Comparison of interaction effects between multi-wave absorber systems

M. Holland, N. McLean, E. Bannon, D. Forehand, T. Giles, K. Smith, L. Jordan and T. Davey

Abstract—**Floating offshore wind (FOW) farms are being proposed in areas with an attractive wave climate, which could lead to future opportunities for co-location of FOW turbines with wave energy converters (WECs). An increase in the comparative rating of a single wave energy system would enhance the attractiveness of wave energy as part of this co-location opportunity. This study has investigated one approach to achieving this, by evaluating multi-wave absorber platform (MWAP) layouts using frequency domain modelling. Different layouts of a notional MWAP approach have been compared against solo isolated WECs and a comparatively spaced, densely clustered array. Outputs have considered how interaction effects influence the relative annual performance of a complete MWAP and on an absorber-by-absorber basis within the platform. Amongst the considerations evaluated are methods of system restraint, orientation to incoming wave direction, and approaches to handle constraints on the absorber response within frequency domain modelling. Annual q-factor values for this manifestation of a 3-absorber and 9-absorber MWAP with constrained characteristics, compared to isolated solo WECs, are ≥1.00 and ≥0.86 respectively. On a sea-state by sea-state basis, both constructive interactions and destructive interference are evident. The MWAP shows minimal sensitivity to orientation, with annual captured energy within 1.5% for all configurations and orientations. The study concludes by presenting several opportunities to progress and increase confidence in the observations.**

Keywords—**Multi-absorber, platform, cluster, array, wave energy, wave energy converter, interaction effects**

I. INTRODUCTION

AN increasing numbers of floating offshore wind (FOW) farm projects are being proposed in locations with an attractive wave energy resource, leading wave energy converter (WEC) developers to investigate how their prospective developments could be co-located to take advantage of opportunities to better utilise the available sea-space, share infrastructure and introduce supply chain collaboration opportunities [1] with the ultimate aim of reducing the cost of energy.

Significant challenges with the co-location of wave and wind energy include the comparatively low ratings of many WEC technologies (<1MW) compared to those of FOW turbines (15MW+), and their smaller physical dimensions. These are two elements that can create difficulties with specifying shared infrastructure of a project, such as vessel sizes or electrical cable ratings. A potential solution to increase the rating of the wave energy system, or to increase its physical size, is to devise a multi-wave absorber platform (MWAP). This could support many WEC absorbers to deliver multi-MW capacity, and potentially provide cost savings through sharing of mooring, electrical and ancillary infrastructure [2]. Although MWAPs could be designed in such a way as to allow future integration of wave and wind technologies on a single platform, for the foreseeable future, it is expected that separate platforms for wind and wave technologies will be favoured from a technical risk and economic standpoint [1].

Clustering of WECs in a densely packed area, regardless of being on a platform or otherwise, introduces questions on the WECs' interaction effects, performance impacts, and sensible baselines for design parameters. This project investigated these aspects through a combination of numerical modelling and tank testing. The background to the overall project, design decisions, and preliminary set-up of the numerical and physical modelling for this study have previously been reported in a paper, McLean et al. [2] presented at the European Wave and Tidal Energy Conference in 2023.

A. Project

This collaborative study into conceptual attractiveness of a MWAP, run in conjunction with the University of Edinburgh, looked at how energy captured by a notional MWAP system (shown in Fig. 1.) is affected by hydrodynamic interactions between the absorbers, and

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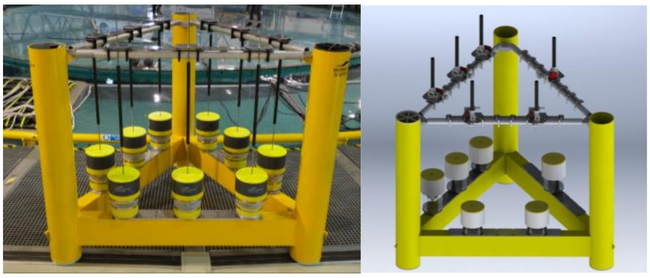

Fig. 1. (left) 1:50 scale physical model of the 9-absorber MWAP built for tank testing and used as the basis for the numerical simulations undertaken, and (right) image of Solidworks model of the notional MWAP system, illustrating how 1, 2 or 3 absorbers could be attached to each horizontal beam of the platform

between the absorbers and the platform columns. Alternative MWAP and array configurations have been compared to equivalent isolated solo WECs to gain an understanding on whether MWAP-type solutions have merit from a purely performance perspective. Wave resource data for a proposed floating offshore wind farm has been used as the basis for sea-states used in both the physical and numerical modelling.

The intention was to gain an understanding of the influence of interaction effects on the performance of the MWAP used in this study, 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 initial outputs demonstrated that impact on energy captured was limited. As the simple WEC-type selected for the MWAP lacked a defined approach for the conversion of captured power to electrical power, this study has considered energy captured by the system as a proxy for performance. Physical model testing of a 1:50 scale MWAP was undertaken in the FloWave Ocean Energy Research Facility at the University of Edinburgh, in parallel with a frequency domain model developed by the University where a number of MWAP configurations can be analysed in a realistic wave energy resource. This paper focuses on the numerical modelling outputs and observations.

To focus the investigation and advance understanding of the system, four key questions were posed for the study:

1. Using the same constituent WEC design, how does the notional 9-absorber MWAP 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. What configuration(s) of the platform can give improved performance compared to the same number of isolated WECs?

3. What orientation of the MWAP or WEC array relative to the incident wave direction results in improved performance?

4. How do various types of MWAP mooring and restraint influence power capture?

TABLE I
BASELINE ABSORBER CHARACTERISTICS AT MODEL SCALE (1:50)

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

The general terminology used throughout this paper 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 on a platform where some of the subsystems and structure are shared.

II. NUMERICAL MODEL

B. Design rationale

1) Platform

The platform design for the MWAP system considered in this investigation 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.

A review of FOW platform designs appearing in the public domain was conducted, with the 2021 Offshore Technology Yearbook [3] showing considerable variation spanning semi-subs, tension leg or spar types. A generic design was identified, with indicative dimensions established using [4], [5] and [6] and refined through informal discussions with FOW platform developers.

The platform has been assumed to be an equilateral triangle semi-sub with three vertical corner columns, and with 3-absorber platform (3-A) and 9-absorber platform (9-A) layouts having 1 and 3 absorbers per platform side respectively. A key design compromise is to space the absorbers appropriately to mitigate against the potential impact of destructive interference on the annual average energy capture, as originally argued by [7], while also maintaining a reasonable platform size that is comparable with the FOW proposals. Observations on spacing effects from previous modelling had been used as a rough guide, with the minimum spacing between absorbers, corresponding to the 9-A layout, assumed to be 4 absorber radii. This is in line with the findings of [8], where “device performance becomes practically independent of the spacing *d* for *d* larger than about four [absorber] radii”, and is close to the recent findings of [9], where an optimal spacing between an array of 3 homogenous WECs was found to be 5.54 radii.

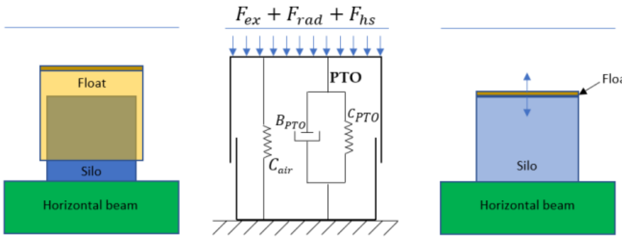

Fig. 2. (left) Schematic of the physical realisation of the modelled absorbers on the MWAP, (middle) reactive control free-body diagram, and (right) illustration of the realisation of the modelled absorber in the frequency domain modelling, where the float is modelled by a moving upper surface above a silo that extends and contracts accordingly.

The three vertical corner columns have the same radius as the absorbers to ensure they have comparable blockage effects. This results in full-scale centre-to-centre spacings of 40m and 20m for the 3-A and 9-A layouts respectively, and a total length per platform side of 90m.

2) Absorbers

The WEC system that provided the basis for the absorbers in the study was a submerged pressure differential WEC, similar to the Waveswing which was developed by AWS Ocean Energy through the Wave Energy Scotland Novel WEC programme [10]. However, it is expected that learnings from this study can also be in part qualitatively transferable to other types of devices that could be deployed as part of an MWAP, such as conventional point absorbers.

The absorber of the WEC system consists of a submerged telescoping can made up of an upper cylinder ("float") and a lower cylinder ("silo"). For MWAP layouts, these absorbers are mounted to the platform's horizontal beam, as shown in Fig. 2. 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 power take-off (PTO) and the restoring force provided by the internal air spring combined with the hydrostatic spring (Fig. 2. (middle)), allowing wave power to be captured. The absorbers are assumed to have a range of characteristics, shown at model scale in Table I, which are used for the implementation of constraints. Two instantaneous maximum power limits were used to give an indication of the impact on energy capture of alternate hypothetical power ratings.

The numerical model uses a simplified geometric shape for the float (Fig. 2. (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.

3) System restraint

Two mooring and restraint systems were considered for the platform layouts. The first of these systems represents a piled 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").

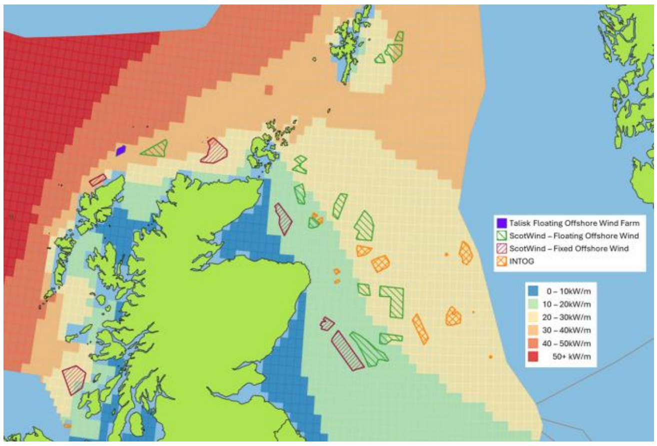

Fig. 3. Floating and fixed offshore wind farm lease sites in Scottish waters awarded in May 2023 displayed along with annual average wave resource, with resource data from the UK Renewable Atlas [11]. The Talisk Floating Offshore Wind Farm, used in this study, is highlighted.

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.

In addition, 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").

4) Control

This initial investigation has considered two strategies of diagonal sea-state by sea-state control, where the PTO damping (B_{PTO}) and spring (C_{PTO}) parameters for a given sea-state are applied identically to each absorber. These two strategies are PTO damping-only control, where C_{PTO}=0 and B_{PTO} is varied, and PTO reactive control, where both C_{PTO} and B_{PTO} are varied.

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

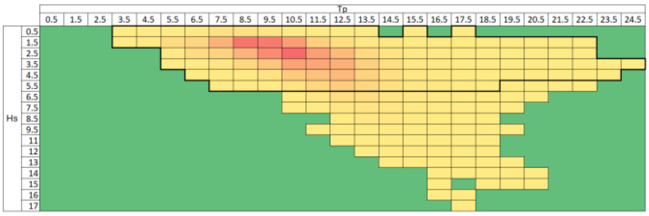

Fig. 4. Wave scatter table for the Talisk Floating Offshore Wind Farm site determined using sea-state time series downloaded from the RESOURCECODE database and using sea-states bins of $0 \leq H_{mo} < 1.0$ and $0 \leq Tp < 1.0$. The subset of 101 sea-states used for the comparison between constraint approaches are contained within the bordered area.

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.

5) Resource

The scatter table for the reference site used in this study (Fig. 4.) corresponds to the ScotWind lease site being developed by Magnora Offshore Wind as the 500MW Talisk Floating Offshore Wind Farm [12], [13]. This was considered to have an attractive energy resource for wave energy, with the annual average incident wave power estimated to be 61.4kW/m using data from RESOURCECODE [14]. Depths at the site are estimated to be 106m-125m using the Scottish National Marine Plan Interactive (NMPi) [15], which closely matches the target water depth of 100m that allowed parallel tank testing at 1:50 to be completed in the FloWave facility.

Main simulations used the full scatter table, while a subset of 101 power producing sea-states, corresponding to 94.4% of the annual occurrence and an annual average incident wave power of 42.5kW/m, were used specifically for the comparisons of results between two constraint handling approaches that are investigated. The subset corresponds to conditions that are anticipated to be within operational limits for power production for WEC devices and shortened the time to run each simulation set.

III. MODELLING APPROACH

C. *Model summary and configurations*

The numerical simulations were set up for four layouts of wave systems, shown in Fig. 5., with each having two restraint configurations, “fixed” or “floating”, as described in the previous section.

Incident wave angles 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 angle does not have any influence on the outputs of this layout.

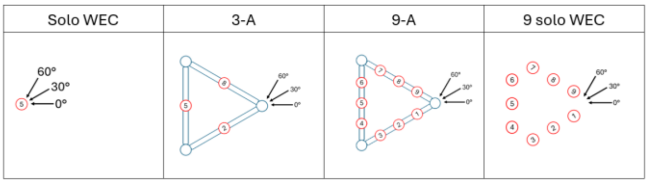

Fig. 5. Model layouts considered in present study, with absorber numbering and incident wave angles shown.

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 Fig. 6.

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 to estimate power capture for the configuration of interest utilising the imported WAMIT calculated hydrodynamics characteristics. 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. 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 [16] to estimate a constrained captured power for the MWAP in user-defined sea-state conditions.

D. *Equation of motion*

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

$$\begin{aligned}\{(\mathrm{C_{hs}} + \mathrm{C_{air}} + \mathrm{C_{PTO}} + \mathrm{C_{moor}}) - \omega_n{}^2(\mathrm{M} + \mathrm{A}(\omega_n)) \\ + i\omega_n(\mathrm{B}(\omega_n) + \mathrm{B_{PTO}})\}\vec{\mathrm{X}}(\omega_n) \\ = \mathcal{A}_n \vec{F}_{ex}(\omega_n, \theta)\end{aligned} \quad (1)$$

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

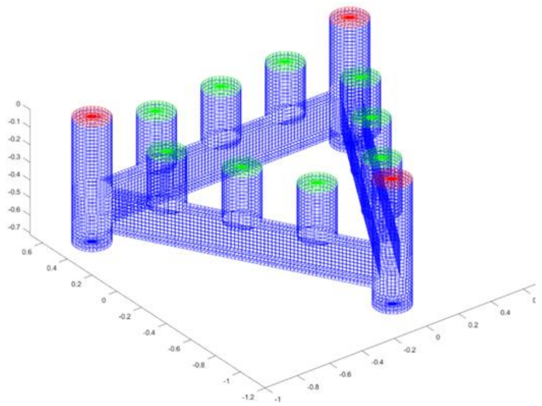

Fig. 6. Panelisation of the 9-A layout. Panelled surface highlighted in green indicate the surfaces to which generalised modes have been applied – one generalised mode per absorber. Red indicates where the MWAP columns pierce the water surface

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 $\mathcal{A}_n$ is the complex amplitude of the incident wave component with an angular frequency ω_n for the incident irregular wave train:

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

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:

$$\eta(x,y,t) = \sum_{n=1}^{N} |\mathcal{A}_n| sin(\omega_n t + Phase(\mathcal{A}_n) - k_n x cos\theta - k_n y sin\theta) \tag{3}$$

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

$$\omega_n{}^2 = g k_n\, tanh(k_n h) \tag{4}$$

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

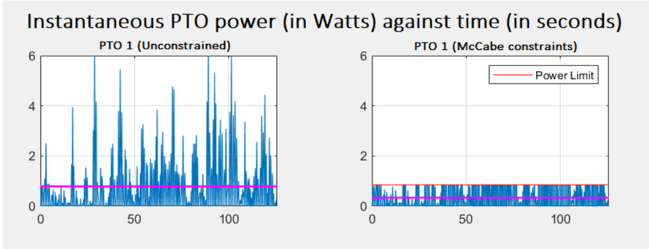

Fig. 7. Instantaneous PTO power for absorber 1 of the 9-A fixed configuration, using reactive control in a sea-state of H_{mo} 0.07m, T_p 1.77s. (left) shows the unconstrained system and (right) shows the system when McCabe is applied with the lower instantaneous power limit.

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).

6) McCabe

The approach originally proposed by McCabe [16] 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:

$$P_{i,xlim} = \begin{cases} P_i(t)\ if\ |x_i(t)| \le x_{lim} \\ 0\ if\ |x_i(t)| > x_{lim} \end{cases} \tag{5}$$

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

$$P_{i,plim}(t) = \begin{cases} P_{i,xlim}(t)\ if\ P_{i,xlim} \leq P_{lim} \\ P_{lim} if P_{i,xlim}(t) > P_{lim} \end{cases} \tag{6}$$

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 thew 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 (Fig. 7.). The post-processing approach also gives no indication of a real control strategy that may enable this performance to be achieved.

7) 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 [17] 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 [18]. 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 [17]. It could also feasibly be used for the multi absorber system coordinated control strategy considered by Bacelli et al. [19] and Cotten et al. [20]. 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 [17] 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.

TABLE II
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

In application of the extreme response theory described by [18], the extreme amplitude for each response variable has been estimated using [18, equation 3] 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 that used optimised PTO control parameters identified using the De Backer method.

The search space for reactive control parameters assumed in the De Backer constrained optimisation was -59.04N/m ≤ C_{PTO} ≤ 900N/m and 0Ns/m ≤ B_{PTO} ≤ 10Ns/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.

TABLE III

Q_{ANNUAL} ACROSS A SUBSET OF 101 POWER PRODUCING SEA-STATES FROM THE SCATTER TABLE FOR THE TALISK SITE AT INCOMING INCIDENT WAVE ANGLE 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*	-	-	-

8) *Critical appraisal of McCabe and De Backer methods of handling constraints*

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.

F. *Measurement of interaction effects*

For any multi-absorber wave array there is a separation distance beyond which the individual absorbers will act as if they are independent of one another with no interactions. As discussed, spacing in this way is likely to be impractical on an MWAP or in a real wave farm due to a multitude of practical considerations, so some form of interference termed the park effect [21] should be expected where the total power from n absorbers on an MWAP is less than n times the power of an isolated WEC. [22] notes that although constructive park effects are theoretically possible, it is unlikely in real conditions due to limitations in the theoretical analysis, "such as nonlinear viscous multi-directional waves, nonlinear computation of hydrodynamic forces, realistic PTO models and realistic control strategies." Park effects are quantified using the q-factor, defined here on a sea-state and annual basis as:

TABLE IV

Q VALUES FOR (TOP) THE 3-A FIXED AND (BOTTOM) 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 ANGLE OF 0°.

		T_P				
		6.5	8.5	10.5	12.5	14.5
H_s	1.5	0.90	0.97	0.99	1.01	1.02
	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
H_s	1.5	0.57	0.69	0.79	0.86	0.93
	2.5	0.73	0.83	0.90	0.97	1.01
	3.5	0.82	0.89	0.95	1.01	1.05

$$q = \frac{\sum_{\mathrm{i}=1}^{\mathcal{N}} P_{\mathrm{i}}}{\mathcal{N} P_{\mathrm{solo}}} \tag{7}$$

$$q_{\mathrm{annual}} = \frac{\sum_{\mathrm{i}=1}^{\mathcal{N}} E_{\mathrm{i,annual}}}{\mathcal{N} E_{\mathrm{solo,annual}}} \tag{8}$$

where P_i is the captured power in a sea-state for absorber i, $\mathcal{N}$ is the number of the absorbers in the array, P_{solo} is the captured power in a sea-state for a solo WEC in isolation, $E_{i,annual}$ is the annual energy captured in all power producing sea-states by absorber i of the array, and $E_{solo,annual}$ is the annual energy captured in all power producing sea-states by a solo (identical) absorber in isolation.

A q-factor > 1.00 is when power production is considered to benefit from constructive interaction between absorbers, with q-factors < 1.00 when the configuration suffers from destructive interference.

One shortcoming of q and q_{annual} is that they do not capture the distribution of power capture between absorbers across a multi-absorber system. For example, q-factors greater than 1.00 for a whole system could be obtained despite some absorbers being comparatively inactive. This is addressed by also utilising an absorber-by-absorber q-factor, $qa_{i,annual}$, defined for absorber i as

$$qa_{i,annual} = \frac{E_{i,annual}}{E_{solo,annual}} \tag{9}$$

TABLE V

RATIO OF ANNUAL ENERGY CAPTURED IN AN 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	Angle 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

TABLE VI

MEAN ABSORBER-BY-ABSORBER $QA_{I,ANNUAL}$ ACROSS THE FULL TALISK SCATTER ASSUMING LONG-CRESTED HEAD SEAS (I.E. A 0° ANGLE 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

IV. OBSERVATIONS

G. 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 II. 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 III 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 (Fig. 4.). q_{annual} reduces for both a higher instantaneous power limit and implementation of the De Backer approach, but is still 0.86 or larger.

H. 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 in Table IV, 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 III).

I. Platform orientation

The incoming wave angles considered took advantage of the platform symmetry, with long-crested waves able to arrive at either 0°, 30°, or 60° (see Fig. 5.). The total annual energy that could be captured at the selected site was compared assuming all sea-states arrived from the same angle. The solo WEC was assumed to be directionally insensitive, so it was 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 V), 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.

J. Absorber by absorber behaviour

Not all absorbers contribute equally to the performance of the MWAP. The spread of $qa_{i,annual}$ by absorber positions shows the largest contribution to annual energy capture comes from the frontmost absorbers (Table VI). While this may change on a sea-state by sea-state basis depending on wave period and directionality, similar to Table IV, the indication on an annual basis using a constant wave incident angle 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 VI).

The differences in $qa_{i,annual}$ values for the absorbers between a fixed and floating platform are also very small, suggesting that both the layout and the effect of applying constraints on interaction effects are more pronounced than whether the platform is fixed or floating. Larger

$q_{ai,annual}$ are seen for reactive cases, where the total spring for each absorber can be tailored on a sea-state by sea-state basis.

K. Key outcomes

The primary high-level observation from the study 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 ($q_{annual} \geq 0.86$).

An important caveat on these observations is 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. 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-absorber MWAP 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 modelling 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 III), while $q_{annual} > 1.00$ and < 1.00 can be seen in individual sea-states (Table IV).

What 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 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.

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 appears insensitive to the angle incident long-crested waves arrive at.

How do various types 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 mooring. However, qualitative observations from parallel physical model tests conducted at FloWave have indicated that the destabilising influence resulting from changes in volume of the absorbers cause the floating MWAP system to become unstable with 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.

L. 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 modelling simplifications and assumptions made, and they could be improved in any follow-on activities.

More focused investigations should consider **time domain** modelling to address nonlinear hydrostatics/ hydrodynamics (including viscous damping effects) and nonlinear mechanical force effects 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 loads and moments on the platform including for example those 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 [23], 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 modelling outputs** is being considered, with progress on this activity explored in [24].

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 operations and maintenance, manufacturing, 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.

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