0.5	1.9	0.07	0.035	5.63
Mono	0.6	1.9	0.07	0.035	5.63
Mono	0.5	2.21	0.096	0.048	7.65
Mono	0.6	2.21	0.096	0.048	7.65
Mono	0.6	2.53	0.125	0.0625	9.99
Mono	0.6	2.85	0.158	0.079	12.65

Poly	0.6	1.3	0.0875	0.0437	N/A
Poly	0.6	3.06	0.12	0.06	N/A

Table 3: Test matrix for hybrid wave-current energy converter with speed-up gearbox

For the tests with co-existence of wave and current, the testing procedures are listed as follows:

Regular waves with current tests

- t=0 s: Start of OCD data acquisition
- t=~30 s: Start of current
- t=~150 s: Start of wave
- Then 60 seconds of wave with a given resistance
- Then 60 seconds of wave with another resistance

Irregular waves tests with current

- t=0 s: Start of OCD data acquisition
- t=~30 s: Start of current
- t=~150 s: Start of wave
- Then 10 min of waves for 0.5m/s current (or 8 min for 0.6m/s current) with a given resistance

2.4 Results

2.4.1 Point absorber baseline tests

In the point absorber baseline tests, the model was subjected to incident waves with periods ranging from 1.5s to 2.85s. For each wave conditions, a series of external resistive loads, ranging from 1Ohm to 100 Ohm, were applied with DC generator to tune the electric damping. The output electric power was calculated according to time series voltage data. Due to calibration issue, generated wave had some amplitude difference comparing with those planned in the test matrix. The power data shown in the following figure was thus normalized according to the wave height data recorded by the wave gauge.

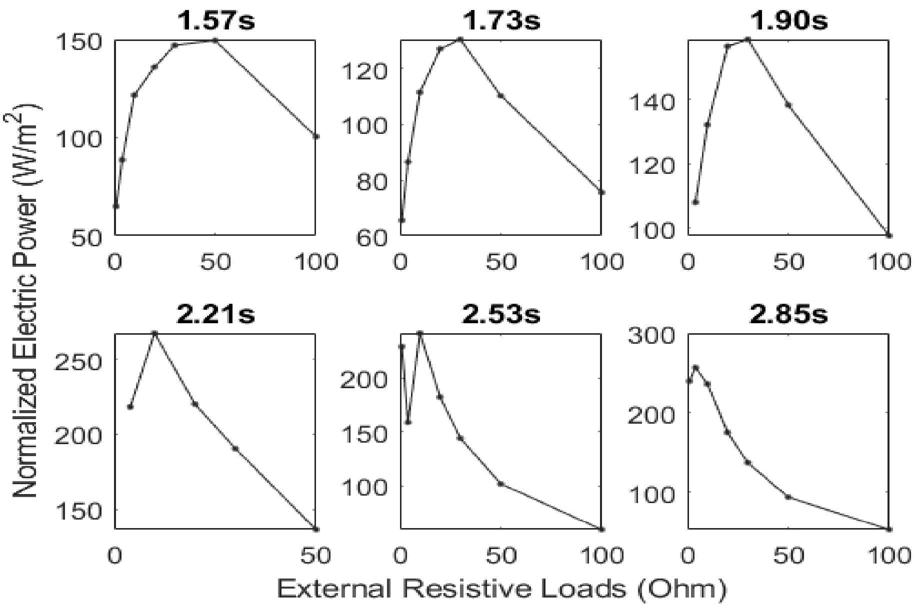


Figure 5: Normalized electric power of point absorber under regular wave excitation

2.4.2 Turbine baseline tests

In the turbine baseline tests, the model was subjected to currents with constant velocity :0.4m/s, 0.5m/s and 0.6m/s. For each different flow velocity, in addition to the external resistive loads, turbine performance is also tested with different gearbox settings (with/without a 3.5 speed-up planetary gearbox between turbine and DC generator) to further tune the electric damping to track the maximum turbine output power. Some of the power performance are recorded in the following figure:

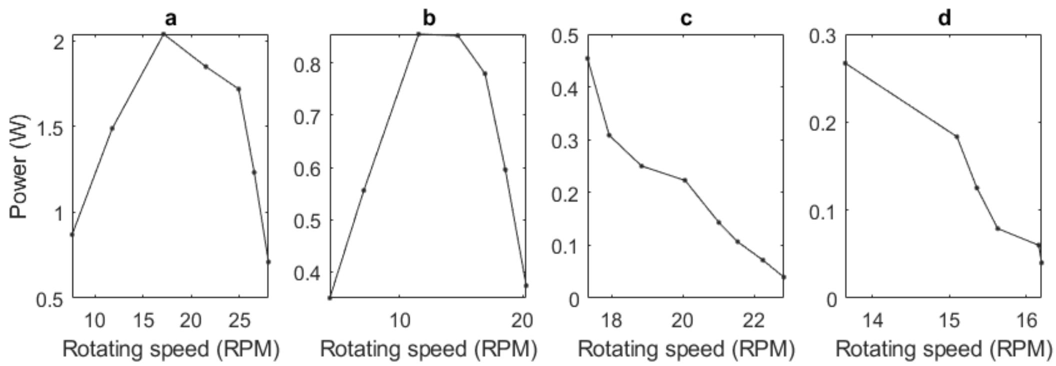


Figure 5: Turbine performance under different conditions. a) 0.6m/s fluid velocity with planetary gearbox between turbine and PTO. b) 0.5m/s fluid velocity with planetary gearbox. c) 0.5m/s fluid velocity without planetary gearbox. d)0.4m/s fluid velocity with planetary gearbox.

2.4.3 Hybrid energy converter performance tests

In the hybrid energy converter performance tests, the model was subjected to both wave and ocean currents. Time series of motions of the buoy and second body are recorded. Examples are shown in the following figure. The tested conditions are as following:

Wave Type	Current velocity [m/s]	Wave (Peak) Period [s]	(Sig.) Wave Height [m]	(Sig.) Wave Amplitude [m]	Approx. Wavelength [m]	Gearbox Ratio
Mono	0.6	2.53	0.125	0.0625	9.99	3.5

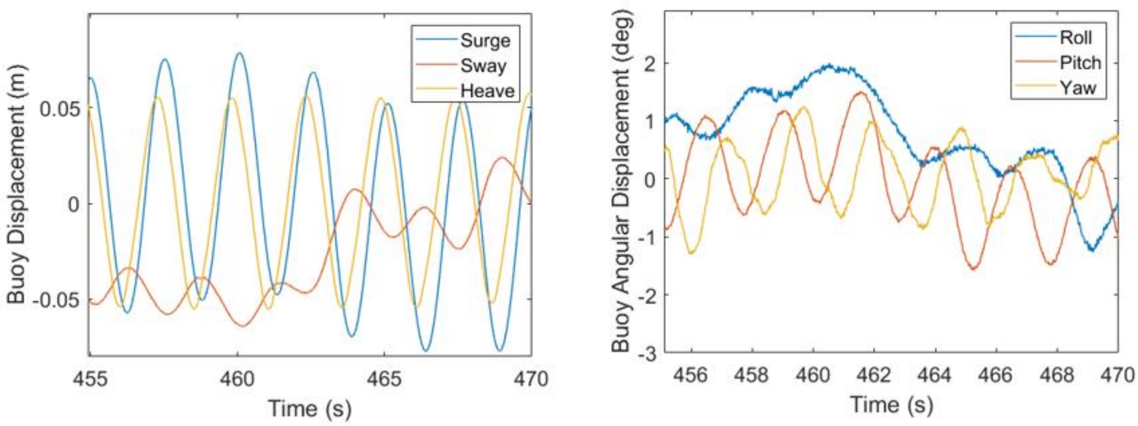


Figure 6: Six degrees of freedom motions of buoy structure. Surge, sway and heave motion (left). Roll, pitch and yaw motion (right).

Velocity of two input shafts (connecting buoy/ turbine) and one output shafts were capable of indicating working status of the PTO and thus valuable in further dynamic analysis.

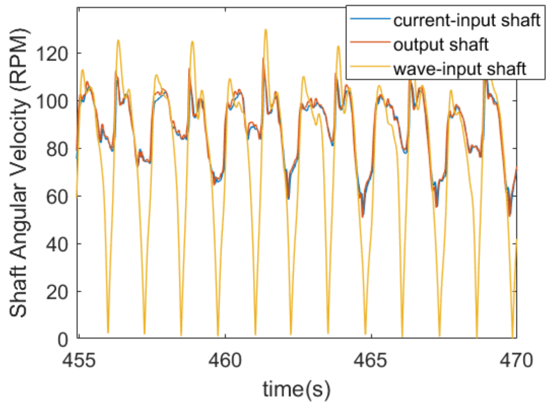


Figure 7: Angular velocity of input/output shafts connecting point absorber, turbine and DC generator.

2.5 Analysis & Conclusions

Maximum output electric power of hybrid energy converter was then compared to that of point absorber and turbine working independently under same wave/current conditions. Some results are shown in the following cable. In all the cases shown, the speed-up gearbox was both applied in the turbine-only configuration and hybrid converter configuration data.

Current velocity [m/s]	Wave (Peak) Period [s]	(Sig.) Wave Height [m]	Max power, WEC only [W]	Max power, Turbine only [W]	Max power, **Hybrid converter** [W]
0.6	1.57	0.048	0.51	2.04	2.53
0.6	1.79	0.063	1.1281	2.04	3.857
0.6	1.9	0.07	0.9166	2.04	3.09
0.6	2.21	0.096	2.78	2.04	4.21
0.6	2.53	0.125	3.76	2.04	4.74

Table 4: Comparison of maximum output power for three structures under different excitation

As for the cases shown, the hybrid energy converter get power increase ranging from 26% to 89% when comparing to the independent working structure with higher power output.

The following figure shows performance difference between hybrid wave energy converter and point absorber under one irregular wave case. The tested irregular wave is constructed based on JONSWAP spectrum with 3.06s significant wave period and 0.12m significant wave height. Current speed is 0.6m/s in average.

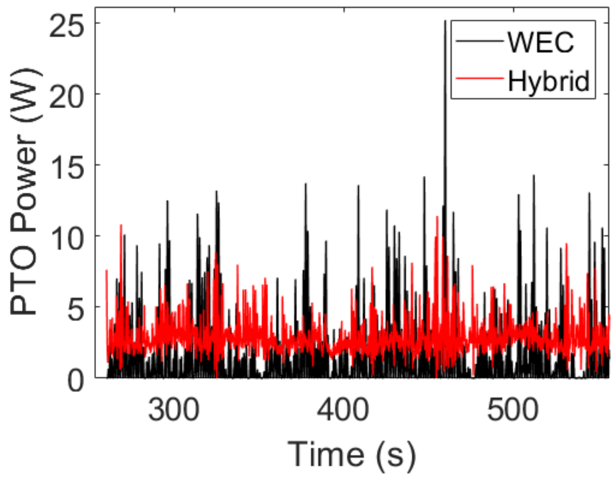


Figure 8: Comparison on output electric power between hybrid converter and WEC

In the cases shown, hybrid energy converter generated an average of 2.92W while point absorber, with same geometry and PTO settings, got 1.63W. Furthermore, the power peak to average ratio of WEC was 15.4 while that of hybrid converter is 3.9.

3. Main Learning Outcomes

3.1 Progress made

The progress made within the entry includes:

Validation of the design of a hybrid wave-current energy converter (1/10th scale) that harvests both ocean wave and marine current energy via a single power take-off under both regular wave excitation and simulated real sea conditions.

Evaluation of the performances and loads (power output, efficiency, PTO force, mooring forces) of a hybrid wave-current energy converter against the wave energy converter only baseline and marine current turbine only baseline.

Identifying avenues for hybrid wave-current device optimization and potential concerns.

3.2 Key Lessons Learned

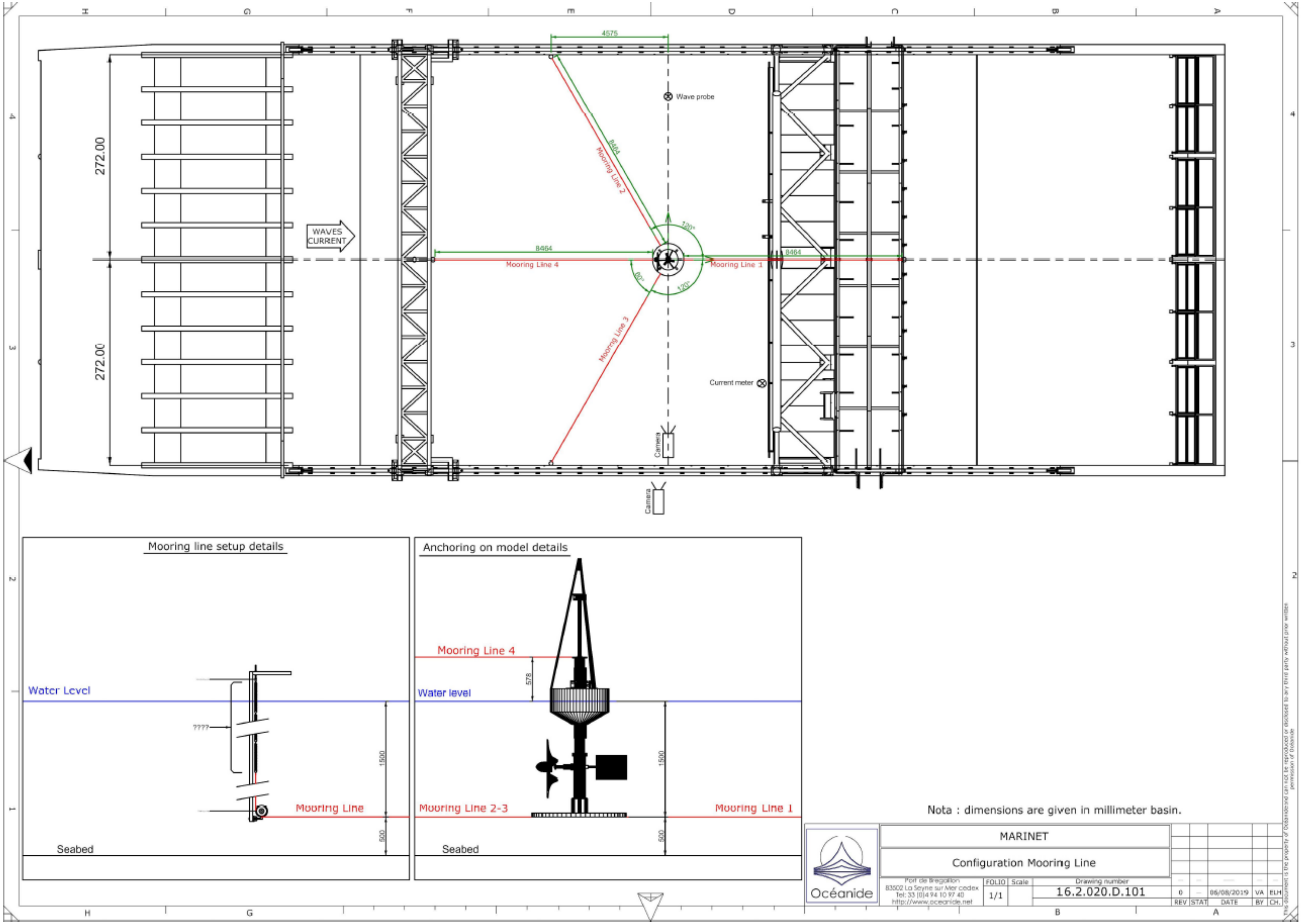
- The design of offshore structure should consider seriously the position of centre of gravity and centre of buoyancy.
- The designer should consider ways to balance external thrust forces when designing structure to decrease the burden of mooring lines.
- The optimal PTO damping of hybrid energy converter can be different from that of individual components.

4. Further Information

4.1 Scientific Publications

- The group would like to polish the simulation and publish papers combining structure design, theoretical analysis and tank test to increase the value of the publication. The user group is now accelerating the process to publish the result as soon as possible.

Appendix: Drawings


4575
Wave probe
8464
Mooring Line 2
WAVES
CURRENT
272.00
272.00
8464
Mooring Line 4
120°
120°
60°
8464
Mooring Line 1
Mooring Line 3
Current meter
Camera
Camera
Mooring line setup details
Water Level
????
1500
500
Mooring Line
Seabed
Anchoring on model details
Mooring Line 4
578
Water level
1500
500
Mooring Line 2-3
Mooring Line 1
Seabed
Nota : dimensions are given in millimeter basin.
MARINET
Configuration Mooring Line
Océanide
Port de Bregaillon
83502 La Seyne sur Mer cedex
Tel: 33 (0)4 94 10 97 40
http://www.oceanide.net
FOLIO
1/1
Scale
Drawing number
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