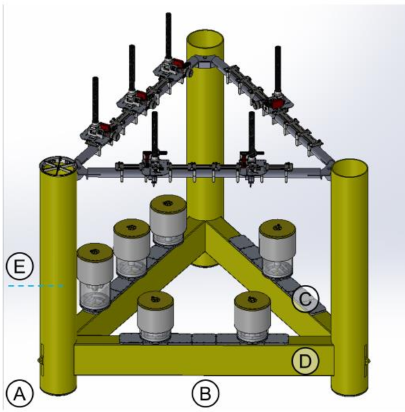
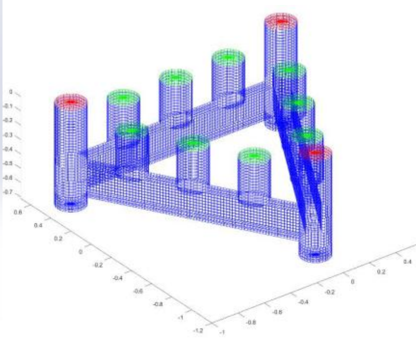
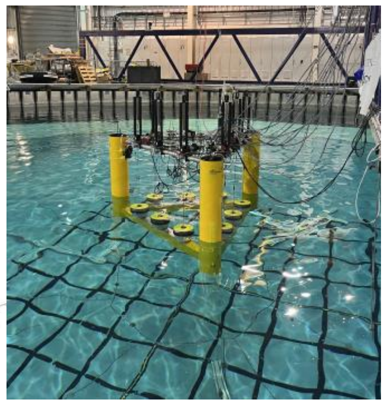
MULTI-WAVE ABSORBER PLATFORM

PROJECT SUMMARY

Wave Energy Scotland

25th April 2025



Contents

Acronyms and terms

CAD	Computed Aided Design
FOW	Floating Offshore Wind
MW	Megawatt
MWAP	Multi Wave Absorber Platform
NWEC	Novel Wave Energy Converter
OPSB	Optimal system control parameters from a single body control
PTO	Power take-off
RAO	Response Amplitude Operator
Semi-sub	Semi-submersible
WEC	Wave Energy Converter
WES	Wave Energy Scotland
TLP	Tension Leg Platform

1 Introduction

With increasing numbers of floating offshore wind (FOW) farm projects being proposed for sites that also have an attractive wave resource, wave energy converter (WEC) developers are increasingly thinking about how their prospective wave energy developments can best integrate with these FOW projects and how to best utilise the supply chain collaboration opportunities these developments offer.

A challenging aspect of co-locating wave energy with wind is the comparatively low ratings of many WEC technologies being developed (<1MW) compared those of FOW turbines (15MW and upwards). One potential solution that could streamline installation and maintenance while delivering multi-MW capacities of wave energy is to deploy multiple wave energy absorbers on a single platform. This can also potentially enable additional cost savings through sharing of infrastructure such as moorings, electrical cables and other equipment. In the future it may then be possible to combine the wave and wind technologies on a single platform.

However, as highlighted in a techno-economic study carried out by Offshore Wind Consultants Limited [1] wind farm developers considering co-location of wind and wave are currently likely to favour separate platforms for each technology from a technical risk and economic standpoint. Platforms developed for FOW applications could still potentially be utilised for the wave systems, if proven to be technically feasible for this application, or bespoke platforms could be manufactured using the same production lines for them.

A key factor in understanding whether such multi wave absorber platform (MWAP) systems are conceptually attractive is to understand how wave power capture is influenced by hydrodynamic interactions between the absorbers, and between the absorbers and the platform. In this instance, the MWAP system could be considered to be a WEC in its own right, comprising a chosen number of active wave absorbers which capture energy. To gain insight into this aspect of MWAP systems, Wave Energy Scotland launched a study in conjunction with the University of Edinburgh in 2022, led by FloWave Ocean Energy Research Facility, to look at how power captured by a notional MWAP system (shown in Figure 2) is affected by these interactions in a real resource. This study has utilised a combination of numerical simulations and tank testing to gain insight into how hydrodynamic interactions influence the performance of multi device systems, either where absorbers are installed on platforms or where WECs are installed on the seabed.

The general terminology used throughout this report is that a “WEC” refers to a standalone wave energy converter including all relevant subsystems including power take-off, moorings, electrical export cable etc., while an “absorber” refers to the main power absorbing part of a WEC system, integrated as part of a platform where some of the subsystems and structure are shared.

Set-up of the numerical and physical modelling for this study were reported in a paper, McLean et al. [2] presented at the European Wave and Tidal Conference in 2023, with a follow-on paper on the numerical simulation outputs submitted for the European Wave and Tidal Conference in 2025 [3].

This document gives a summary of this project. It covers progress since [2] was completed, observations from project work, and next steps.

2 Preliminaries

The influence of absorber-absorber and absorber-platform hydrodynamic interactions on power capture have been compared in this study for a notional MWAP system and comparable systems utilising the same type of absorbers.

The intention was to gain an understanding of the influence of interaction effects on the performance of the MWAP used in this study in a wave resource which is representative of the wave resource at sites where the MWAP and the comparable systems might be deployed, rather than to de-risk or develop a full design of a fully realistic MWAP system and its moorings.

The design of the MWAP remained conceptual throughout, with an investigation into the specifics of the absorber design, platform integration, optimisation of control strategies, and relevant operational subsystems expected to come during any subsequent activities which may be undertaken if the outputs from this initial study demonstrated that impact on energy captured was limited.

Power capture is considered an appropriate proxy for power production at this stage, given the simple WEC-type selected does not have a defined power take-off (PTO) approach (i.e. hydraulic, linear generator, etc.) for the conversion of captured power to electrical power. It is assumed that the spring and damping control parameters could feasibly be applied through the PTO, and no attempt has been made to quantify the energy necessary to add into the system to actuate PTO forces associated with these. At a more advanced stage of development, it would be appropriate to take account of the capability of each absorber's power take-off to deliver the considered control strategy and convert captured power into electrical power.

In this work, these interaction effects are mainly considered in the context of the *park effect*. The park effect describes how the overall power or energy captured by a number of absorbers or WECs arranged close together is influenced by hydrodynamic interactions. While many parameters relating to the design and arrangement of an array impact the park effect, it is desirable to ensure that an array performs as well as possible compared to the same number of isolated devices.

The park effect is often categorised using the *q-factor* which can be defined equivalently using either the captured energy or mean captured power as:

$$q = \frac{E_{array}}{\mathcal{N} E_{solo}} = \frac{P_{array}}{\mathcal{N} P_{solo}} \tag{1}$$

where:

E_{array} is the energy captured by the array of absorbers or WECs;

E_{solo} is the energy captured by a WEC deployed in isolation;

P_{array} is the mean captured power absorbed by the array of absorbers or WECs;

P_{solo} is the mean captured power absorbed by a WEC in isolation; and

$\mathcal{N}$ is the number of absorbers or WECs in the array.

When $q > 1$ the effect of interactions between absorbers or WECs on power capture is said to be constructive, when $q < 1$ it is said to be destructive, and when $q = 1$ it is said to be neutral.

The specific *q-factor* for an individual absorber or WEC in an array (the *qa-factor*) is also useful and is defined as:

$$qa_i = \frac{E_i}{E_{solo}} = \frac{P_i}{P_{solo}} \tag{2}$$

where E_i and P_i are the energy captured and mean power capture by device i in the array.

Annual equivalents of q and qa are defined as:

$$q_{annual} = \frac{AEC_{array}}{\mathcal{N} AEC_{solo}} = \frac{P_{array,ann_a v}}{\mathcal{N} P_{solo,ann_a v}} \tag{3}$$

$$qa_{i,annual} = \frac{AEC_i}{\mathcal{N} AEC_{solo}} = \frac{P_{i,ann_a v}}{\mathcal{N} P_{solo,ann_a v}} \tag{4}$$

where

AEC_{array} is the annual energy captured by the array;

$AEC_{solo}$is the annual energy captured by a WEC deployed in isolation;

AEC_i is the annual energy captured by absorber or WEC i in the array;

$P_{array,ann_a v} = AEC_{array}/(365.25 * 24)$ is the annual average captured power by the array

$P_{solo,ann_a v} = AEC_{solo}/(365.25 * 24)$ is the annual average captured power by the solo WEC

$P_{i,ann_a v} = AEC_i/(365.25 * 24)$is the annual average captured power by absorber or WEC i in the array

3 Study parameters

3.1 Design rationale for the MWAP

This section provides a summary of detailed reasoning for choices of the notional MWAP system considered. This includes the rational for the selection of:

- the absorber type,
- the platform, and
- the mooring.

The background to these design choices is covered in detail in [2].

The design rationale followed was deemed sufficient for the level of assessment being performed in this study. Revisiting performance modelling for a more realistic WEC, platform, and mooring design when more information on a suitable full-scale design is available would seem a sensible course of action. Inclusion of platform and mooring design in system optimisation is also a potentially interesting option that could be explored in the future.

3.1.1 Absorber

The WEC system that provided the basis for the absorbers mounted on the MWAP is a generic submerged pressure differential absorber that is similar to the Waveswing absorber developed by AWS Ocean Energy [4].

The reasons this family of WEC device types was chosen over other options were that:

- WES has a lot of experience with this kind of WEC through technologies developed in their R&D programmes.
    - AWS Ocean Energy Ltd completed Stages 1, 2 and 3 of the Novel WEC (NWEC) programme, developing their Archimedes WaveSwing device.
    - A submerged differential pressure absorber utilising a dielectric elastomer generator as the prime mover was developed by Scuola Superiore di Studi Universitari e di Perfezionamento Sant' Anna during their Stage 2 project in the PTO programme.
- This type of WEC has some features which lend itself to deployment on a MWAP, including its small footprint, single mode of motion, and utilisation of an air system that could potentially be coupled between absorbers.
- This type of WEC has very similar operational similarities with point absorbers, potentially enabling some transferability of learnings from this project to them.

The absorber of the WEC system consists of a submerged telescoping can made up of an upper cylinder (“float”) and a lower cylinder (“silo”), with these absorbers mounted to the platform’s horizontal beam for MWAP layouts, as shown in Figure 1(a). Volume change of the absorber is activated by incident wave induced hydrodynamic forces acting on the float. In turn, this volume change is counteracted by a control force exerted by the internal PTO and the restoring force provided by the internal air spring combined with the hydrostatic spring, as illustrated in Figure 1(b), allowing wave power to be captured.

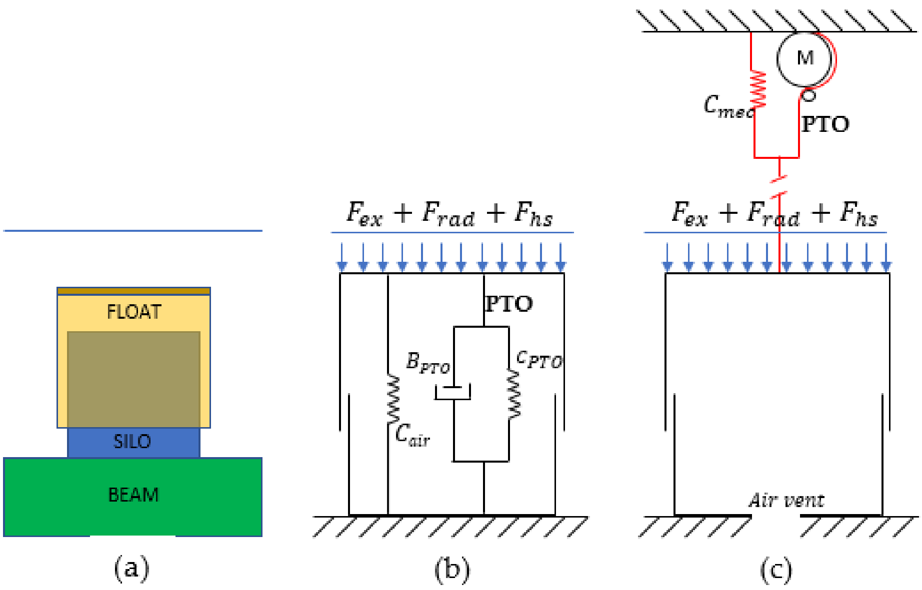


Figure 1:Operating principle of actual and modelled absorbers. (a) shows schematic of absorber (float, silo and support beam) sitting below the water surface, (b) and (c) show free-body diagrams of full scale and modelled absorber respectively. F_{ex}, F_{rad} andF_{hs} are respectively the excitation, radiation and hydrostatic forces acting on the absorber float. C_{mec} is a mechanical spring rate providing the model scale equivalent to the full-scale air system spring rate C_{air}, and C_{PTO} and B_{PTO} are the PTO spring and damping rates. The absorber connects to the motor and spring with a taut line. (Note in (b) reactive control is shown for illustration purposes only, while other types of control for this device type continue to be developed).

Key dimensions of the absorber, at tank scale, are tabulated in Table 1.

Table 1: WEC or absorber characteristic dimensions at model scale. Note, the hydrostatic spring quoted here just relates to hydrostatic forces acting on the top surface of the float. This is reduced slightly for tank absorbers as the diameter of the float is slightly larger than the diameter of the silo below it, permitting the hydrostatic force to also act on the underside of a small ring around the outside of the float.

Parameter	Value
Diameter	0.20 m
Submergence at mid-stroke	0.11 m
Stroke (excursion)	±0.05 m
Hydrostatic spring acting on absorber float	-308 N/m
Air spring	368 N/m
Velocity amplitude limit	0.35 m/s
Force amplitude limit	46.83 N
Instantaneous power limit (low rating)	0.85 W
Instantaneous power limit (high rating)	4.2 W

3.1.2 Platform

The platform design for the MWAP system was pragmatic, motivated by ensuring sufficient space was provided to accommodate multiple absorbers on the structure and that common features of frequently proposed FOW platforms were incorporated. The design was thus motivated by two related questions:

1. What is a rational choice of spacing from a performance perspective for a 9-absorber MWAP (referred to as "9-A") layout, and
2. Which types of platforms being developed for FOW applications could feasibly accommodate 9 absorbers with such a spacing?

3.1.2.1 Absorber spacing

A minimum centre-to-centre spacing of 4 absorber radii between absorbers on the 9-A layout, corresponding to a 20m centre-to-centre spacing for a 9-A layout at full scale, was made based on findings of numerical modelling of Ricci et al. reported in [5]. In particular, when assessing the impact of spacing on power capture made using frequency domain modelling for small arrays of points absorbers, Ricci found that *"device performance becomes practically independent of the [centre-to-centre] spacing d for d larger than about four [absorber] radii"*. This is also close to the recent findings of [6], where an optimal spacing between an array of 3 homogenous WECs was found to be 5.54 radii.

For layouts with fewer than 3 absorbers per platform side, absorbers are equally spaced between the vertical columns and each other, i.e. a 40m centre-to-centre spacing for a 3-absorber MWAP (referred to as "3-A") layout at full scale.

The choice of spacing would ideally have been made based on an optimisation carried out within numerical simulations that had been validated with tank tests. However, the modelling was being developed in parallel during this project and so a more pragmatic approach was needed. Thus, the findings of the Ricci et al study [5] were primarily utilised for the choice of spacing as:

- They were the most relevant from reported modelling when design decisions about platform design were being made, particularly as their modelling considered spacing of absorbers in irregular seas: both long-crested seas with a range of directions and short-crested seas.
- One of the various absorber radii considered by Ricci et al is comparable to the radius of the absorbers being considered in the present study.
- Plots of the annual average power capture against separation distance for the wave resource considered (Figueira da Foz, Portugal) predicted by their modelling [5, Figures 12 and 13] indicate that the annual average power capture converges to a constant value when the centre-to-centre separation exceeds 4 radii. It seems likely, given these plots of the annual average captured power reach an asymptote at the constant value, that the value reached corresponds to the annual average captured power when the separation distance is big enough for park effects to become negligible.

Even if spacings of absorbers have been found by others to facilitate gains in annual energy capture due to hydrodynamic interactions ($q_{annual} > 1$), see e.g. Penalba et al. [7], there's no guarantee that this is feasible in practical applications i.e. when practicable control, real sea conditions, relevant deployment sites, specific absorbers, and methods of deployment are accounted for (see e.g. [8] or[9]). On this basis, Thomas [10] has argued that *"absorber arrangements should be optimised to minimise destructive interactions"*. This was the aspiration of the spacing chosen in this MWAP project, particularly in respect of minimising the impact of destructive interactions on the annual average captured power.

One other spacing option was briefly considered based on recommendations given by Babarit [11], who argues that "*for small arrays (fewer than ten devices of typical dimension B), with standard layouts and separating distance 10B to 20B, the park effect should be negligible"*. This recommendation is intended to be independent of absorber choice so is likely to be conservative. No platforms under development for FOW would be able to accommodate 9 of the absorbers considered in this study with a spacing of 10 diameters or greater, so this was discounted as a plausible spacing option.

3.1.2.2 Platform type

To understand what kind of platform could be feasible for the notional MWAP system, a review was carried out of designs of floating wind platforms which appear in the public domain. The 2021 Offshore Technology Yearbook produced by renews [12] gave an overview of approximately 40 companies pursuing floating offshore wind platform designs, while [13], [14] and [15] were also found to be useful in this review exercise as they provide indicative dimensions for FOW platforms being developed. The Floating Offshore Wind 2022 conference in Aberdeen was also attended, to meet platform designers to discuss and corroborate their broad approaches to dimensions, masses and moorings.

Recurring themes in the review of platform designs were that:

- Most platforms being developed for FOW applications seem to be of the semi-submersible (semi-sub) platform type.
- Many semi-sub platforms being developed consist of three vertical columns connected by horizontal beam of equal length in a triangular shape.
- Semi-sub platforms offer the most potential space to mount wave absorbers when compared to other types of FOW platforms being considered.
- Semi-sub platforms of the size needed to accommodate the absorbers with a corner column spacing of 80m are under development.
- TLPs tend to have a more compact platform footprint than semi-sub platforms and have a larger draught.

Based on these observations, a triangular semi-sub type platform that loosely resembles the type being developed for FOW, with three vertical corner columns connected together by horizontal beam, was selected for the study. This is shown in Figure 2. Details of the dimensions of the platform are presented in Table 2.

The three vertical corner columns have the same radius as the absorbers to ensure they have comparable blockage effects. Assuming the corner vertical columns are separated from the absorbers with a minimum of same 4 radii spacing for a 9-A layout leads to the requirement for a host platform with an 80m vertical column centre to centre distance. The horizontal beams of the platform have been sized based on tank testing requirements and to provide sufficient structural strength, mounting area for absorbers (width as well as length) and to contribute buoyancy to the system.

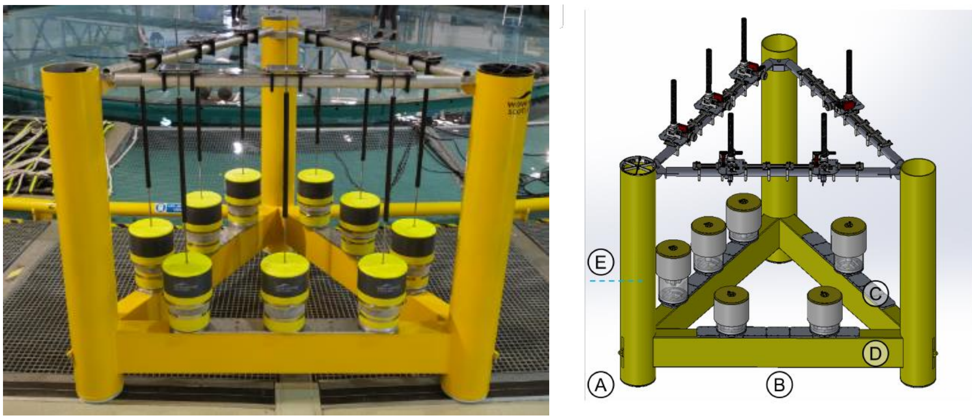


Figure 2:(left) As-built MWAP system tested at FloWave, and (right) rendered mage of Solidworks model of the MWAP system designed by FloWave illustrating that 1, 2 or 3 absorbers could be attached to each horizontal beam of the platform. Both images show the upper horizontal beam, used during the physical modelling to mount equipment high above the water line.

Table 2: Platform dimensions (labels match with Figure 1 (right))

Label	Description	Value (m)	
		Full	Tank
A	Platform corner column diameter	10	0.2
B	Platform corner to corner spacing	80	1.6
C	Lower beam width	5	0.1
D	Lower beam height	10	0.2
E	Platform draft	35	0.7
	Absorber spacing centre to centre for 9-A layout (4 * absorber radius)	20	0.4

Since the test model is not based specifically on a full system that is currently under development, data for the representative mass distribution at a full scale is not available. On this basis, a relatively light approach to platform and mooring design (considering buoyancy, ballasting and mooring pretension needed to install the platform at the targeted submergence) was employed which didn't attempt to address all the concerns of a full-scale platform and mooring design.

3.1.2.3 Heave plates

Semi-submersible platforms often, but not always, employ heave plates at the bottom of the vertical columns to supress motions in heave, pitch and roll. The physical model of the MWAP platform has been furnished with mounting points in order that they could be considered for inclusion in future tests. Thus far, they have been omitted from testing and numerical simulations, and their omission merits some further explanation.

The method heave plates use to supress motions in heave, pitch and roll is achieved in two ways. The first is by increasing the added mass (in heave) and added inertia of the platform (in pitch and roll), effectively moving the moored platform's resonant response in heave, pitch and roll to lower frequencies outside the range of wave frequencies which are typical of the seas where the platform may be installed. The second way is by increasing viscous damping of the platform in heave, pitch and roll by presenting sharp edges to fluid flow which encourage the boundary layer to separate. The use of added mass, added inertia, and viscous damping in this way can facilitate lighter, more compact, and ultimately cheaper platforms.

WEC developers by contrast often go to great lengths to avoid structural features in their WEC design which provoke viscous damping because it is typically parasitic to wave power capture, and its effect can be difficult to predict. The measurement of its effect during tank tests is potentially misleading too, as viscous flow effects don't necessarily Froude scale. Equally, the most commonly used tool for numerical modelling of WECs, based on potential flow modelling, can only address viscous damping via inclusion of empirical viscous correction terms in the equation of motion. These correction terms typically need to be calibrated using measurements or computational fluid dynamics (CFD) modelling.

On this basis, and also because developing understanding of hydrodynamic characteristics of heave plates used in offshore renewable energy applications is still an active area of research (e.g. [16]), it was decided to consider a platform without heave plates for this initial study.

3.1.3 Mooring, and restraint configurations for MWAP layouts

Semi-submersible platforms used in the oil and gas sector and floating wind applications are most commonly moored with a compliant mooring utilising either catenary chain or taut synthetic lines (such as polyester or nylon), or a combination of the two which allows the moored platform to shed load through motions of the platform.

Consistent with other aspects of the design, a relatively pragmatic approach has been taken towards mooring design on the MWAP project which ensures the system captures the broad characteristics of a potential full-scale mooring, rather than develops and tests a representation of an actual full-scale mooring. This is considered to be the case since:

- Compromises have been made in how representative the test platform is of a real platform to allow absorber PTO forces and air spring to be modelled at small scale.
- Details of a potential full-scale system, particularly its mass matrix, are not known.
- It is desired to expedite the development of tools which can be used to study interaction effects between the absorbers.

Instead of developing a real mooring for a full-scale realisation of the system, various mooring and restraint configurations were developed with the goal of ensuring platform motions were kept within safe operating limits for testing the MWAP at FloWave and to ensure that tests could deliver insight into how power capture is affected by different levels of platform compliance. Levels of platform compliance considered included fully fixed; moderate compliance based on a tension leg platform (TLP) style mooring; and a more compliant mooring.

This approach is considered acceptable in the current work, as the platform design is not a scale representation of an optimised or specific full-scale system, and platform mooring design remains a significant challenge that is a focus of wider ongoing design research.

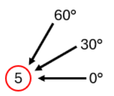
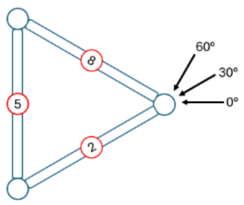
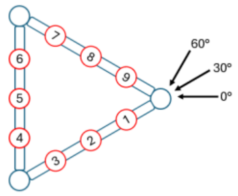
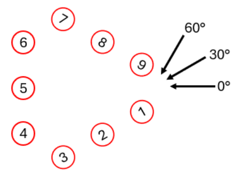
3.2 MWAP layouts

To gain insight into how hydrodynamic interactions affect the MWAP, four layouts shown in Table 3 with indicated restraint configurations have been subject to numerical and physical simulations.

The baseline MWAP layout considered in this project is a notional 9-absorber MWAP (hereafter termed “9-A”) utilising 9 submerged pressure differential absorbers mounted on a platform. A 3 absorber MWAP (termed “3-A”) was also considered as a variant of this baseline.

The 9-A and 3-A layouts were set-up for physical testing at 1:50 scale and numerical simulation, with two additional layouts being used in numerical simulation only - a solo WEC, and a 9 solo WEC layout that assumes the WECs are in the same arrangement as the absorbers in 9-A. The solo WEC option provides a basis to estimate *q-factors* and the 9 solo WEC layout provides a basis to understand the relative benefits for power capture of installing absorbers on a platform versus installing WECs directly to the seabed.

Table 3:WEC and MWAP layouts considered in present multi-absorber system study

Solo WEC	3-A	9-A	9 solo WEC
			
Numerical model only	Numerical and physical modelling	Numerical and physical modelling	Numerical model only
Restraint configurations: • Silo of WEC held fully fixed (float heave only) • WEC attached to seabed with inextensible tether which allows pitch and roll of WEC about seabed.	Restraint configurations: • Platform fixed • 3-line TLP-style, low-compliance mooring • 3-line taut compliant mooring (physical modelling only)	Restraint configurations: • Platform fixed • 3-line TLP-style, low-compliance mooring • 3-line taut compliant mooring (physical modelling only)	Restraint configurations: • Silo of WEC held fully fixed (float heave only) • Each WEC attached to seabed with inextensible tether which allows pitch and roll of WEC about seabed.

3.3 Site and resource

As discussed in the introduction, motivation for development of MWAP system is to create a large multi-device system which can be deployed alongside FOW at wind farm locations where attractive resources for both energy sources are available.

On this basis, sites where FOW farms were proposed in the ScotWind leasing round (lease sites are shown in Figure 3) which could be attractive for co-deployment of wave energy capacity have been considered and one of these was selected for consideration in the MWAP study. The scatter matrix used for this study corresponds to the ScotWind lease site being developed by Magnora as the Talisk Floating Offshore Wind Farm [17], [18].

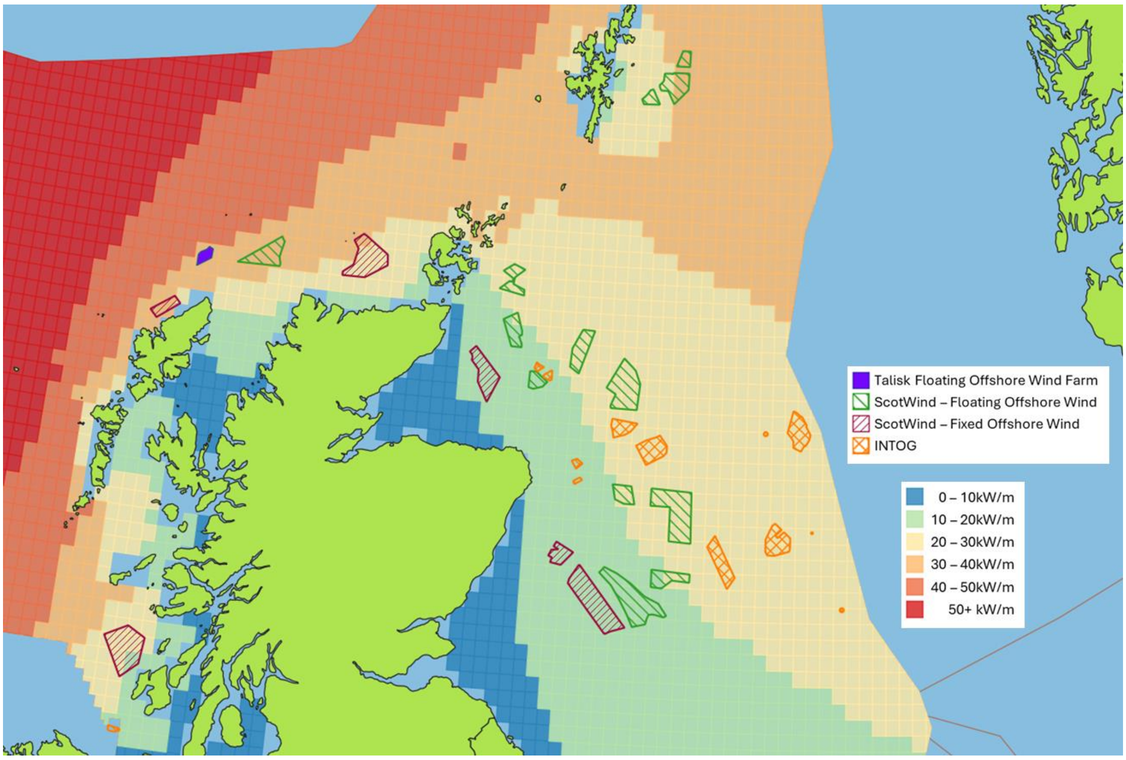


Figure 3:Floating and fixed offshore wind farm lease site awarded in May 2023 displayed along with annual average wave resource, with resource data from the UK Renewable Atlas [19]. The Talisk Offshore Wind Project, used as part of this case study, is highlighted.

RESOURCECODE datapoint 277698 was identified as being within the boundaries of the Talisk Floating Offshore Wind Farm lease site (Figure 4). A dataset covering 11 years of (Hm0, Tp) wave statistics of model predictions for this node was downloaded from RESOURCECODE database [20] to get a more accurate estimate of annual average wave power and to produce a site scatter diagram. This site scatter diagram (Figure 5 (top)) was used to select appropriate sea states for tank testing and modelling. Water depth across the site is estimated to vary from 106-125 metres [21], so a water depth of 100m is assumed for this project in order to match the scaled depth in the parallel tank testing completed in the FloWave facility at 1:50 scale. Estimates of the annual average incident wave energy at this site vary according to which wave models were used to estimate this, with an annual average of 61kW/m estimated using the RESOURCECODE data.

The majority of numerical simulations used the full scatter table, while a subset of 101 power producing sea-states were used specifically for the comparisons of results between the two constraint handling approaches that are investigated. The subset corresponds to conditions that are generally within operational limits for power production for WEC devices and shortened the time to run each simulation set.

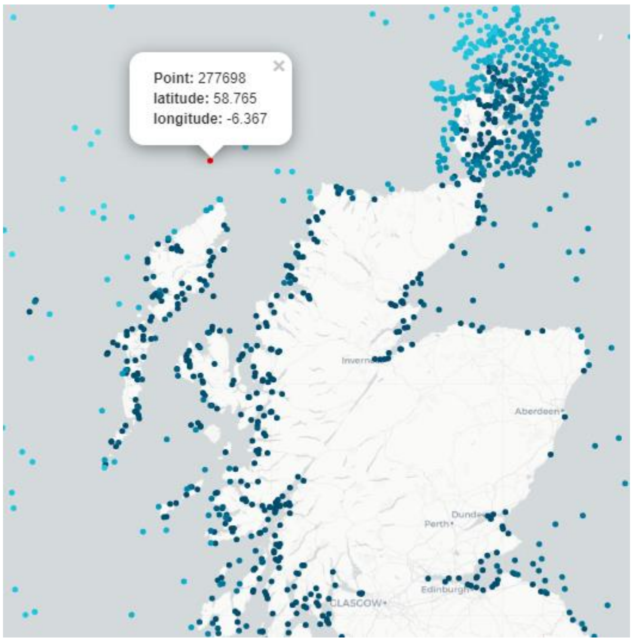


Figure 4:Location of the underlying WaveWatch 3 model cell for which sea state time series have been extracted

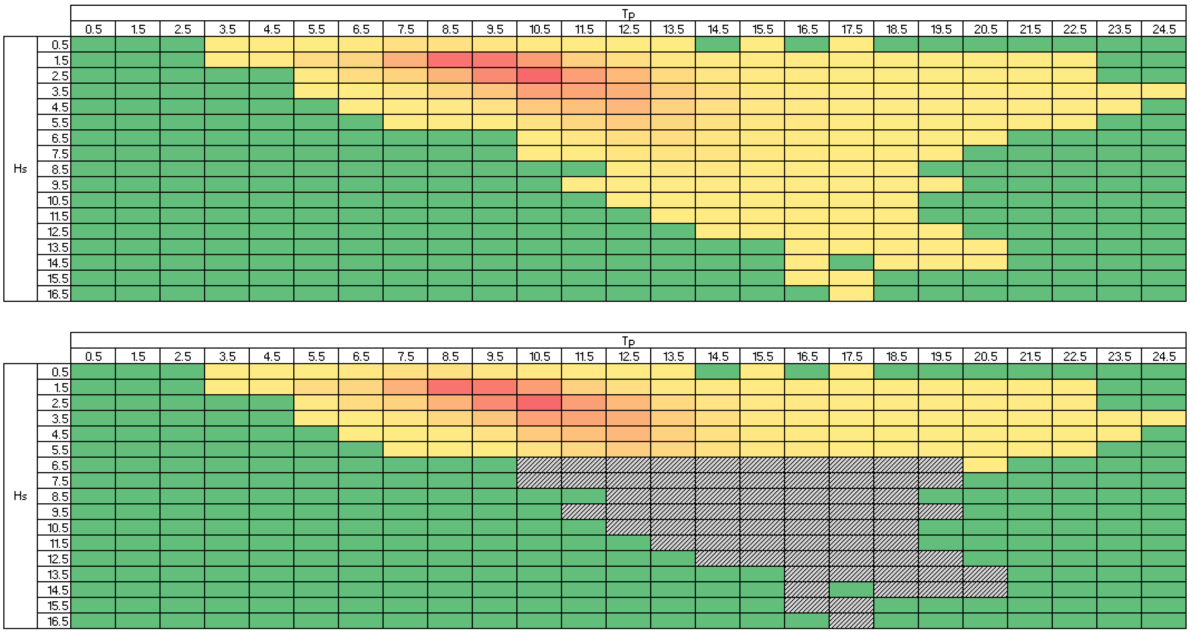


Figure 5:(top) Wave scatter table for the Talisk Floating Offshore Wind Farm site determined using sea-state time series downloaded from the RESOURCECODE database and using sea-states bins of 0 ≤ Hmo <1.0 and 0 ≤ Tp <1.0. (bottom) Indication of the subset of 101 sea-states used in the comparison of results for constraint approaches during numerical modelling, with other sea-states greyed out.

Many sea states which occur at this site will be short crested and have multi-peaked energy density spectrums. However, for the initial investigations carried out on the MWAP project it has been assumed that sea states are long crested and have a single peaked energy density spectrum which can be represented by a Pierson-Moskowitz or JONSWAP spectrum defined based on the significant wave height (H_s) and peak period (T_p) for which the scatter table has been tabulated.

3.4 Control strategies considered

MWAP systems allow for a large number of potential control strategies to maximise power capture.

Control strategies for the MWAP system can broadly be categorised into the following areas that could be applied either as sea state-by-sea state or wave-by-wave control:

1. Control strategies that could be applied to individual absorbers in isolation to boost power capture or maintain the response within its safe working limits,
2. Control strategies which tune hydrodynamic interactions (i.e. park effects) to boost power capture,
3. A combination of the two.

In the first category, developers of point absorbers and similar systems, such as the submerged pressure differential absorber considered on the MWAP project, have found that some kind of sophisticated control strategy is needed to achieve an attractive power capture for sea states. This could be through phase control, which is a wave-by-wave control strategy that aims to provoke a resonant response in a prime mover to enhance power capture.

In the second category, a variety of control strategies have been proposed such as diagonal control, independent control and coordinated (sometimes called 'general') control. See e.g.[22],[23] or [24].

The value or otherwise of more sophisticated control strategies needs to be benchmarked against simple control strategies, particularly where additional hardware or measurement capability is needed for the former. On this basis the MWAP project has focused on:

- Diagonal sea state-by-sea state PTO damping-only control,
- Diagonal sea state-by-sea state PTO reactive control.

Diagonal in this case refers to application of the same PTO control settings to each absorber or WEC in the layout.

A solo WEC control strategy which is targeted at identifying sea state-by-sea state control parameters that tries to maximise power capture while avoiding breaching system constraints has also been briefly explored. This is explored in more detail in Section 5.2.3.2.

For both control options, the absorbers are still subject to the spring forces provided by the absorber's air spring and hydrostatic spring. In damping-only control, the combination of the air and hydrostatic springs effectively tune the natural period of the absorbers to a particular wave period, and in simulations done considering this control the air spring has been set to ensure the natural period broadly aligns with a target wave period at the chosen reference site. By contrast, with reactive control the overall spring can be corrected using the PTO spring, allowing the absorber natural period to be changed on a sea-state by sea-state basis.

Since a realistic PTO design has not been defined for the absorbers as part of this study (i.e. hydraulic, linear generator, etc.) it is assumed that the spring and damping control parameters could feasibly be applied through the PTO, and no attempt has been made to quantify the energy necessary to add into the system to actuate PTO forces associated with these.

Whilst little can be directly inferred about how the systems will perform when more advanced control strategies are used, results obtained on the MWAP project should in principle give an initial insight as to what might be expected for an MWAP relative to solo WECs.

3.5 Study questions

Based on the configurations proposed, the following high level questions were posed for the overall project:

1. Using the same constituent WEC design, how does the notional 9-A layout perform compared to either 9 isolated solo WECs, or 9 solo WECs placed in a close array of the same spacings without a platform?
2. Which absorbers on the MWAP perform the best?
3. Does the performance of each MWAP absorber in the numerical simulations match what is seen in the tank?
4. What layout(s) and configuration(s) of the platform can give improved performance compared to same number of isolated WECs?
5. What orientation of the MWAP or WEC array relative to the incident wave direction results in improved performance?
6. How do various configurations of MWAP mooring and restraint influence power capture?
7. What PTO control settings delivers improved performance?

It is stressed that at this stage the observations corresponding to these questions will be specific to the systems, layouts and configurations tested in this study. The relevance and comparison to different WEC-type, and different configurations of mooring, control, layout, platform design, etc. would need to be considered on a case-by-case basis.

In particular, the complex physics of the inter-absorber interactions makes it difficult to generalise how a particular multi-absorber system might behave in a specific wave resource.

4 Physical modelling

The philosophy and ambition for the 1:50 scale physical model tested at FloWave during the project is discussed in detail in [2].

The tank testing comprised four testing campaigns, with the focus of each being:

- Initial shakedown testing of platform with absorber floats locked at mean position, and to calibrate and validate mooring analyses
- Initial performance trials carried out with platform fixed
- Additional performance trials carried out with platform fixed or floating
- Performance trials carried out with refined motor and control operation using a fixed or floating platform.

4.1 MWAP implementation

4.1.1 Absorber PTO and air spring

Development of a physical model of a system as complex as the baseline MWAP for 1:50 scale testing at FloWave inevitably required some compromises to represent an equivalent full-scale system. Most of these compromises on representativeness of the tank test model to an equivalent full-scale system were driven by the need to find innovative solutions to physically model the absorber's PTO and air spring forces at such a small scale. Both were achieved by applying these forces to the top side of each absorber's float externally rather than to the bottom side of float internally as would be done in a full-scale system, the general principle for which is shown in Figure 1(c).

Delivery of these forces required a motor and mechanical spring assembly to be mounted above each absorber in a carriage high above the waterline to avoid water getting into the motor and associated sensors. PTO forces in the physical model are supplied by a motor connected via a pulley to a taut line back to the absorber. The actual physical implementation of this is shown in Figure 6. Each taut line is also connected to a mechanical spring which approximates the response of the real internal air spring, moving complexity to a mechanical system away from the air system. In particular, it removes the need to use external compensation volumes to model the full-scale air spring of individual absorbers at model scale, a common approach when modelling pneumatic WECs in scale tests albeit with various potential limitations as discussed in [25]. Note, residual air in the scaled absorber is vented through the hollow platform to atmosphere to prevent it impacting on the absorber dynamics. An inevitable consequence of this is that the test MWAP has a significantly higher proportion of mass above the water line than an equivalent full-scale version of the system.

FloWave subcontracted Sequentec to develop a controller that would be used during the physical testing of the MWAP system. This controller determines the instantaneous PTO control force to apply to each absorber according to the control strategy being considered. The control force is based on the float position measurements and the corresponding estimate of float velocity for each absorber and demands the required torque from the relevant motors. This torque is applied to the pulley which leads the taut line to apply the required force to the float. The controller has the option to utilise either a spring potentiometer or a position encoder within the motor to measure the absorber float position, with each being mounted on the carriage hosting the mechanical spring and motor assembly above each absorber (see Figure 6). The spring potentiometer measurements were ultimately used as they provided a more reliable signal compared to the encoder.

An image from the CAD model used to design the spring and PTO assemblies with key components annotated together with a photo of the as-built assembly installed on the platform are presented in Figure 6. Photos of the control box and the control software in action are presented in Figure 7.

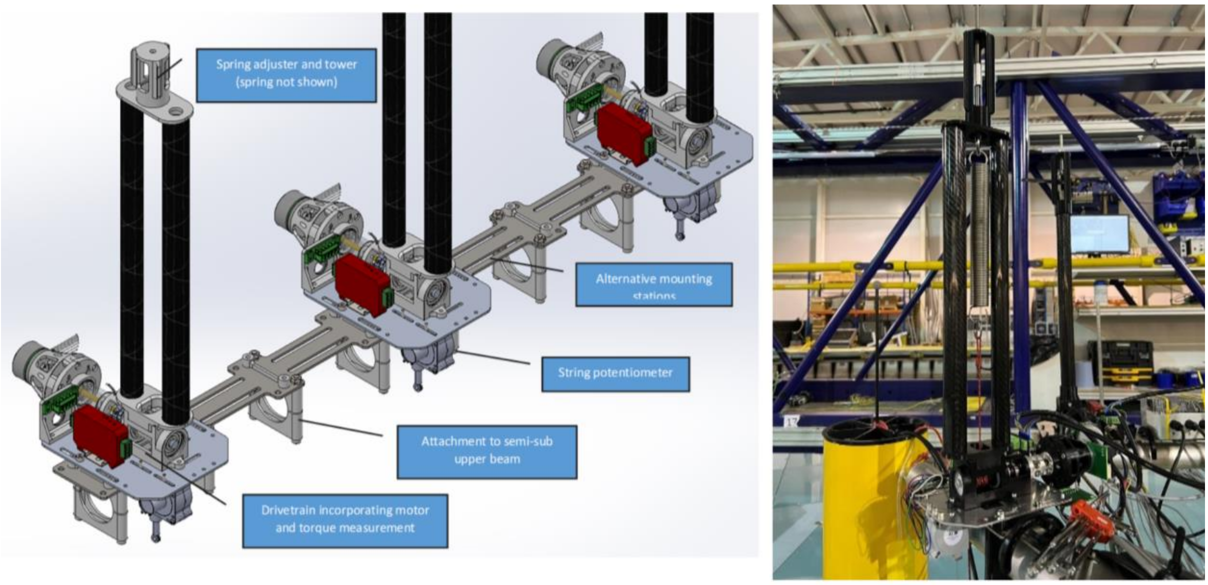


Figure 6:Image from CAD model of each absorber's spring and PTO assembly with key parts annotated (left) and a photo of the as-built assembly for one of the absorbers (right)

Figure 7:Control system cabinets (left) and control system software interface in action (right)

At present it is not possible to physically model PTO control forces which have a spring component as there is no mechanism to prevent the taut lines, used to apply the control force to the floats, from going slack when this type of force is applied. Approaches to modelling PTO control strategies which include PTO spring are currently being considered by FloWave as part of ongoing research on WEC control so it may be possible to do this in the future. Reactive control can however be handled in the numerical simulations.

4.1.2 Platform

Platform design followed broadly the principles outlined in Section 3.1.2.2, with consideration of submergence requirements of the absorbers, and also mounting of test hardware needed to represent the absorbers.

Full details of the platform and mooring designs for physical modelling are provided in McLean et al. [2].

One of the key considerations necessary in the construction of the platform used in the physical testing was to ensure that it would allow for the variable volume of the pressure-differential absorbers. In the test system, although the mechanical representation of the PTO was implemented externally to the absorber, each absorber still needed to have access to an air reservoir that prevented unwanted spring and damping effects due to the movement of air. This was achieved by allowing a passage of air through a hole in the bottom of the silo into the beams of the platform and having the vertical corner columns open to the atmosphere.

An initial concept considered use of a modular aluminium and closed cell foam construction, but this was deemed to be too challenging to maintain structural robustness and waterproofness. The final design of the semi-submersible platform used a painted, welded aluminium structure, with detailed design and manufacture undertaken by Deevek Ltd. A CAD image of the final fabricated design is shown in Figure 8.

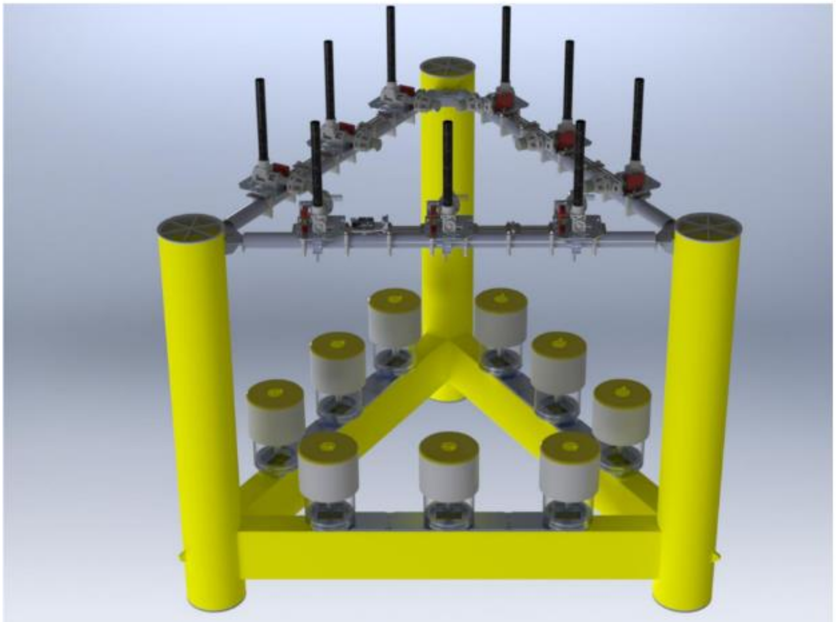


Figure 8: CAD illustration of the final fabricated MWAP structure in the 9-A layout

The platform design allows for different number of absorbers to be mounted on each of the horizontal beams, with 7 preset mounting locations that allows up to 4 equally spaced absorbers to be attached. During this project and testing campaign, only two layouts are tested, using either 1 or 3 absorbers per side. Aluminium blanking plates with o-ring seals were used over locations not in use with an absorber (see Figure 9).

Each vertical column included a fixed padeye that allowed attachment of moorings lines. Three detachable padeyes were also provided so that the position of the mooring point on each column could be varied if necessary. In practice, the fixed padeye was used for the TLP-style mooring, while the movable attachment was used for the taut-compliant system.

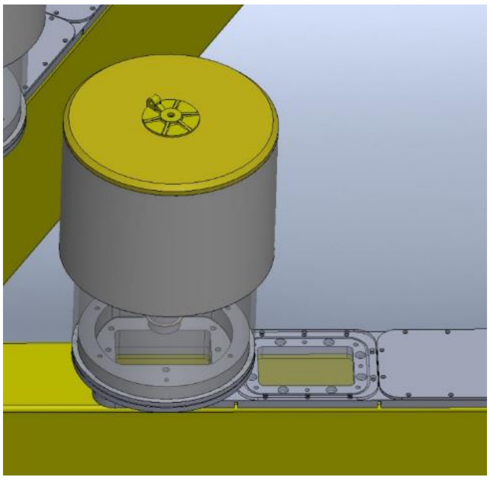


Figure 9:CAD illustration of how the absorbers and blanking plates are fitted to the lower horizontal beam. The plate for the right of the absorber has been removed for illustrative purposes.

4.1.3 Mooring implementation

The essential details of the approach taken with mooring and restraint system design are described in Section 3.1.3. This section provides some details of the processes applied in design and installation of moorings and restraint systems in the tank.

4.1.3.1 Mooring designs

The mooring and restraint configurations used in the physical testing include:

- A "fixed" system, where a restraint holds the platform fully fixed and is represented in physical model testing by mounting the platform onto a jacket structure (shown in Figure 10)
- A "TLP-style" mooring, which allows the platform to surge and sway (see Figure 11 below)
- a "taut-compliant" mooring, which permits a degree of motion in all of the platform's degrees of freedom (see Figure 12 below)

Figure 10:Fixed configuration, with the MWAP mounted on a jacket structure that holds it fixed to the tank floor.

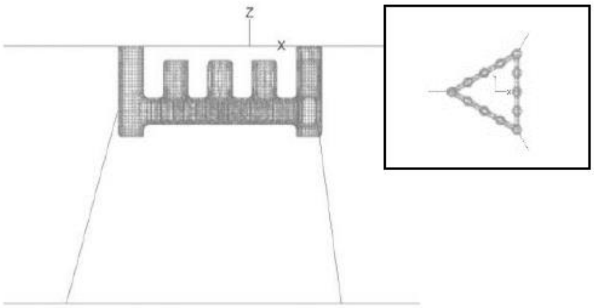


Figure 11:ORCAFLEX model image of the TLP style mooring. Note, it is described as a "TLP-style" mooring as the platform is more akin to a semi-submersible platform, and an actual TLP mooring is made up of bundles of tendons rather than individual lines.

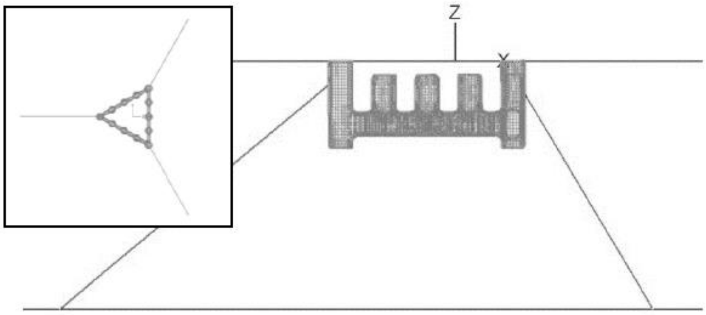


Figure 12:ORCAFLEX model image of the taut-compliant mooring.

The only restriction on mechanical properties of lines considered in the analyses was that line mechanical properties can be represented at model scale. This did not exclude lines with mechanical properties that don't have a full-scale counterpart.

To simplify the mooring analyses, the floats of each absorber were assumed to be fixed at their mid-positions.

For both the TLP-style and taut compliant moorings, systems with three mooring lines have been considered for simplicity. During physical modelling tests, mooring loads on each line were then measured using the available load cells at FloWave.

ORCAFLEX analyses were undertaken to assess whether performance testing of the MWAP system could be safely performed at FloWave for each mooring system, with a focus on the energetic sea states that would be used at model scale so that data outputs could be validated against the tank test measurements. In these analyses safe bounds of operation were considered for mooring loads, and surge and pitch excursions. It was only necessary to consider surge and pitch excursions as only head seas were simulated, and the platform is symmetrical about this wave direction.

The taut compliant mooring option posed some issues in ORCAFLEX simulations regarding safety criteria and a decision was made to not test this in the tank. Some physical tests were undertaken with a substitute mooring developed for a FOW platform, but platform stability issues were encountered and testing with it curtailed.

4.1.3.2 Design analyses for platform system moorings with ORCAFLEX

For each of the platform mooring configurations, the design process involved three distinct parts:

1. Determination of environmental basis of design (completed once for all considered layouts), using sea states that would be tested in the tank.

2. Determination of hydrodynamic parameters[1] for the platform using ORCAWAVE simulations, run for the 9-A platform at its target draft. This used a boundary element representation of the mean wetted surface of platform generated in Rhino [26] by importing the platform CAD model and using Rhino's inbuilt meshing tools to produce the boundary element mesh (Figure 13).

3. ORCAFLEX time domain simulations were run for each considered mooring configuration in the design environmental conditions to estimate platform excursions and line loads This was repeated, with modification to mooring parameters such as the line angles, until platform excursions and line loads were all within safe limits for testing at FloWave.

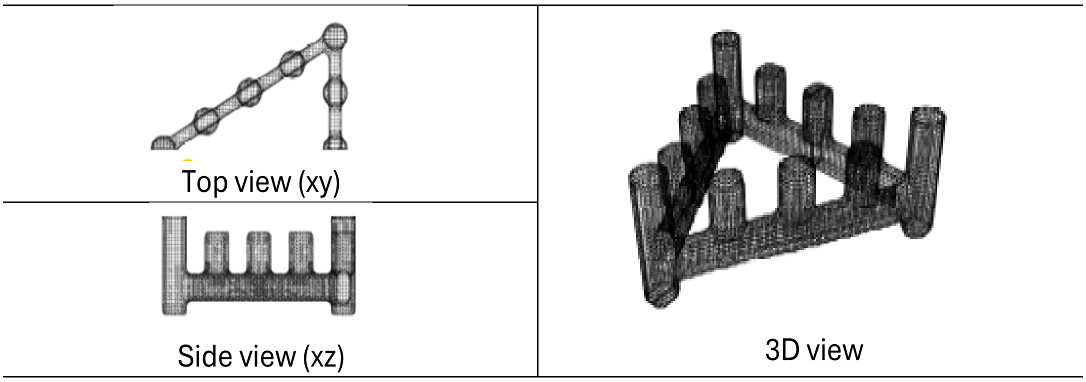


Figure 13: Boundary element mesh used in ORCAWAVE analyses for the platform

Once the design for each configuration had been established, a viscous damping correction for each configuration was made, using a linear coefficient for surge, pitch, roll and yaw platform mode of motion estimated using decay tests conducted in the tank.

Models could then be validated by comparing both the motion amplitude RAOs estimated from white noise and regular wave frequency sweep tank tests and the mooring loads with the simulation models.

The ORCAFLEX models were then able to be used to estimate the mooring stiffness matrices for floating, TLP-style MWAP layouts for use in the numerical simulations, assuming the platform is at stable and horizontal in still water.

Strictly speaking, the mooring stiffness matrix would be estimated for each sea state accounting for the mean offset position (drift) and orientation of the platform for that sea state and the effect of power capture on it. This was considered to be beyond the level of accuracy needed for the current stage of investigations into MWAP systems, but it is expected to be particularly important for more compliant moorings and in more energetic seas.

It is stressed that:

- the mooring design activity done for this project is more of a sense-check that possible platform excursions and mooring loads are both within an order of magnitude that are manageable for testing than a formal mooring design aligning with mooring design codes (e.g. DNV-OS-E301)
- mooring components used for some layouts (such as dyneema mooring lines in TLP mooring) have properties (e.g. axial stiffness) that have no full-scale counterpart.

[1] The first and second order hydrodynamic parameters of the platform were estimated using boundary element representation of the platform with ORCAWAVE. The estimation of these parameters was also cross-checked with those determined with WAMIT for use in the numerical simulations. The sensitivity of the motion and excitation force RAOs to the panel size was checked to ensure that the resolution of the boundary element mesh was sufficiently fine.

4.1.3.3 Implementation of moorings in the tank

The FloWave basin has a number of pre-set attachment points on the raisable tank floor and by attaching rails to these, mooring lines can be anchored via any point on the floor. Therefore, once a specific mooring layout was established in ORCAFLEX, suitable attachment points and rails were identified and fixed in position. Mooring lines were passed through pulleys attached to the rails and fixed via a second pulley to a pole on the edge of the tank and above the waterline. Springs mounted in series with the mooring line at the pole end termination allowed the axial line stiffness of the line to be easily preset or adapted, as required (Figure 14). Load cells were included at the MWAP end connections.

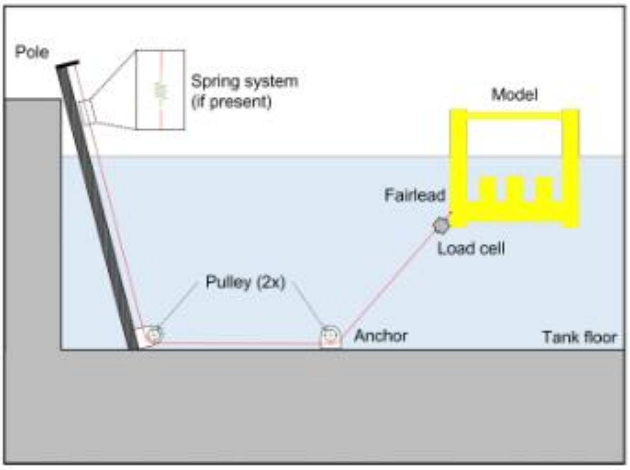


Figure 14: Standard mooring set up for floating MWAP tank tests

4.2 Observations from physical testing

4.2.1 Objective

Deploying and measuring performance of absorbers on a MWAP at a scale of 1:50 came with significant challenges. Due to the Froude scaling for power, the absolute powers measured are extremely low (< 1W), while at this scale friction exerts an unrepresentatively large influence on device performance. The tests undertaken were therefore not intended to provide data that can be extrapolated to estimate mean powers at full scale, but rather to provide a comparison between individual absorbers, and system layouts and configurations.

4.2.2 Test cases

A number of conditions were specified for the tank testing campaign, which considered the motivations for the project, the scale of the physical model, and the capabilities of the FloWave tank. These conditions are shown in Table 4, and covered regular waves and white noise tests for Response Amplitude Operator (RAO) analysis. A number of irregular sea states (defined with a JONSWAP spectrum using $\gamma = 1.0$) were also used for qualitative observations of the MWAP in performance seas and generation of data sets that may support future comparison against numerical simulations.

Table 4: Environmental conditions used during tank testing campaigns. Regular waves were run at 0.05m and 0.1m for a frequency sweep of 10 frequencies for all directions at 30° increments. White noise runs were completed at 0.05m for a range of frequencies and all directions at 30° increments. Irregular sea states utilised pre-existing waves defined for the EuropeWave programme (indicated EUW#) and were supplemented by 7x additional waves considered relevant for the Talisk Offshore Wind Farm location.

Case		Regular wave height (m)	Frequency (Hz)	Significant wave height Hs (m)	Peak period Tp (s)	Incident wave direction (degrees)
Regular		0.05	0.219 : 0.781			0 : 30 : 360
White noise		0.05	0.3 – 0.8			0 : 30 : 360
Irregular (γ = 1)	1 (EUW1)			0.06	1.26	0
	2 (EUW2)			0.06	1.53	0
	3			0.06	1.82	0
	4			0.02	1.26	0
	5			0.04	1.26	0
	6			0.04	1.53	0
	7			0.08	1.53	0
	8			0.08	1.67	0
	9			0.08	1.82	0
	10 (EUW4)			0.06	2.38	0
	11 (EUW5)			0.06	2.66	0
	12 (EUW6)			0.06	2.94	0

4.2.3 General observations

The following observations were made during the course of the test campaigns:

- There is some variation between the responses of individual absorbers on the MWAP, leading to apparent asymmetry which is not considered representative behaviour. For example, absorber #2 (see Table 3) was often observed showing lower motions than the other absorbers. Although all absorbers were frequently checked for free-running characteristics, very small differences in frictional behaviour were assumed to be the cause of the variations observed. Tests were completed from multiple incident wave directions to help to mitigate the influence of these absorber variations on any conclusions.
- The absorbers are sensitive to both their submergence and the draft of the platform. This was a particular challenge during tests with a floating platform. Approx. 5mm changes in submergence would cause the mean absorber float position to shift to a point where it would reach maximum excursion. As a result, the mechanical spring was designed to give a stronger self-centring behaviour than would be anticipated in a representative full-scale absorber but this came at a performance cost by pushing the absorber's natural frequency into a non-optimal region.
- Collectively, the 9 absorbers comprise a relatively large, variable displaced volume, leading to buoyancy forces that cause changes in the pitch and draft of the platform in floating configurations. This was particularly noticeable when attempting to correct the submergence of the absorber floats, whereby a small reduction in platform draft would cause the absorber floats to rise, increasing buoyancy and reducing the platform draft further.
- Directional sweeps did not appear to show any impact of the large instrumentation cable bundle connecting back to the gantry of the tank, even when the platform was in a low compliance mooring configuration.

- The platform itself is of a generic and reconfigurable design and is not optimised for the deployment of this type of wave energy converter. Evolution of the design for the moorings, platform, and WEC may help to improve heave and pitch stability as well as performance.

4.2.4 Regular waves

The H = 0.05m and H = 0.1m tests show considerably highest power outputs at a damping gain value of 1 (corresponding to 36.9 Ns/m), before reducing for values of 1.5 and 2. This suggests that a damping gain of 1 is close enough to the optimum performance of the physical representation of the MWAP to be a good default choice.

The regular wave runs also show some tendency for the rearmost absorbers to perform slightly more effectively than those nearest the incoming wave.

The frequency response of the absorbers is quite broad based on these results, with the best overall platform performance occurred in the region of 0.5 – 0.6 Hz, relating to a full scale wave period of approximately 12s.

4.2.5 White noise

White-noise direction sweeps were primarily undertaken to identify if the MWAP has an optimal operating direction. Considering the centre absorbers on each beam, the outputs remained consistent regardless of direction, suggesting that there is no dominant orientation.

Fixed and floating configurations outputs were broadly comparable, despite the challenges and uncertainties in ensuring consistent platform draft.

4.2.6 Compliant mooring configuration

In addition to testing the MWAP with a fixed and floating (TPL-style) mooring configuration, a series of qualitative tests were run with a taut compliant mooring which represented a type of catenary mooring system.

The compliant mooring provided minimal pitch and heave restraint, which made maintaining a constant submergence of the absorber floats very challenging.

For the WEC-type used in this study, the submerged volume increases as the float approaches the surface, while it conversely will decrease as it moves deeper in the water, resulting in an overall change in buoyancy. In the case of this MWAP, as the platform pitches, the absorbers are changing volume and there is a lack of stability until eventually one or more of the absorbers will pierce the surface. At this point all hydrostatic forcing is lost, and these absorbers cannot recover to their mid-stroke or default position without external assistance.

Thus, to make a compliant mooring viable, the inherent pitch and roll stiffness of the platform of the MWAP would have to be significantly increased to such an extent that it is greater than the pitch moment generated by the buoyancy changes in the absorber floats.

4.2.7 Irregular waves

Optimal damping gain in the representative power production sea state (EUW6) for fixed configurations appears to be no higher than 1.0 (36.9 Ns/m), although there may be some variation in this between fixed and floating cases. For further confirmation, this would need to be explored in more sea states, using a more robust floating mooring configuration, and ideally in a test programme concentrating on the PTO control influence and optimisation.

Power produced appeared to be relatively even between absorbers, with the tendency of the rearmost WECs to generate increased power in regular tests not observed for irregular waves. Again, additional runs in different sea state conditions would help confirm this to be the case.

4.2.8 Physical modelling outcomes

The physical modelling delivered a number of outcomes and qualitative insights into the behaviour of MWAPs. The qualitative insights included:

- Dealing with the physical model in tank testing campaign resulted in a significant advancement in understanding and learning:
    - Qualitative insights into interaction effects between absorbers,
    - Validation of mooring analyses used to design mooring for moored configurations has established that mooring analyses are predicting platform motion response and mooring loads,
    - Identification of aspects of hydrodynamic behaviour of absorbers not addressed by numerical simulations.
- Confidence in the physical modelling test hardware has yet to reach the level needed to calibrate or validate the numerical simulations, or to reliably make standalone predictions of system performance based on tank tests alone. The main challenges remaining to be resolved include:
    - Differences in the behaviour of absorbers that are not resulting from hydrodynamic interactions and are instead likely caused by unintended friction/stiction in the absorber drivetrains.
    - Improving tuneability of the PTO spring of absorbers to better target the incident wave conditions being tested.

A number of key outcomes that are identified from the physical testing campaign include:

- Pressure differential WEC systems can generate power when fitted on a floating platform where heave and pitch are constrained.
- Power performance appears broadly similar between a fixed and a floating (TPL-style) mooring system.
- The optimum damping value may differ between the fixed and floating configurations.
- At wave periods ~>2s (14s at full scale), power production appears broadly uniform across all nine absorbers.
- Centre absorbers (#2, 5 and 8) remain relatively consistent in their performance, independent of the wave direction and restraint configurations. The exact mechanisms behind this, including why it appears insensitive to wave direction, cannot be conclusively drawn from the tests undertaken to date.
- The MWAP, as currently implemented, requires pitch/roll and heave constraint to operate effectively. A compliant mooring is not viable with the current platform and absorber arrangements as the variable buoyancy results in negative pitch and roll stability.

The issues encountered with testing arise largely on account of the challenges of testing such a complex system, both in terms of the type of PTO used for the absorbers and also the number of components in the model, at a very small scale of 1:50 and the necessary comprises needed to do so. Further investigations would help to identify if these issues are relating to scaling effects or an accumulation of testing variability, with each component or measurement within sensible margins-of-error.

Systematic resolution of the challenges identified during the course of tank testing is being carried out as part of ongoing PhD work on optimisation of multi wave absorber platform systems at FloWave laboratory at the University of Edinburgh, part-funded and supervised by Wave Energy Scotland.

5 Numerical simulations

5.1 Overview

The code for the numerical simulations has been written in MATLAB and has been set up to run in two modes using a frequency domain equation of motion solver that enables power capture to be estimated for the configuration of interest utilising hydrodynamics characteristics imported from WAMIT. The code can be used for both regular and irregular used-defined wave conditions.

Initially, an *optimisation* mode is run for an unconstrained scenario, which uses a grid search to identify single values for control parameters that are applied to all absorbers, and which optimises the total captured power in each of the user-defined sea-state conditions. The search space for control parameters was 100 N/m ≤ C_{PTO} ≤ 100 N/m and 1 Ns/m ≤ B_{PTO} ≤ 100 Ns/m.

These optimised control parameters are then used in a *predictive* mode, which has the option of applying constraints on absorber excursion and power, using a method proposed by McCabe [27] to estimate a constrained captured power for the MWAP in user-defined sea-state conditions (see Section 5.2.3).

It was envisaged that numerical simulations in the frequency domain would be used primarily to support screening of potential MWAP layouts and configurations, given it is an order of magnitude more computationally efficient than equivalent time domain simulations.

It is accepted that this gain in computational efficiency does come at the expense that frequency domain simulations deal less well with nonlinear load effects. These include intended nonlinear forces, such as nonlinear PTO control forces, those related to nonlinear aspects of hydrodynamic forces, such as viscous damping, non-linear hydrostatic spring force etc., and unintended nonlinear mechanical forces, such as friction, stiction and end-stop forces.

5.2 Model configurations

5.2.1.1 Simulation restraint

The numerical simulations were set up for four layouts of WEC systems, shown in Table 3, with each having two restraint configurations depending on whether the layout has a platform or not.

For the platform layouts, the first of the two restraint configurations represents a piled or jacket design that prevents any movement in the platform's degrees of freedom (referred to as "fixed"), and the second system uses a mooring stiffness matrix representing a design with three taut, low-compliance, TLP-style mooring lines which permits motion in all the platform's degrees of freedom (referred to as "floating").

The "floating" configuration mooring stiffness matrix was determined and output from ORCAFLEX for a 9-A layout. While limited validation of the frequency domain model has been undertaken so far, this project has previously validated ORCAFLEX time domain modelling of the floating system against tank tests using absorbers fixed in their mean position.

Solo WEC layouts used two versions of a single point mooring, namely a rigid rod-style connection permitting heave-only of the float (referred to as "heave"), and an inextensible, rigid tether that allows the WEC to pitch and roll about a connection point at the seabed, with the float able to heave (referred to as "p/r").

5.2.1.2 Absorber model

The numerical model uses a simplified geometric shape for the float (Figure 15 (right)), comparable to a single cylinder that can be vertically extended or compressed at its top end, and which omits the slight change in diameter between the float and silo seen on a real system.

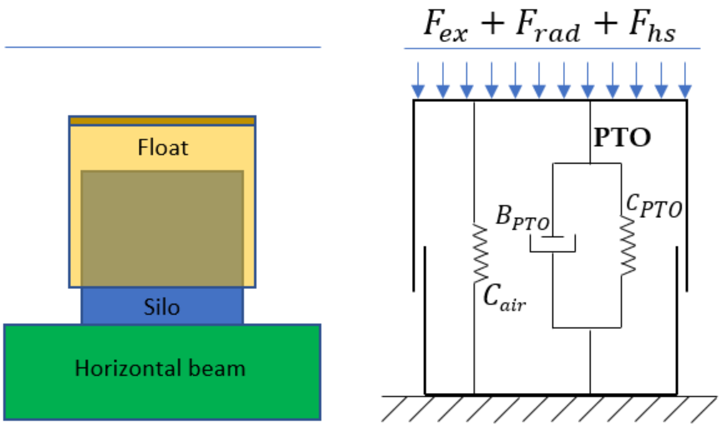


Figure 15: (left) Schematic of the physical realisation of the modelled absorbers on the MWAP, (middle) reactive control free-body diagram, and (right) illustration of the realisation of the modelled absorber in the frequency domain modelling, where the float is modelled by a moving upper surface above a silo that extends and contracts accordingly.

The absorbers are assumed to have a range of characteristics, shown at model scale in Table 1, which are used for the implementation of constraints. Two instantaneous maximum power limits were used in the simulations to give an indication of the impact on energy capture of alternate hypothetical power ratings.

The linear boundary element potential flow solver WAMIT has been used to predict the hydrodynamic characteristics of each system (added mass, radiation damping and exciting force coefficients) with generalised modes used to predict the hydrodynamics characteristics of the power capturing modes of motion of the absorbers. To estimate these parameters, WAMIT utilises a panelised version of the surface of the MWAP. This is illustrated for the 9-A configuration in Figure 16

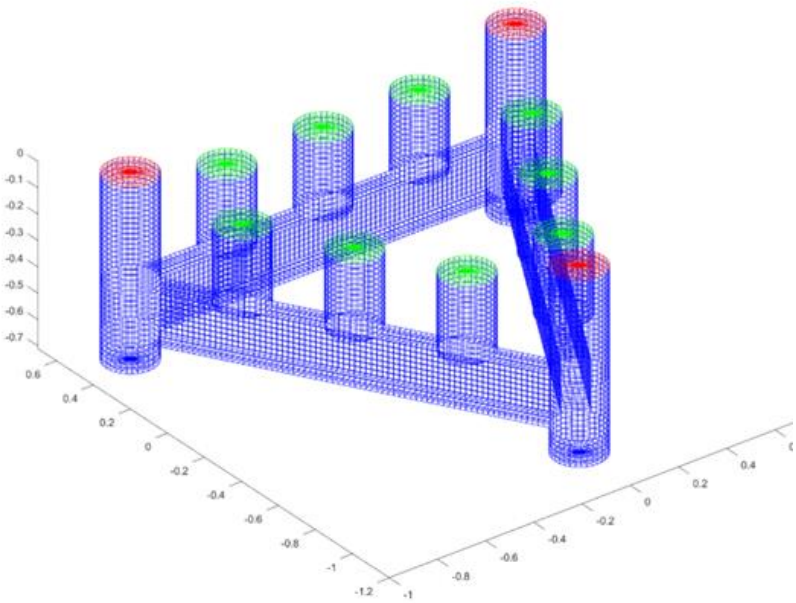


Figure 16: Panelisation of the 9-A layout. Panelled surface highlighted in green indicate the surfaces to which generalised modes have been applied – one generalised mode per absorber. Red indicates where the MWAP columns pierce the water surface.

5.2.1.3 Incident wave directions

Incident wave directions have been chosen to investigate waves approaching the platform directly at a point of the triangle (0°), parallel to a side (30°) and perpendicular to a side (60°). The solo WEC is symmetrical, so the incident wave direction does not have any influence on the outputs of this layout.

5.2.2 Equation of motion

The equation of motion solved in the frequency domain for each system has the form:

$$\{(C_{hs} + C_{air} + C_{PTO} + C_{moor} + C_{other}) - \omega_n{}^2(M + A(\omega_n)) + i\omega_n(B(\omega_n) + B_{PTO} + B_{other})\}\vec{X}(\omega_n) = \mathcal{A}_\mathrm{n}\vec{F}_{ex}(\omega_n, \theta) \quad (5)$$

where C_{hs} is a matrix representing the hydrostatic spring acting on the absorber floats, C_{air} is a matrix representing the air spring acting on the absorber floats, C_{PTO} is a matrix representing the spring that can be applied by the PTO, C_{moor} is a matrix representing the mooring spring forces acting on the WEC or platform (depending on configuration considered), M is the modelled configuration's mass matrix, $A(\omega_n)$ and $B(\omega_n)$ are respectively the frequency dependent added mass matrix and the radiation damping mass matrix determined by WAMIT for the angular frequency ω_n, B_{PTO} is a matrix representing damping that can be applied by the PTO, $\vec{X}(\omega_n)$ is the complex motion response spectrum vector obtained by solution of the equation of motion at the angular frequency ω_n, $\vec{F}_{ex}(\omega_n, \theta)$ is the complex exciting force and moment vector transfer function determined by WAMIT for the angular frequency ω_n and incident wave direction θ, and $\mathcal{A}_\mathrm{n}$ is the complex amplitude of the incident wave component with an angular frequency ω_n for the incident irregular wave train:

$$\mathcal{A}_n = \sqrt{2S_A(\omega_n)\Delta\omega}\; exp\big(iS_{PH}(\omega_n)\big) \quad (6)$$

where $S_A(\omega_n)$ and $S_{PH}(\omega_n)$ are respectively the energy density and phase spectra for the incident irregular wave considered at the angular frequency ω_n, $\omega_n = \omega_1 + (n\text{-}1)\Delta\omega$ for n = 1, 2, ..., N are the N equally spaced angular frequencies for which calculations have been completed, and $\Delta\omega$ is the difference between the sequential angular frequencies.

The equation of motion solved complies with wave direction and phase conventions assumed in WAMIT. According to these direction and phase conventions, in the real space, the wave profile η is given by:

$$\eta(x, y, t) = \sum_{n=1}^{N} |\mathcal{A}_n| sin(\omega_n t + Phase(\mathcal{A}_n) - k_n x cos\theta - k_n y sin\theta) \quad (7)$$

where the wavenumber k_n for each wave component is the real solution of the dispersion relationship:

$$\omega_n{}^2 = gk_n\, tanh(k_n h) \quad (8)$$

Note the diagonal matrices C_{other} and B_{other} were included in the equation of motion (Eq. 5) to capture spring and damping effects in the system dynamics not addressed by other spring and damping terms in the equation of motion. They could address things like mechanical friction in the absorber drive train, or viscous damping forces or moments acting on the platform and absorbers, etc.

The philosophy for numerical simulations on the project was to start with as simple and computationally light numerical models as is possible and only introduce additional sophistication when it is found to be necessary. In reality, many of these *'other'* force effects are nonlinear and the viability of modelling them with a linear description depends on whether they can be represented by a suitable linear approximation. For some of these forces and moments, it may be necessary to switch from frequency domain to time domain modelling so that a full nonlinear description of the additional load and moment effects can be included in the equation of motion. The accuracy of the models may also be improved by including nonlinear representation of other forces and moments included in Eq. 5, such as those related to moorings and hydrostatics.

It was anticipated that the primary mechanism for specification of C_{other} and B_{other} would be to calibrate them based on measurements made during tank testing. Attempts to do so have proved to be challenging due to nonlinear load effects, particularly those associated with absorber drivetrains.

It is believed that, even without inclusion of these other forces and moments (i.e. with $C_{other} = B_{other} = 0$), the linear frequency numerical models capture the physics of the systems of absorbers considered sufficiently well to provide at least some initial insight into how hydrodynamics interactions influence power capture by them. This assumption will be revisited as necessary as work on calibration and validation in the ongoing PhD research at the University of Edinburgh become available.

5.2.3 Handling of constraints

In a realistic system, absorbers would typically be subject to numerous constraints that limit their response, such as the allowable excursion of the float, the velocity and force limits that can be handled by the PTO, the maximum power of the PTO, and how the PTO deals with excess power capture.

The strategy for managing how a WEC remains within its operational constraints is specific to each technology. Commonly WECs employ one or several solutions, from passive measures such as physical end-stops or a survival mode for certain ranges of conditions, to active measures such as utilising the PTO forces and damping to dynamically control the response of the system to stay within allowable limits of constrained parameters.

An example of this would be to adapt the PTO settings when one of the parameters is getting close to its limit, perhaps by increasing damping.

In a realistic system, this adaption of PTO settings based on position, velocity, force or power would likely be nonlinear and so cannot be modelled appropriately in the frequency domain code being used in this study. However, it is recognised that the effect of constraint management on power capture can be significant. It therefore remains useful to implement some simplistic approaches for constraint management in the modelling undertaken to demonstrate the broad effect on captured power, and to prevent the absorbers from responding in a grossly unrealistic manner.

The effect of system constraints on power capture has thus been approximated in two different ways. One approach simply limits the power if certain constraints are breached (the “McCabe” approach) and the other tries to identify control parameters that prevent the constraints being breached in the first place (the “De Backer” approach).

5.2.3.1 McCabe

The approach originally proposed by McCabe [27] estimates the effect of constraints by post-processing the time series of instantaneous power, reconstructed from the output of the frequency domain solution of the equation of motion.

While the control parameters specified do not account for the constraints, the approach does allow the effects of constraints on motion and instantaneous power to be considered, with the instantaneous power adjusted according to the following two rules.

Rule 1 addresses the influence of absorber motion constraint on the instantaneous power:

$$P_{i,xlim} = \begin{cases} P_i(t)\ if\ |x_i(t)| \le x_{lim} \\ 0\ if\ |x_i(t)| > x_{lim} \end{cases} \tag{9}$$

where

$P_i(t) = \mathcal{R}e\{\sum_{n=1}^{N}(K_{PTO}\ X(\omega_n) + B_{PTO} i\omega_n X(\omega_n)\ exp(i\omega_n t)) \cdot i\omega_n X(\omega_n)\ exp(i\omega_n t)\}$

is the reconstructed instantaneous captured power for absorber *i* for the unconstrained system,

$x_i(t) = \mathcal{R}e\{\sum_{n=1}^{N} X(\omega_n)\ exp(i\omega_n t)\}$ is the reconstructed instantaneous excursion time series of absorber *i*, and

x_{lim} is the absorber float’s excursion amplitude limit.

Rule 2 addresses influences of instantaneous power constraints on the instantaneous power:

$$P_{i,plim}(t) = \begin{cases} P_{i,xlim}(t)\ if\ P_{i,xlim} \leq P_{lim} \\ P_{lim} if P_{i,xlim}(t) > P_{lim} \end{cases} \tag{10}$$

where P_{lim} is the absorbers' instantaneous power limit.

The McCabe method has several advantages for an initial investigation into the impact of constraints, including its ease of application and the ability to handle constrained parameters which are nonlinear, such as the captured instantaneous power by each absorber. However, its usefulness is limited due to its post-processing application not capturing the influence of the constraints on system dynamics, with the system radiating as if unconstrained power values are capped as required (Figure 17). The post-processing approach also gives no indication of a real control strategy that may enable this performance to be achieved.

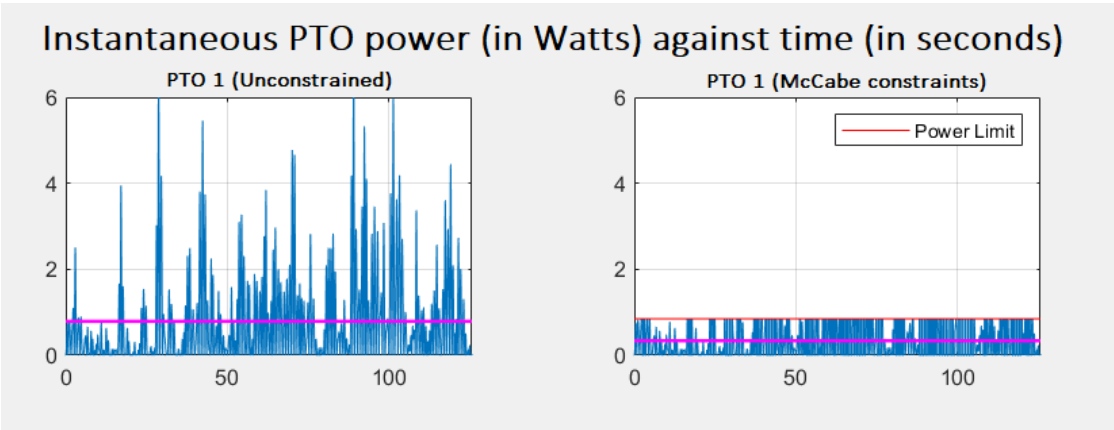


Figure 17 Instantaneous PTO power for absorber 1 of the 9-A fixed configuration, using reactive control in a sea-state of H_{mo} 0.07m, T_p 1.77s. (left) shows the unconstrained system and (right) shows the system when McCabe is applied with the lower instantaneous power limit.

5.2.3.2 De Backer

In the De Backer based method of handling constraints, reactive PTO control parameters have been optimised for power capture subject to constraints on absorber excursion, absorber velocity and PTO force. It is essentially based on the WEC constrained optimisation methodology applied by De Backer et al. in [22] for the F03 multi-absorber system developed by Fred. Olsen, with some minor modifications. These modifications include application of the methodology to control parameters and constraints which are relevant to this present study, and a minor improvement in the approach used to estimate extreme amplitudes of the constrained response variables using the Rayleigh distribution.

The De Backer method avoids the signal capping effects of McCabe by finding optimised control parameters that attempt to always keep systems operating within defined constraint limits. Limits are applied to the short-term extreme amplitude of each constrained parameter, estimated in each state of interest for trial PTO control parameters using the extreme response theory based on the Rayleigh distribution described in [28]. As all calculations are done in the frequency domain without reference to the sea-state's phase spectrum, this methodology is computationally very efficient. A limitation is that it can only be applied to variables that are defined by linear functions, and it relies upon a probabilistic extreme estimation methodology that may result in overconservative control parameters for many realisations of sea-states.

This constrained optimisation methodology could be employed for diagonal control or independent control for multi-absorber systems, as done in [22]. It could also feasibly be used for the multi absorber system coordinated control strategy considered by Bacelli et al. [23] and Cotten et al. [29]. In the present work, it has only been applied to the solo WEC heave configuration. Captured power for other configurations has then been estimated using the solo WEC heave control parameters applied to all absorbers, a strategy that [22] refers to as 'optimal system control parameters from a single body (OPSB)' control. For all simulations with OSPB control done in the study, the extreme amplitudes of constrained absorber variables, estimated using reconstructed time series, were found to still satisfy the prescribed constraints even though the constrained optimisation methodology had only been applied to the solo WEC heave configuration.

In application of the extreme response theory described by [28], the extreme amplitude for each response variable has been estimated using [28] with a value of the risk parameter (α) of 0.1. This value of risk factor was used as extremes predicted by theory using this value matched reasonably to reconstructed time series estimates of extremes for the trial phase spectra when PTO control parameters found in the De Backer optimisation were utilised.

The search space for reactive control parameters assumed in the De Backer constrained optimisation was -59.04 N/m ≤ C_{PTO} ≤ 900 N/m and 0 Ns/m ≤ B_{PTO} ≤ 10 Ns/m. These limits were chosen based on regular wave complex conjugate control parameters for the solo WEC across wave frequencies in WAMIT analyses run for each configuration. While negative C_{PTO} values were allowed, the total system spring C_{PTO} + C_{air} is always greater than zero. For the majority of sea-states considered in this analysis, optimal C_{PTO} values were positive, with only a few of the less energetic sea-states requiring small values of negative C_{PTO} settings. This could also be achieved by a reduction of C_{air}, if the PTO wasn't able to deliver negative spring forces.

As indicated, both the methods considered for handling constraints are necessarily approximate because the physics of the constraints cannot be explicitly numerically modelled in the frequency domain, and the practical methodology for handling constraints that would be utilised by the real system is currently undefined.

This study implements both constraint handling methods, as the effect of constraints has a significant impact on the power capture by systems modelled and each of the methods has different benefits and shortcomings in terms of representing realistic constraint handling. Nevertheless, of the two methods, the De Backer approach is considered the more credible form of constraint implementation as this captures the effect of constraints on radiated waves by individual absorbers, which in turn influences hydrodynamic interactions.

Outputs and observations presented in subsequent sections should be read with these benefits and shortcomings of each constraint handling methodology in mind.

5.3 Observations from numerical simulations

5.3.1 Absorber constraints

In the extreme and unrealistic operating case where an absorber system is fully unconstrained, simulations indicate that interaction effects have a strong influence on captured energy, with q_{annual} for 9-A configurations ≤ 0.50 in Table 5. The implementation of constraints broadly reduces the annual energy captured compared to unconstrained cases and leads to improvements in q_{annual}, i.e. on an annual basis there is less destructive interaction and some constructive interaction.

Table 5: Table considering impact of constraints on q_{annual} and energy captured using the full scatter table for the Talisk site, when McCabe constraints with the low instantaneous power limit are applied using damping-only control.

Configuration	q_{annual} for no constraints	% reduction in annual captured energy for a McCabe constrained system	q_{annual} for system using McCabe constraints
Solo WEC heave	1.00	80%	1.00
Solo WEC p/r	1.00	80%	1.00
3-A fixed	0.85	85%	1.04
3-A floating	0.83	85%	1.05
9-A fixed	0.50	74%	1.07
9-A floating	0.47	72%	1.10
9 solo WEC heave	0.50	74%	1.07
9 solo WEC p/r	0.47	73%	1.06

Table 6 shows a comparison between the results for different control approaches, varying power limits, and varying constraint approaches, and how these affect the calculated q_{annual} for the different MWAP configurations across a subset of performance sea-states at the Talisk site (Figure 5 (bottom)). q_{annual} reduces for both a higher instantaneous power limit and implementation of the De Backer approach, but is still 0.86 or larger.

Table 6: q_{annual} across a subset of 101 power producing sea-states from the scatter table for the Talisk site at incoming incident wave direction 0°, with control and constraint-handling strategies indicated. In (a), the control is changed to reactive control, in (b), the instantaneous maximum power limit is increased to the high value from Table 1, and in (c) the control parameters are changed to those estimated using the De Backer OPSB method. For each variation, the q_{annual} is related back to the respective solo WEC heave configuration value.

	Baseline	(a)	(b)	(c)
Change		***Control settings***	***Instantaneous maximum power***	***Constraint handling approach***
Control approach	*Damping-only*	*Reactive*	*Reactive*	*Reactive*
Method of identifying optimised control settings	*Unconstrained optimal diagonal*	*Unconstrained optimal diagonal*	*Unconstrained optimal diagonal*	*Optimal parameters determined for solo WEC heave using De Backer optimisation*
Constraint handling approach	*McCabe*	*McCabe*	*McCabe*	*De Backer (OPSB)*
Instantaneous maximum power	0.85W	0.85W	4.2W	N/A
Sea-state duration	125.66s	125.66s	125.66s	125.66s
Configuration	q_{annual}	q_{annual}	q_{annual}	q_{annual}
Solo WEC heave	*1.00*	*1.00*	*1.00*	*1.00*
Solo WEC p/r	*1.00*	-	-	-
3-A fixed	*1.04*	*1.07*	*1.04*	*1.01*
3-A floating	*1.04*	*1.08*	*1.04*	*1.01*
9-A fixed	*1.07*	*1.16*	*0.95*	*0.86*
9-A floating	*1.10*	*1.19*	*0.97*	*0.87*
9 solo WEC heave	*1.07*	*1.15*	*0.95*	*0.86*
9 solo WEC p/r	*1.06*	-	-	-

5.3.2 Sea-state by sea-state effects

Comparing q for the De Backer OPSB results on a subset of sea-states for the 3-A and 9-A fixed cases presented in Table 6, it can be seen that both constructive interactions and destructive interference can occur on a sea-state basis, depending on the sea-state parameters, noting that q_{annual} for each configuration was 1.01 and 0.86 respectively (Table 7).

Table 7: q values for (top) the 3-A fixed and (bottom) the 9-A fixed compared to solo WEC heave configuration on a sea-state by sea-state basis, for the De Backer constraint approach, assuming an incoming incident wave direction of 0°.

		T_p				
		6.5	**8.5**	**10.5**	**12.5**	**14.5**
	1.5	0.90	0.97	0.99	1.01	1.02
H_s	**2.5**	0.99	1.01	1.02	1.03	1.05
	3.5	0.99	1.01	1.02	1.04	1.05

		T_p				
		6.5	**8.5**	**10.5**	**12.5**	**14.5**
	1.5	0.57	0.69	0.79	0.86	0.93
H_s	**2.5**	0.73	0.83	0.90	0.97	1.01
	3.5	0.82	0.89	0.95	1.01	1.05

5.3.3 Platform orientation

The incoming wave directions considered took advantage of the platform symmetry, with long-crested waves able to arrive at either 0°, 30°, or 60° (see Table 3). The total annual energy that could be captured at the selected site was compared assuming all sea-states arrived from the same direction. The solo WEC was assumed to be directionally insensitive, so different directions were not included.

Assuming all waves arrive from the same direction, the annual energy captured at the Talisk site for the specific MWAP configurations used in this study are relatively insensitive to the orientation of the MWAP relative to the direction of the incoming long-crested sea-states, with normalised values for energy captured between 0.985 and 1.000 (Table 8), suggesting neither the platform or array layout are overly sensitive to orientation relative to the incident wave direction on an annual basis. This study did not review orientation sensitivity on a sea-state by sea-state basis, although it is expected that useful insight would be gained by considering this for a more mature and optimised MWAP solution.

Table 8: Ratio of annual energy captured in a particular orientation to the annual energy captured in the best orientation for each configuration. Runs completed using the full Talisk scatter table assuming long-crested seas, damping-only control and optimal control parameters for head seas (0° orientation), with constraints handled with McCabe approach and the low instantaneous power limit.

Configuration	Direction with largest annual energy captured	Annual energy at 0°	Annual energy at 30°	Annual energy at 60°
3-A fixed	30°	0.999	1.000	0.996
3-A floating	0°	1.000	1.000	0.995
9-A fixed	60°	0.985	0.993	1.000
9-A floating	60°	0.996	0.998	1.000
9 solo WEC heave	60°	0.990	0.995	1.000

5.3.4 Absorber by absorber behaviour

Not all absorbers contribute equally to the performance of the MWAP in the defined sea states that correspond to the Talisk Offshore Wave Farm occurrence matrix. The spread of $qa_{i,annual}$ by absorber positions shows the largest contribution to annual energy capture comes from the frontmost absorbers (Table 9), which differs from what was observed in physical tests under regular wave conditions. While the spread of $qa_{i,annual}$ may change on a sea-state by sea-state basis depending on wave period and directionality, similar to Table 7, the indication on an annual basis using a constant incident wave direction suggests that at directionally insensitive sites it may be possible to tailor the absorber ratings and capabilities to their position on the platform for techno-economic advantage.

The impact on $qa_{i,annual}$ from interactions between the absorbers and the vertical columns and horizontal beam of the platform structure appear to be minimal when considered over an annual basis, since the $qa_{i,annual}$ values are shown to be comparable between the 9-A and the 9 solo WEC heave configurations (Table 9).

The differences in $qa_{i,annual}$ values for the absorbers between a fixed and floating platform are also very small, suggesting both the layout and that the effect of applying constraints on interaction effects are more pronounced than whether the platform is fixed or floating. Larger $qa_{i,annual}$ are seen for reactive cases, where the total spring for each absorber can be tailored on a sea-state by sea-state basis.

Table 9: Mean absorber-by-absorber $qa_{i,annual}$ across the full Talisk scatter assuming long-crested head seas (i.e. a 0° direction of incidence), and McCabe constraint handling, with the low instantaneous power limit. All damping-only values are compared to the solo WEC heave damping-only configuration, with all reactive values compared to the solo WEC heave reactive configuration.

		Absorber number								
		1	2	3	4	5	6	7	8	9
Damping-only										
	Solo WEC heave	-	-	-	-	1.00	-	-	-	-
	Solo WEC p/r	-	-	-	-	1.00	-	-	-	-
	3-A fixed	-	1.09	-	-	0.95	-	-	1.09	-
	3-A floating	-	1.09	-	-	0.96	-	-	1.09	-
	9-A fixed	1.20	1.15	1.11	0.90	0.85	0.90	1.11	1.15	1.20
	9-A floating	1.24	1.17	1.14	0.95	0.88	0.95	1.14	1.17	1.24
	9 solo WEC heave	1.23	1.17	1.08	0.91	0.86	0.91	1.08	1.17	1.23
	9 solo WEC p/r	1.23	1.15	1.06	0.88	0.85	0.88	1.06	1.15	1.23
Reactive										
	Solo WEC heave	-	-	-	-	1.00	-	-	-	-
	3-A fixed	-	1.13	-	-	0.99	-	-	1.13	-
	3-A floating	-	1.14	-	-	1.00	-	-	1.14	-
	9-A fixed	1.32	1.27	1.23	1.02	0.98	1.02	1.23	1.27	1.32
	9-A floating	1.37	1.30	1.26	1.07	1.02	1.07	1.26	1.30	1.37
	9 solo WEC heave	1.34	1.28	1.19	1.02	0.98	1.02	1.19	1.28	1.34

5.3.5 Numerical simulation outcomes

The primary high-level observation from the numerical simulations is that the impact of the park effect on q_{annual} for layouts of densely clustered absorbers, such as those on an MWAP, is limited. Modelling undertaken of a notional MWAP with a simple implementation of constraints has shown q_{annual} could be comparable or even improved relative to the same number of solo WECs ($0.95 \leq q_{annual} \leq 1.04$), while for De Backer OPSB simulations, which as previously indicated are considered more credible, q_{annual} is reduced but still avoids significant destructive interference ($q_{annual} \geq 0.86$).

6 Key outcomes from testing and numerical simulations

6.1 Key outcomes

It is important to caveat the observations with the fact that they relate to a specific platform, restraint implementation, absorber type, absorber spacing, control settings, and constraint implementation when compared to a specific solo WEC, and that they remain tentative, pending ongoing calibration and validation activities.

The annual *q-factor* for alternative systems would need to be considered on a case-by-case basis to confirm that the findings can be extrapolated to different systems and remain valid.

Referring back to the original questions posed in the study:

Using the same constituent WEC design, how does the notional 9-A perform compare to either 9 isolated solo WECs, or 9 solo WECs placed in a close array of the same spacings without a platform?

q_{annual} values estimated using numerical simulations indicate that the park effect is limited ($q_{annual} \geq 0.86$) for 9-A fixed and floating MWAPs. Performance of clustered WECs in the same layout but not mounted on a platform is comparable. The lowest value of q_{annual} obtained is 0.86 (see Table 6), while $q_{annual} > 1.00$ and < 1.00 can be seen in individual sea-states (Table 7).

Which absorbers on the MWAP perform the best?

Modelling has confirmed that performance of absorbers does vary across the platform, although it is not possible to conclusively say which absorbers perform best. The absorbers that perform best appears to vary depending on the wave period and with the damping applied.

Simulations showed that under optimum damping conditions in irregular waves with periods Tp < 12.5s, the frontmost absorbers contributed a higher proportion of energy captured, while in the tank testing in regular seas with T < 14s and larger damping values, the rearmost absorbers contributed a marginally higher proportion of energy captured.

Does the performance of each MWAP absorber in the numerical simulations match what is seen in the tank?

Validation of the numerical simulations against the outputs of tank testing is ongoing. Currently, the energy captured by absorbers in the tank is heavily influence by the absorber 'personalities'[2], which results in these not able to reliably deliver comparable stroke excursions to those seen in the numerical simulations. An additional discrepancy is that subsequent investigation into control parameters has also identified that excessive levels of PTO damping were used within the physical model testing compared to the optimum values proposed in the numerical simulations, and these higher values would also have the effect of limiting absorber response.

Activities to strengthen the validation of the numerical simulation tools are ongoing and an area of the focus for a current PhD at the University of Edinburgh.

What layout(s) and configuration(s) of the platform can give improved performance compared to the same number of isolated WECs?

The 3-A configurations exhibit reduced park effects, with a higher q_{annual} than the 9-A, and a q_{annual} of 1.00 or higher for both the McCabe and De Backer constraint approaches. The 9-A has a q_{annual} <1.00 across all sea-states for

[2] Despite extensive troubleshooting, some absorbers and related power train continued to exhibit behaviour that was consider an outlier compared to the others. This is likely due to an accumulation of small variations in system build which are each indistinguishable in isolation.

the same settings. In the modelled scenarios, the difference in q_{annual} between an MWAP that is fixed or floating with a low-compliance mooring is very small.

Only a limited number of WEC layouts could be investigated at this time, and further exploration of different quantities and locations of absorbers on the platform may strengthen any observations made.

The decision on the number of absorbers placed on a platform will ultimately come down to overall cost of energy, so a comparatively lower q_{annual} could be acceptable if there is sufficient cost savings for the higher rated MWAP.

What orientation of the platform relative to the incident wave direction results in improved performance?

Assuming all power producing sea-states have the same wave direction, the annual energy captured by this MWAP or a comparable array without a platform appears insensitive to the direction incident long-crested waves arrive at (Section 4.2.5, Table 8).

How do various configurations of MWAP mooring and restraint influence power capture?

The modelling done on this is inconclusive. Simulations of the MWAP suggest that there is little difference in energy captured between a fixed and floating system. However, qualitative observations from parallel physical model tests conducted at FloWave have indicated that the destabilising influence resulting from changes in submerged volume of the absorbers cause the floating MWAP system to become unstable when using a more compliant mooring. This is a scenario that cannot be represented by the frequency domain modelling completed so far, which assumes the platform is intrinsically stable.

What PTO control settings delivers improved performance?

The code developed for the numerical simulations is capable of identifying the optimum control parameters (B_{PTO} and C_{PTO}) that result in the maximum power capture from an unconstrained WEC or absorber system in user-defined sea state or regular wave conditions. A separate investigation has identified suitable control parameters for a constrained WEC or absorber system, which ensure constraints are not breached during the simulation. Each of these optimum values from the simulation approaches has yet to be correlated against comparable tank testing runs.

Simple damping-only or reactive control strategies can be implemented on the developed systems, with the same control parameters currently applied to all absorbers on an MWAP or WECs in an array on sea-state by sea-state basis. Further refinement of the design to incorporate a realistic PTO and an optimised control strategy is expected to deliver further improvements in estimated energy capture. Absorber by absorber control may also offer opportunities to enhance power output.

6.2 Improvement opportunities

It is believed that the critical physical phenomena are captured sufficiently well by the numerical models developed in this study to gain a level of insight on comparative interaction effects required to address the study's specific questions. It is important however to recognise that any observations remain tentative due to simplifications and assumptions made in the physical and numerical simulations, and they could be improved in any follow-on activities.

The implementation of the physical model could be refined further to improve consistency and reliability of outputs. This could include

- Attempting to further **minimise any potential sources of friction** in the absorber and PTO system by replacing absorber dry bushings with roller bearings and utilising a wire or toothed belt for the PTO system instead of the spindle and taut line system.

- **Control of the absorber positioning**, either through active adjustment of the PTO mechanical spring preload to aid accurately set the absorbers at their mid-stroke, or having the capability of driving the absorbers in to desired positions using the control system.
- **Minimise the influence of cable bundles** on motions in a floating configuration by moving motor control and some signal conditioning onboard the MWAP, using for example the Sandia Labs MiniDAQ, thus reducing the size and weight of the cable bundle carried away from the system.

Further opportunities to enhance the physical test equipment may also be possible. Although the use of mechanical power as the basis for the analysis of tank testing is consistent with accepted practice (for example, [30]), this could be improved by **considering how the mechanical power translates to electrical output** once there is some knowledge or understanding of how a full-scale PTO generation system may be implemented. An advanced implementation of the air spring simulation, for example through a hybrid mechanical/motor system, would allow for a **more accurate replication of an air spring system and air spring interactions** between absorbers to be simulated, enabling the potential interactions that drive power captured and absorber dynamics to be explored in more detail.

Time domain modelling addressing nonlinear hydrostatics/hydrodynamics (including viscous damping effects) and nonlinear mechanical force effects should be investigated to assess what impact these have on the performance of the configurations considered. At present, the representation of the WEC and platform hydrodynamics is relatively simplistic, particularly in relation to representation of system nonlinearities as a linear frequency domain modelling approach was used. As a result, constraints on excursion, velocity, PTO force and instantaneous power can only be handled in a very approximate way, while the model also does not consider any of the nonlinear platform loads and moments resulting from compliant moorings and volume changing absorbers.

Control strategies that are applied to individual absorbers in isolation (e.g. independent control or coordinated control) and on a wave-by-wave basis could improve individual performance to enhance the overall MWAP power capture or maintain the level of power capture while still ensuring all absorbers are operating within their safe working limits. Control options considered in the modelling undertaken to date are relatively simplistic and focused on either damping-only or reactive control, with the same spring and damping parameters set for all absorbers on a sea-state-by-sea-state basis. Benchmarking the opportunities available through refined control would strengthen the confidence that the observations made in this study can be realised or improved upon.

While a pragmatic design rationale has been used in investigations undertaken to date to support comparative analysis, any subsequent analysis that focuses on optimisation of specific outputs should consider phenomena that will influence the performance of MWAP systems, such as platform stability, platform design and realistic full-scale moorings. This would include consideration of realistic absorber, platform, and mooring designs, ideally in the form of a **co-design approach**. An **optimised design** should build upon design considerations for platform structures that meet the specific needs of wave energy, such as those outlined in [31], while use of more **complex and representative WEC and absorber geometries** should be considered during subsequent optimisation and validation against physical modelling. While improving the quality of specific outputs, it would increase confidence in the representation of the floating MWAP configurations and the apparent low impact of the platform structure on the absorber interactions. Undertaking additional physical modelling that addresses **validation of the numerical simulations outputs** is being considered, with progress on this activity explored in [32].

A further step would be to explore the wider **techno-economic opportunities** associated with MWAP systems, which was outside the scope of this initial study. An attempt to quantify the manufacturing requirements, operations and maintenance, and system reliability improvements, and to consider these alongside the economic impact of the additional capital cost associated with any platform structure, will enhance the broader understanding about the attractiveness of any MWAP solution.

7 References

[1] Offshore Wind Consultants Limited, commissioned by Wave Energy Scotland, “Wave and Floating Wind Energy - Cost Benefit Analysis”, May, 2023, [Online]. Available: https://www.waveenergyscotland.co.uk/research-strategy/strategic-research/wave-and-floating-wind-energy-cost-benefit-analysis/

[2] N. McLean, E. Bannon, M. Holland, D. Forehand, T. Giles, K. Smith and T. Davey, “Multi wave absorber platform design, modelling and testing: Investigating the integration of multiple wave energy absorbers into a floating offshore wind platform considering a future wind and wave energy hybrid system”, in proceedings of the 15th European Wave and Tidal Energy Conference, Sep 2023, Paper 354. Draft version of paper available at: https://www.waveenergyscotland.co.uk/wes-media/european-wave-and-tidal-energy-conferences/ewtec-2023-bilbao/

[3] M. Holland, N. McLean, E. Bannon, D. Forehand, T. Giles, K. Smith, L. Jordan and T. Davey, “Comparison of interaction effects between multi-wave absorber systems”, in proceedings of the 16th European Wave and Tidal Energy Conference, Sep 2025, Paper 968.

[4] AWS Ocean Energy Limited. Public reports from AWS Ocean Energy’s WES NWEC projects during 2016 – 2022. [Online]. Available: https://www.waveenergyscotland.co.uk/wave-technology/novel-wave-energy-converter/advanced-archimedes-waveswing/

[5] P. Ricci, A.F.d.O. Falcão and J.B. Saulnier, “Point-absorber arrays: a configuration study off the Portuguese West-Coast”, Proceedings of European Wave and Tidal Energy Conference, 2007.

[6] H. Abdulkadir and O. Abdelkhalik. "Optimization of heterogeneous arrays of wave energy converters". *Ocean Engineering* 272 (113818), Mar 2023.

[7] M. Penalba, I. Touzón, J. Lopez-Mendia and V. Nava, “A numerical study on the hydrodynamic impact of device slenderness and array size in wave energy farms in realistic wave climates”, *Ocean Engineering*, 142, pp.224-232, Sep. 2017.

[8] G.P. Thomas and D.V. Evans, “Arrays of three-dimensional wave-energy absorbers”, *Journal of Fluid Mechanics*, 108, pp.67-88, 1981.

[9] M. Göteman, “Optimisation of wave farms”. Chapter 9 of D. Ning and B. Ding (ed). “Modelling and optimization of wave energy converters”, CRC Press, 2022, https://doi.org/10.1201/9781003198956

[10] G. Thomas, “Some observations on modelling arrays of wavepower devices”. In: Slideshow of presentation at NUIM wave energy workshop, Maynooth, Ireland, October 25th; 2011.

[11] A. Babarit, 2013. “On the park effect in arrays of oscillating wave energy converters”. *Renewable Energy*, vol. 58, pp. 68-78, Oct 2013.

[12] reNEWS. “Offshore Technology Yearbook 2021”, Jun. 16, 2022. [Online.] Available: https://renews.biz/media/25314/renews_oty2021.pdf

[13] Quest Floating Wind Energy LLC. “PDF database of FOWT technologies currently under development”, Jun. 2, 2023. [Online.] Available: https://questfwe.com/download/36372

[14] J. Cruz, M. Atcheson (ed), “Floating Offshore Wind Energy: The Next Generation of Wind Energy”, Springer, 2016.

[15] M. Borg, M. Walkusch Jensen, S. Urquhart, M.T. Andersen, J.B. Thomsen and H. Stiesdal, "Technical Definition of the TetraSpar Demonstrator Floating Wind Turbine Foundation", *Energies 13*, vol. 18, pp. 4911, Sep. 2020. Available: https://doi.org/10.3390/en13184911

[16] École Centrale de Nantes. “HP_Flow – Hydrodynamic modelling heave-plates for floating wind”, Mar. 7, 2025. [Online]. Available: https://www.weamec.fr/en/projects/hp_flow/

[17] Magnora Offshore Wind. “Successful application in ScotWind leasing round”, Mar. 7, 2025. [Online]. Available: https://www.magnoraoffshorewind.com/2022/01/17/magnora-offshore-wind-successful-application-in-scotwind-leasing-round

[18] Magnora Offshore Wind. “Talisk Offshore Wind Project”, Mar. 7, 2025. [Online], Available: https://www.magnoraoffshorewind.com/talisk/

[19] ABPmer “UK Renewable Atlas”, Oct. 22, 2022. [Online]. Available: https://www.renewables-atlas.info/

[20] N. Raillard, S. Chabot, C. Maisondieu, D. Darbynian, G. Payne and L. Papillon. “Resourcecode Toolbox. Datapoint 277698”, Sep. 22, 2022. [Online], Available: https://gitlab.ifremer.fr/resourcecode/resourcecode

[21] Marine Scotland. “Marine Scotland Maps”, Mar. 7, 2025. [Online]. Available: https://marinescotland.atkinsgeospatial.com/nmpi/

[22] G. De Backer, M. Vantorre, C. Beels, J. De Rouck and P. Frigaard, "Power absorption by closely spaced point absorbers in constrained conditions", *IET Renewable Power Generation 4*, vol. 6, pp. 579-591, Nov 2010.

[23] G. Bacelli, P. Balitsky. and J.V. Ringwood, “Coordinated control of arrays of wave energy devices – benefits over independent control”, *IEEE Trans. on Sustainable Energy*, Vol.4, No.4, pp 1091-1099, 2013.

[24] P.B. Garcia-Rosa, G. Bacelli and J.V. Ringwood. “Control-informed optimal array layout for wave farms”, *IEEE Transactions on Sustainable Energy*, 6(2), pp.575-582, 2015

[25] A. Pecher, J. Kofoed (ed.), “Handbook of Ocean Wave Energy”, Springer, 2017

[26] Rhino3D. Oct. 24, 2024, [Online.] Available: https://www.rhino3d.com/

[27] A.P. McCabe, “Constrained optimization of the shape of a wave energy collector by genetic algorithm”, *Renewable Energy*, 51, pp. 274-284, Mar 2013.

[28] Orcina. “ORCAFLEX Extreme value statistics theory”, Mar. 20, 2025. [Online.] Available: https://www.orcina.com/webhelp/OrcaFlex/Content/html/Extremevaluestatisticstheory.htm

[29] A. Cotten, and D. Forehand, “Numerical simulation of a full spine of Edinburgh Duck modules in uni-and multi-directional irregular wave climates, with a view to design optimisation”, *Ocean Engineering* 285, p.115214, 2023.

[30] International Electrotechnical Commission, IEC TS 62600-103:2024, “Marine Energy - Wave, Tidal and Other Water Current Converters – Part 103: Guidelines for the early stage development of wave energy converters -Best practices and recommended procedures for the testing of pre-prototype devices”.

[31] Blackfish Engineering Design Limited, commissioned by Wave Energy Scotland, “Wave Energy Cluster Concept Design report”, Mar. 18, 2025, [Online]. Available: https://www.waveenergyscotland.co.uk/research-strategy/strategic-research/wave-energy-cluster-concept-design/

[32] T. Giles, T. Davey, D. Forehand, L.B. Jordan, M. Holland, N. McLean, E. Bannon, “Experimental validation of pressure differential wave energy converters on a versatile floating platform using advanced experimental techniques”, in proceedings of the 16th European Wave and Tidal Energy Conference, Sep 2025, Paper 973.