Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	New power take-off (PTO) and control system for DUO wave energy technology to enable access to emerging market
Lead Grantee (Organisation)	Pure Marine Gen (Ireland) Ltd
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Report Submission Date	18/2/24

	Name	**Organisation**
Project Partner(s)	Ian Power	Lir National Ocean Test Centre
Collaborators		

Project Summary (max 500 words)

The project involved the development, build and test of a new power take-off (PTO) system for the DUO wave energy convertor. The PTO development was predicated on a DUO configured to meet the needs of ocean observation and aquaculture markets which have need of small to intermediate-scale power generation at sea. Following hydrodynamic modelling of different DUO configurations, a preferred configuration was selected. Different technical approaches to development of a suitable PTO were considered and a rotary, direct-drive system ultimately selected for incorporation on to the DUO device and tank-testing.

A single PTO system was initially built and 'dry' tested' in the lab to characterise its generator. This allowed control algorithms capable of applying a requested damping to the PTO based on the speed of movement of the generator to be developed and tailored to apply an optimal damping during the different test conditions. Three such PTO's were then mounted on the DUO and tested at LIR under a series of different wave conditions.

The PTO selected showed improved performance (in comparison to previous tests where a simulated PTO had been incorporated on to the DUO) but was less efficient in small-wave conditions. We believe this was due to a 'cut-in' inertia induced in the PTO system by the commercial off-the-shelf gear system included to increase the speed of the generator and ensure it operated within an efficient speed envelope for the majority of the time.

The tests confirmed the potential of the DUO to deliver lower costs of energy compared to point absorbers, attenuators and other first generation wave energy devices. It demonstrated performance improvement in the PTO in larger sea-states but also helped highlighted the need for future work to focus on optimising PTO performance in smaller sea-states.

We have been encouraged by the results of the project and will now seek to obtain funding to progress to testing a larger DUO system (incorporating a custom-built PTO system optimised based on the learning from this project) at the scale of a prototype device capable of providing power at sea to meet the existing demands of ocean observation and aquaculture operators.

Keywords (min 3 and max 10)	Wave energy convertor; power take off

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

In the following Section, please provide a clear overview of your project, including details of the key findings, outcomes and recommendations. The section headings below are provided as a guide, please update or add to these as best suits your project.

By submitting this project report to SEAI, you confirm you are happy for Section 1 and Section 2 of this report to be made publicly available. If you wish to request edits to this section in advance of publication, please contact SEAI at EnergyResearch@seai.ie.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION	(max 10 pages)

2.1 Executive Summary

The project involved developing and testing a power take-off (PTO) system for the DUO wave energy convertor.

Following a market review of the needs of existing users of small/intermediate-scale power at sea (e.g. ocean observation equipment, aquaculture installations etc.), a DUO configuration was selected upon which to base the project. Options for providing a suitably scaled PTO for a 1.2m diameter test DUO device were then considered and a mechanically geared, direct drive rotary generator was selected.

The specified PTO was constructed and initially 'dry' tested in the lab to characterise the generator. This information was then used to develop algorithms capable of supplying the optimal damping to the device depending on its speed of operation at any point in time.

The initial test demonstrated that the commercial off-the-shelf gear/generator combination selected operated efficiently at rated speeds but presented a significant 'cut-in' inertia to the system at low speeds. This meant that the optimal force/speed characteristic damping could not be delivered in all circumstances which had a particularly negative impact in smaller sea-states. However, in larger sea-states where the sub-optimal, low-speed operation did not have as significant an effect, power capture improvements of over 40% were recorded in the tank-tests compared to results from testing in the Wave Energy prize competition.

The project has therefore demonstrated that significant improvements in power capture are possible with a suitably controlled PTO system, however improvements in low-speed operation will be required when the next iteration of the PTO is developed.

The results of the project demonstrate that the DUO can deliver lower cost of energy metrics than current wave energy systems being proposed for pilot projects at sea. Pure Marine will now move to develop a prototype at a scale capable of meeting the requirements of existing users of power at sea (ocean observation equipment, aquaculture developers etc.) and aim to test this system at sea with a further optimised PTO.

2.2 Introduction to Project

The DUO is an axisymmetric, two-body, self-reacting wave energy convertor that simultaneously captures power from multiple modes of motion, in particular – heave (vertical motion) and pitch/surge (a rocking/horizontal motion). The lower fully submerged body is designed to have a total mass greater than its displaced volume and is suspended below the floating body by cables, thus creating a pre-tension in the connecting cables. The relative motion between the bodies is used to turn a generator and a power-take off (PTO) system is used to damp the motion between the bodies thereby controlling the power capture process.

Prior to the project, the concept had been tested by damping the motion between the bodies to demonstrate the power capture capability. The aim of the project was to develop and construct a PTO system capable of generating power, then tank-testing this device on a DUO with a view to maximising power capture and gaining an understanding of practical issues associated with optimising power-capture.

The outputs anticipated were:

- Gaining an understanding of the technical capability of the new PTO/DUO combination and its potential to generate electricity cost-effectively;
- Identification of further R&D activities required to commercialise the concept; and,
- Analysis of the potential for the new system to be competitive in 'off-grid' applications that could act as an initial step on the path to commercialisation.

2.3 Project Objectives

We had set the initial target of demonstrating that the new concept would have the capability of achieving an ACE metric (a metric based on power captured/$ capital) of 5. In the 3 years since the application was written the cost of the capital components of the WEC have increased significantly therefore the absolute value of the ACE is no longer a valid comparator. We have therefore focused on the power capture of the DUO with the new PTO versus the mechanical power captured previously by damping the motions of the two bodies. Given the DUO device is effectively the same device in both sets of tests then power-capture is a valid comparator of the new PTO and the original damping mechanism.

In reaching a point where a single PTO would be tested, the project also aimed to:

- Identify an optimal DUO configuration (based on the needs of smaller off-grid applications) using hydro-dynamic modelling;
- Assess the advantages and disadvantages of different approaches to implementing a PTO for the DUO before selecting the preferred option to implement on the test device; and,
- Measure the performance of the selected PTO through a series of 'dry' (bench tests) and 'wet' (tank tests) that would allow the following to be assessed:
    - Commercial viability of the DUO/PTO combination in (initially) smaller 'off-grid' applications; and,
    - Identification of the follow-on work that would need to be undertaken to fully commercialise and bring the DUO technology to market.

2.4 Summary of Key Findings/Outcomes

As well as the performance measurements captured from the final tank-testing work package, there were useful findings from the work packages undertaken in developing the unit to be tested. These are summarised below:

(a) Optimisation of the configuration of a 2-body point absorber

The modelling and optimisation work considered a range of different configurations – the different mechanical configurations shown in Figures 1. The performance of the device was then considered while modifying a variety of other aspects of the system e.g. physical size of the buoy and tank, different pre-tensions in the springs connecting the two bodies, different damping strategies, different centres of gravity in the floating body.

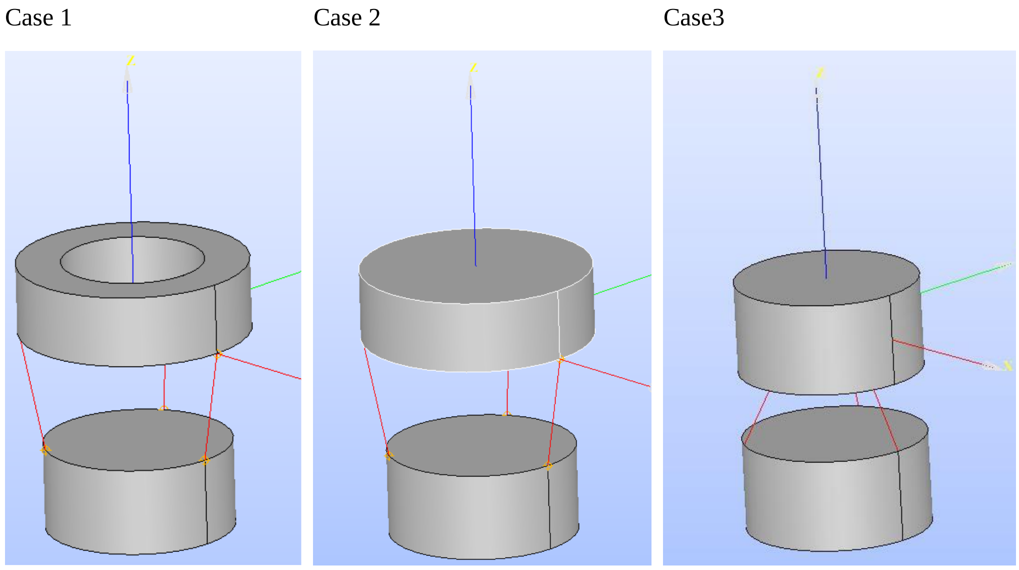

Figure 1 DUO Configurations Considered

This work showed that while relatively small gains could be achieved by optimising the spring force, damping and connection points, the key parameters to consider in the design process were:

- Size of buoy and tank – broadly speaking the larger these are the more power can be captured, however there are clearly physical limitations (e.g. handling constraints) in terms of weight, dimensions, cost of manufacture etc. that may constrain the design depending on the application.
- The maximum stroke for which the device is designed also influences power capture. Any configuration of device will need to 'shutdown' at some point depending on the size of wave climate to which it is exposed. In finalising a design for a particular application or wave climate, selecting this shutdown point is critical to the viability of the device – a physically smaller device will be lower cost but will have to shutdown in lower wave heights than an equivalent but larger device therefore reducing the overall amount of energy that can be captured across all sea conditions. Optimising the configuration of the device to the wave climate in which it is expected to operate is therefore critical to the commercial viability of design.

While this optimisation process is complex – and theoretically endless – the work undertaken in work package 1 of the project was a valuable learning experience which would ensure that given a different application and set of likely sea-states, an optimum configuration could be arrived at much more quickly and efficiently.

(b) Preferred PTO Option

The project reviewed a number of PTO options. The conclusions from this work were as follows:

- Rotary versus linear PTO

  The DUO WEC produces low speed, high force motion and as with all WEC's has a small average to peak power ratio. The same applies to the average to maximum stroke requirement for the PTO. Following review of the work undertaken in wave energy to date, rotary generators would appear to offer more options than their linear equivalents, as the development of rotary generators with suitable characteristics has to some extent been driven by the wind power industry where similar requirements exist. In short, there are off-the-shelf options available for a (say 6m diameter) DUO with a specification capable of meeting the requirements of small, off-grid applications. This is not the case for linear generators. For this reason, a rotary generator was selected scaled to meet the needs of the 1.2m diameter model DUO.

  While the off-the-shelf generator selected as capable of being controlled to offer suitable damping characteristics for the tank-testing, it was concluded that when development moves to the next stage (likely to be development of a 4m-6m device for testing in the sea), it would be desirable to develop a bespoke generator to ensure that the optimum control systems can be developed. Clearly this will be more expensive than using an commercial off-the-shelf device and will be dependent on the funding available for the project, however it will be a requirement to ensure optimal control and maximise power-capture.

- Gear Mechanism

  The work package that reviewed the gear options assessed the potential of both a direct-drive mechanical system and a magnetic gear.

  The characteristics of a magnetic gear system are extremely appealing for a wave energy device, not least due to the inherent safety mechanism whereby too high an input force causes the gear to slip and prevents the PTO from damaging itself. An equivalent mechanical system has the potential to fail catastrophically in the same circumstances and will require protection mechanisms to be 'designed in' to the overall WEC system to ensure that this does occur.

  Unfortunately, a magnetic gear of a suitable specification for this project was not available therefore a mechanically geared direct drive system was specified. The project did however conclude that further investigation of magnetic gearing would be something of value in a follow-on project. This would inevitably require the design and construction of a bespoke magnetic gear system which would be expensive.

(c) Limitations of a mechanically geared direct drive system

The preferred gear system ultimately selected for the project was an off-the-shelf, 10:1 mechanical system. It became apparent however that this system induced a significant 'cut-in' damping force on the system which prevented the ideal linear damping force being applied across the velocity range. As shown by the typical force/velocity curves measured from the tank testing, this exhibited itself as a permanently applied 'fixed' force at low velocities.

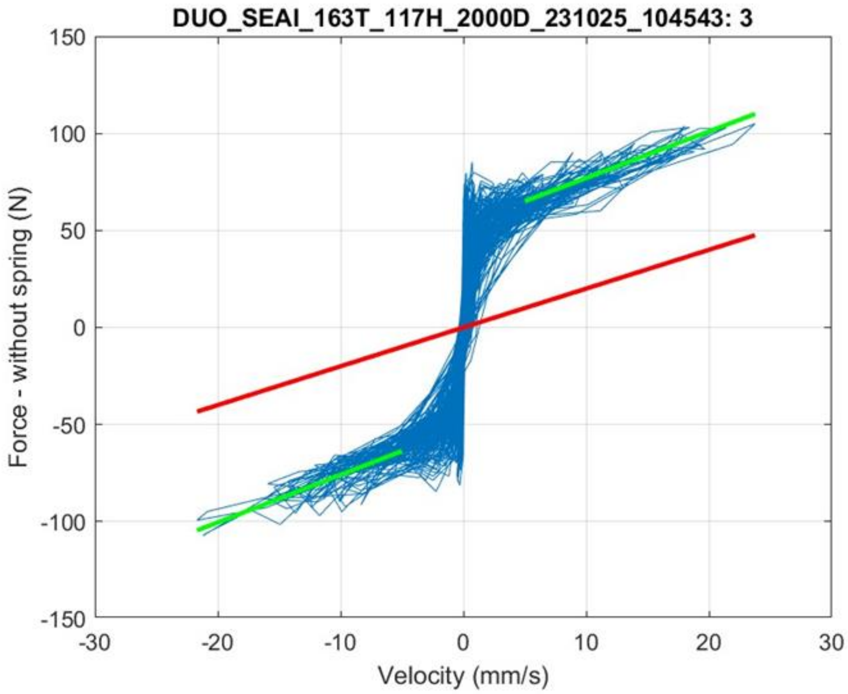

Figure 2 Ideal (red) and measured (blue/green) damping forces

This significantly impacted the power captured, particularly in smaller sea-states where the PTO spent much of its time moving at lower speeds.
Addressing this 'cut-in' issue will be form a significant part of any subsequent project.

Key Innovations

- **Innovation 1 – Improved Power Capture in larger sea states**

The power captured in larger sea-states showed a significant increase in two of the larger sea-states tested (gains of 30% and 44%).

Sea State 1	Wave Period Tp (secs)	Wave Height Hs (m)	Change in Power Captured versus simulated PTO (without Gear/Generator)
1	1.63	0.117	-41.7%
2	2.2	0.132	-7.3%
3	2.58	0.268	44.1%
4	2.84	0.103	-11.8%
5	3.41	0.292	-0.6%
6	3.69	0.163	29.5%

Figure 3 Comparison of power measured with new PTO versus power measured in previous tank tests with simulated PTO

There was a slight drop off (7%-12%) in power captured in two of the smaller sea-states, but with a significant drop-off in the smallest sea-state (42%). While the absolute power captured in this smaller sea-state is small, it is the sea state that occurs most frequently at many sites and therefore the loss is more significant than may at first appear.

A discussed at point (c) above, a means of solving the 'cut-in' force issue which impacts performance in these smaller sea-states while retaining the gains in the larger seas would be a major focus of a follow-on project.

- **Innovation 2 - Storm Survival System**

The DUO incorporating the new PTO performed extremely well in the larger sea-states. It continued to operate and capture significant amounts of power in what had previously been deemed sea states where operation was not feasible and the device needed to be shut down.

We did however also design and incorporate an additional 'storm survival' system. Although not planned as part of the original project, a winching mechanism capable of 'shutting down' operation by lifting the lower mass off the operating PTO cables via separate connections was incorporated. When activated, this system ensures that the PTO would not be compromised in larger sea-states. This was demonstrated using a manual winching system, however the identical mechanism could be automated using a battery driven winch. This is an extremely important innovation which will potentially prove invaluable as the DUO is further developed and moves to sea trials where the wave climate is not controlled as it was in the tank tests.

2.5 Project Impact

The project has had demonstrable technological impacts by:

- Improving the understanding of design and performance issues associated with a WEC PTO system;
- Demonstrating a PTO capable of improving the power capture of a two-body WEC in larger seas;
- Highlighting the need to focus on the technical issues around overcoming inertia in a direct-drive PTO in smaller sea-states.

Development of the marine energy resource in Ireland has had a single focus on moving to 'grid-scale' marine renewables as quickly as possible. The analysis work associated with this project has focused more on intermediate-scale applications for wave powered system to power, for example, ocean observation and sensing devices, recharge autonomous underwater vehicles and power offshore aquaculture systems. This is more in line with the US Department of Energy strategy[1] to use these intermediate-scale applications as a 'stepping stone to full-scale grid developments. The out-workings of this project would suggest that Ireland's current approach of focusing entirely on grid-scale systems risks Ireland missing out on these smaller-scale but more immediate opportunities. A strategy incorporating multiple strands of market opportunity may be more advisable to mitigate the risk of the grid-connected systems taking longer than anticipated to emerge.

2.6 Recommendations

The project has helped identify the technological issues to be addressed going forward in developing the DUO WEC concept. The next stage of technology development will involve:

- Moving to a larger-scale device capable of meeting the needs of small/intermediate applications (e.g. aquaculture or ocean observation) that can be tested at sea;
- Optimising the PTO to consolidate the gains made in this project with respect to larger sea-states whilst seeking to address the 'cut-in' issue impacting performance in smaller sea-states.
    - This will involve moving from use of commercial off-the-shelf components (generators and gears) to a custom-designed generator and gear system.

[1] Powering the Blue Economy, [Powering the Blue Economy | Department of Energy]

We would encourage policy makers to develop policy interventions that would encourage the emerging and developing ocean sensing industry cluster in Ireland to work together. This would involve end users of marine sensing equipment and the technology developers working on devices capable of delivering power at sea coming together to meet current market needs for intermediate-scale solutions that are required today and could be developed immediately. Suitable schemes to incentivise this collaboration need would not be at the expense of the on-going push to develop ‘grid-scale’ technology but complementary to it.

2.7 Conclusions and Next Steps

- The project has demonstrated the potential of the DUO system to meet the needs of intermediate-scale ‘power at sea’ applications.
- The next steps will involve:
  - Developing a prototype WEC system, at intermediate scale, capable of providing power for ocean observation platforms, aquaculture applications and for re-charging autonomous underwater vehicles (AUV’s) at sea.
  - Further development of a larger PTO capable of being mounted on a sea-going device. This project has provided useful insights into the form and function of the preferred PTO to be mounted on that prototype.