Multi wave absorber platform design, modelling and testing

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

Abstract - **The subject of this paper is the development of physical and numerical models and a tank test programme to investigate the performance of a multi wave energy absorber platform (MWAP). The platform is inspired by the proposed designs for large scale platforms to be used for floating offshore wind (FOW). The modular design of the physical model enables a variable number of absorbers to be mounted to the platform, with up to 9 absorbers tested simultaneously. The absorbers used are a simplified version of a submerged pressure differential device, with each absorber incorporating a set of mechanical springs to approximate the response of the real internal air spring. Physical model tank tests will be undertaken during 2023, utilizing a range of environmental conditions representative of those at an exposed site on the west coast of Scotland, leased through the ScotWind programme and which has an appropriate water depth and wave resource for large scale wave energy exploitation. Measurements taken during physical model testing will be used to validate numerical models of the MWAP and will allow subsequent investigation of key drivers of annual energy performance, exploring platform configuration options not tested in the wave tank. The motivation for this project, design considerations and balance between tank scale & full-scale design requirements will be given. Discussion will be provided on the implications of the limitations and assumptions made during the physical and numerical modelling work, as well as next steps for utilisation of the tools beyond the scope of this project.**

Keywords – **floating wind, numerical modelling, tank testing, wave energy, wind energy.**

1 Introduction

FLOATING wind is heading rapidly towards commercialization with a number of floating offshore wind (FOW) turbine prototypes already being tested in various countries. Within the United Kingdom many sites have been made available for development of large-scale floating wind projects through several leasing rounds including ScotWind, INTOG and Celtic Sea which may provide upwards of 15GW installed capacity. Several of these leased sites have characteristics which may support hybrid or versatile platforms in the future. A *versatile* platform is one designed for mass production and enables integration with either wind turbines or wave energy devices. A *hybrid* platform takes the integration a step further with both wind and wave on the same structure.

There are some clear synergies between the technical requirements and suitable location for floating wind and wave energy that will provide opportunities for the two sectors to learn from one another and facilitate cost reduction. There may also be potential opportunities for FOW and wave energy converter (WEC) developers to collaborate for mutual benefit, sharing a range of elements of a whole project.

Opportunities exist for *close-location* of projects, where a wind and wave farm are developed close by allowing for some sharing of some offshore infrastructure, or on-shore facilities; *co-location* of projects, with technologies occupying the same lease area and sharing inter-array infrastructure; or *versatile/hybrid* projects with technologies mounted on to a common platform, sharing a majority of onshore and offshore infrastructure, and facilities.

As a result, Wave Energy Scotland has commenced investigations to try and understand which of these opportunities could offer the most benefit for the floating offshore wind and the wave energy sectors. This investigation has so far explored two strands covering both economics of combined projects, and the performance of versatile/hybrid platforms.

In the first strand of this investigation, Wave Energy Scotland has collaborated with Offshore Wind Consultants (OWC) to produce a high-level techno-economic model to assess a wide range of potential collaboration opportunities between wind and wave developers. A number of scenarios are explored ranging from sharing the consenting process for close-located projects, sharing of physical infrastructure such as cables and anchors, sharing port facilities and maintenance personnel through to fully integrated single project including both wind and wave technology.

Outputs of this work have recently been self-published by Wave Energy Scotland [WES].

One of the conclusions in this techno-economic work, in the context of the research reported in this paper, is that

This work has been fully funded directly by Wave Energy Scotland and contracted to FloWave. This project forms part of wider investigations into crossover and collaboration opportunities with the floating offshore wind sector. The paper was submitted to EWTEC 2023, but this is not the final version that will appear in the proceedings.

E. Bannon, M. Holland and Dr. N. McLean are at Wave Energy Scotland, An Lòchran, 10 Inverness Campus, Inverness, IV2 5NA, UK. (e-mail: info@waveenergyscotland.co.uk). Dr. T. Davey, T. Giles and K. Smith are at FloWave Ocean Energy Research Facility, The University of Edinburgh, Max Born Crescent, King's Buildings, Edinburgh, EH9 3BF and Dr. D. Forehand is at University of Edinburgh, King's Buildings, Edinburgh EH9 3BF.

many benefits can be realised without the need to use fully integrated hybrid platforms. A versatile platform, a term coined by OWC, provides cost reductions for both wind and wave energy elements of a combined project. One of the outstanding questions of the versatile platform idea raised by this OWC report is on the power performance aspects of a wave energy technology when mounted on a platform.

For the second strand of this investigation, presented in this paper, Wave Energy Scotland has collaborated with FloWave Ocean Energy Research Facility at the University of Edinburgh to develop the physical and numerical modelling capability to investigate the relative performance of a number of configurations of WECs mounted on to a versatile or hybrid floating platform.

1.1 Previous related research

Considerable research effort has been given to deployment of multiple WECs on generic platforms and on the type proposed for FOW. Mostly the work considering deployment of WECs on FOW platforms has focused on inclusion of WECs on a hybrid platform where both technologies are deployed as a single system [HAN], [THO], [LEE], [YAZ].

Research carried out on deployment of WECs on more generic platforms has tended to focus on platforms facilitating closely packed arrays of absorbers [BAC], [GAR], [WEL].This latter research highlights the ability of cross-coupling effects (where motions in one degree of freedom provoke motions in other degrees of freedom through cross-coupling terms in the modelled system's equation of motion) to broaden a WEC's power production bandwidth compared to the bandwidth of a WEC system that operates without them. Cross-coupling effects are discussed in detail in [EVA].

Deployment of multiple absorbers on a shared platform can also facilitate use of shared infrastructure between multiple absorbers, potentially reducing costs discussed in more detail in [WES1].

Separately, considerable research effort has been devoted to modelling and testing of volume changing (submerged pressure differential) WECs of the type typified by the Waveswing currently being developed by AWS Ocean Energy Limited (see [DES], [VAN] and [AWS1] on numerical modelling, and [CRU1] and [AWS1] on physical testing). Following extensive scale model tank testing and new numerical modelling, a half-scale deployment took place in Scotland in 2022 through a programme funded by Wave Energy Scotland. This deployment tested innovations introduced by AWS to demonstrate evolution of Archimedes Waveswing since testing of the original prototype of this technology by Teamwork Technology BV in Portugal in 2004.

However, very little information is available on modelling (either numerical or physical) the deployment of Waveswing-type WECs on a platform. The closest similar work relates to multi-absorbers of the volume changing type which are horizontally rather than vertically activated, such as the Coventry Clam [BEL], the AWS III (a previous technology by AWS Ocean Energy [AWS]), and the C-HYP platform [SOU]. These devices seem again to benefit from cross-coupling effects (of the type discussed above), while the Coventry Clam/AWS III devices may also benefit from cross-coupling effects associated with air transport between individual absorbers in their inter-connected air system.

1.2 Project Outline

The work presented in this paper is part of the Multiple Wave Absorber Platform (MWAP) project started in October 2022 and includes numerical and physical modelling aspects. Basic platform and WEC designs were carried out in early months of the project, followed by development of the numerical model and mooring design. The physical model was built and commissioned in Spring 2023 with initial wave tank testing carried out in June 2023. Results of the testing are not available at the time of preparing this paper.

The project as a whole seeks to explore a number of high-level questions:

1. how does the performance of multiple absorbers mounted on a platform compare with the same absorber installed in isolation?
2. how is the performance of the absorbers influenced by their arrangement on the platform?
3. how is whole platform performance influenced by how the platform is restrained?
4. how directionally sensitive is the power performance of the whole platform?

This paper details work done to date for numerical and physical modelling and poses additional topics of interest for future investigation. External research by other organisations and industry is continuing at pace. These external findings may also influence the future or additional work undertaken by WES on the MWAP concept.

2 MWAP Characteristics

The basic design of the MWAP, show in Fig. 1, utilizes a platform with similarities to those being developed by the floating offshore wind sector, and a WEC with similar characteristics to the AWS wave energy technology supported through the Wave Energy Scotland programme.

2.1 FOW Platform types

Platforms being developed by floating offshore wind developers fall broadly into five types: (i) spar buoy; (ii) counterweight platforms; (iii) barge; (iv) semisubmersible (semi-sub); and (v) tension leg platform (TLP). Barge and semi-sub type platforms tend to be buoyancy stabilized, whereas TLPs are moorings stabilized, spar buoys are ballast stabilized and suspended counterweight platforms

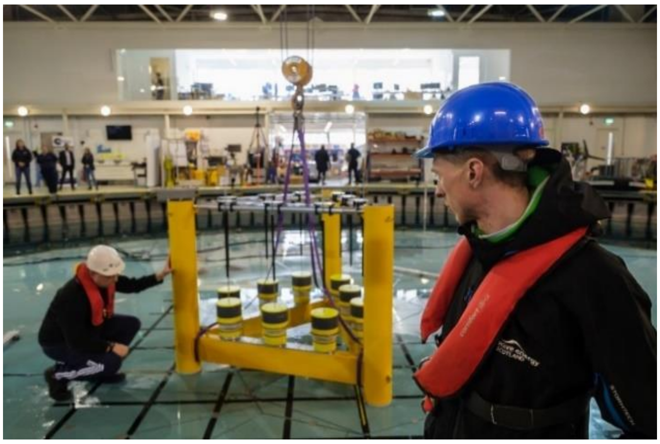

Fig. 1. Initial build of MWAP at FloWave. Main structure and 9 absorbers prior to installation of PTO and other instrumentation. Credit & Copyright: Mike Wilkinson, commissioned by WES.

are counterweight stabilized. (Pictures of these platform types are shown in Fig. 2.)

For the purposes of this project, a semi-sub type platform has been chosen based on a few key considerations. These are that this type of platform:

1. generally has sufficient on-platform space upon which multiple WECs could feasibly be mounted.
2. tends to be relatively versatile in terms of the range of water depths in which it can be deployed.
3. tends to have a structural design that minimizes the number of structural elements which can have a detrimental effect on power capture e.g., vortex shedding.

A review was carried out on designs of floating wind platforms which appear in the public domain. A useful reference for this topic is an annual industry publication from UK based renewable energy news agency reNEWS [REN]. The Offshore Technology Yearbook gives an overview of approximately 40 companies pursuing floating offshore wind platform design. Several common features of semi-sub designs were identified which fit the requirements for the design for the MWAP – triangular shaped platform, minimal water plane area, and horizontal beams suitable for mounting absorbers. In the future it is conceivable that a wind turbine may be mounted with its weight equally distributed across the three corners, as seen in some examples from [REN]. [QUE], [CRU] and [BOR] were also found to be useful in this exercise as they provide indicative dimensions for FOW platforms being developed.

Based on dimensions of semi-sub platforms publicly available, 10m diameter circular vertical columns and a centre to centre spacing of 80m was selected as a full-scale design. A 10m diameter column is also consistent with full-scale WEC designs being proposed by AWS through work with Wave Energy Scotland, giving the same column and absorber diameter. This allows the model to maintain a 2x diameter centre to centre spacing between all absorbers and columns, which previous research has suggested minimizes interaction between them in an array [RIC]. In particular [BAB] notes that in numerical modelling of a

Fig. 2. Supporting platform types being explored by floating offshore wind project developers (Source: https://www.rwe.com/en/research-and-development/wind-power/floating-offshore-wind/floating-wind-education/).

small array of point absorbers, of comparable size to those considered here, in a real resource reported in [RIC], "device performance becomes practically independent of the spacing for separating distances greater than 4 radii (where the radii ranged between 2.5 and 10 m)", where the radii referred to is the point absorber radius.

The dimensions and cross-sectional shape of the lower beam on the tank model were selected to readily allow mounting of the absorbers and are not necessarily representative of a full-scale system. The overall dimensions of the platform and the absorbers at full-scale and 1:50 tank scale are given in Table I.

2.2 *Platform design for tank testing*

The priority configuration for investigation in this project is a 9-absorber platform, but other configurations will also be tested for comparison. As a result, a modular physical model design has been developed for the tank testing which enables a variable number of absorbers to be mounted to the platform.

There are a total of 21 different positions, with 7 on each side of the triangular structure and a maximum of 4 positions on each side that can be used simultaneously using the current absorber design. This flexibility allows for 9 of the current absorbers to be tested simultaneously using the target 2x diameter spacing, and for the arrangement to be optimized in the future based on findings from initial testing and numerical model runs.

It is also feasible to mount different types or different sizes of absorbers at these mounting positions, ensuring the platform can be used for additional projects beyond the scope of MWAP. Images of the platform are shown in Fig. 1 and Fig. 5.

With their ability to inhibit pitch and roll motions, heave plates are often seen as an attractive addition to semi-subs as they allow dynamic stability to be achieved with smaller and lighter platforms.

However, an important trade-off of using heave plates in a wave energy application is that they can, as well-illustrated in CFD modelling in [JIA], provoke vortex shedding which is often detrimental to wave power capture. Also, as vortex shedding is a viscous flow effect it

Table I Main MWAP dimensions. All units in metre (m)

	Full-scale	Tank scale
Platform corner column diameter	10	0.2
Platform corner to corner spacing	80	1.6
Lower beam width (rectangular section)	5	0.1
Lower beam height (rectangular section)	10	0.2
Absorber diameter	10	0.2
Absorber spacing centre to centre (assuming 9 absorber configuration)	20	0.4
Absorber operating stroke	5	0.1
Nominal absorber submergence (mid-stroke) *	5.5	0.11
* Target values range tested in tank		

is not straightforward to model either physically, as viscous flow effects generally don't Froude scale, or numerically, as most WEC modelling is based primarily on assumptions of potential flow.

As such, heave plates are not currently used in this project, but the platform has been designed such that heave plates can be added at a later date if additional suppression of platform motions is needed.

The reader should note that the test platform design is targeted at gaining insight about physics of absorbers on a FOW type platform, and it hasn't been optimized in any sense for full scale stability, dynamics or structural loading as the design of real platform would need to be.

2.3 *WEC type*

The absorbers used for this investigation are a simplified version of a submerged pressure differential device similar to that being developed by AWS Ocean Energy through the Wave Energy Scotland programme.

The absorber, both at model and full scale, consists of a submerged telescoping *can* made up of an upper cylinder ("float") and a lower cylinder ("silo") as shown in Fig. 3(a). Volume change of the absorber is activated by incident wave induced hydrodynamic and hydrostatic 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, as illustrated in Fig. 3(b), allowing wave power to be captured.

As illustrated in Fig. 3(c), PTO forces in the physical model are supplied by a motor connected by a taut line to the absorber. Each absorber also incorporates a mechanical spring to approximate the response of the real internal air spring. This moves 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. Use of compensation volumes to model the air spring of pneumatic WECs in scale tests and potential limitations of this approach are discussed in [PEC, Section 6.1.5]. Note, residual air in the scaled absorber is vented through the platform to atmosphere to prevent it impacting on the absorber dynamics.

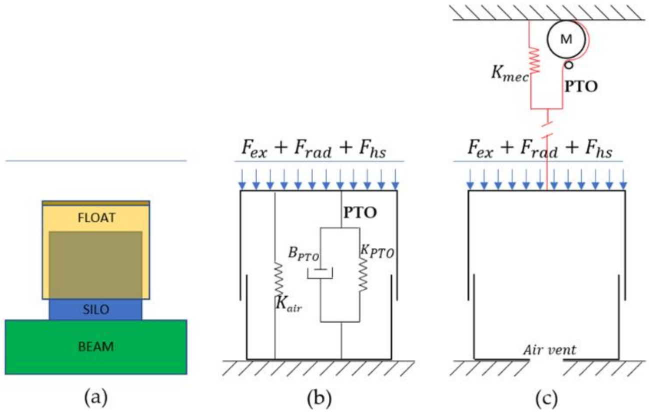

Fig. 3. Operating principle of actual and modelled absorbers. (a) shows schematic of absorber (float, silo and support beam), sitting below water surface, (b) and (c) show free-body diagrams of full scale and modelled absorber respectively. (Note in (b) reactive control is shown for illustration purposes only- K_{PTO} and B_{PTO} are the PTO spring and damping rates. Other types of control for this device type continue to be developed). F_{ex}, F_{rad} and F_{hs} are respectively the excitation, radiation and hydrostatic forces acting on the absorber float. K_{mec} is a mechanical spring rate providing the model scale equivalent to the full-scale air system spring rate K_{air}. The absorber connects to the motor and spring with a taut line.

In the physical model each absorber's PTO motor and mechanical spring – described together as the 'PTO block' in the remainder of this paper – is mounted directly above the absorber on the upper horizontal beam shown in Fig. 5. Further details on PTO block build and its functionality are provided later in the paper.

2.4 *Mooring, stability and restraint systems considered*

Semi-sub platforms, in both oil & gas and proposed FOW applications, typically employ a compliant mooring consisting of either catenary chain or taut/semi-taut low-axial stiffness synthetic lines (such as polyester or nylon) which allows the moored platform to shed load through motions of the platform.

To reflect this, a compliant taut mooring has been designed as one of the mooring options for the tank testing. The choice of a taut mooring over a semi-taut or catenary mooring was made based on the ease of deploying such a mooring in the tank and its potential use for this type of application within various sectors. [SOR], [WES2] and [WFO] all highlight considerable traction in use of compliant synthetic mooring in the marine renewable sector.

An important consideration for developers of wind turbines and/or wave energy converters on a FOW type platform is how platform motions might impact energy production and overall techno-economic feasibility. A further nuance for hybrid wind-wave systems is how wave energy extraction influences the platform motions, and in turn wind energy production or vice-versa. To attempt to isolate the impact of these motions, two additional types of restraints are considered in both tank tests and numerical modelling.

The first, and less realistic, of these is a restraint which completely inhibits all motions of the platform. In the tank tests this will be achieved by mounting the platform on a rigid frame, while in numerical modelling this will be achieved by setting all platform force, moment and motion parameters to zero in the equation of motion. Consideration of this configuration is twofold:

1. It allows more targeted troubleshooting of the absorber modules and power take off (PTO) systems to be undertaken.
2. It is expected to provide a useful benchmark for both tank test and numerical modelling on performance of the various absorber configurations where the platform is permitted to move.

The second is a tension-leg type mooring system where the platform is moored using inextensible near-vertical lines. While this mooring configuration is representative of the type of moorings which are utilized to moor tension leg platform (TLP) type FOW platforms, it may not a suitable mooring for a real deployment of the semi-sub MWAP. Semi-sub platforms normally utilize buoyancy restoring forces rather than mooring restoring forces as a TLP does. Nevertheless, although this mooring is considered unrealistic for a full-scale deployment of a MWAP semi-sub it provides a useful intermediate configuration for performance assessment between the compliant mooring and fully restrained platform configurations described above.

In particular, the tension-leg mooring:

1. Permits some motions of the platform (notably surge and sway motions), but the platform is more constrained than when moored with a compliant mooring system.
2. Inhibits heave, pitch and roll motions, ensuring the mean submergence position of the absorber remains at the target value.

Another interesting question that this work intends to explore is whether motions of the supporting platform (for example, pitch and roll motions) could enhance or impede the overall wave power production. As highlighted in previous research section above, such coupling effects can sometimes enhance the power capture capability of WECs.

Allowable pitch and roll motions of FOW platform are generally limited to ensure optimal functioning of the wind turbine. [CRU, p144] notes that for one FOW platform design "a maximum mean pitch/roll angle of 5 degrees +/- 15 degrees of dynamic amplitude" was tolerable. Thus, exploiting pitch and roll motions may be viable for WEC deployment on versatile platforms more than on a hybrid platform if these motions are detrimental to the power performance or loading on the wind turbine.

The aspiration of testing with three different proposed restraint systems is to gain insight into the extent to which power production is affected by platform motions.

2.5 *Reference deployment site and wave resource*

As part of the wider WES study into the combination of floating wind and wave energy, a high-level analysis of sites leased under the ScotWind offshore wind auction was carried out. Sites were assessed for their annual average incident wave power and water depth, to find a site which may be suitable for a wave energy array or deployment of a versatile platform. The site identified as most desirable for this study lies approximately 40km north of the island of Lewis, along the Scottish west coast, and has been leased to Magnora Offshore Wind AS for a 500MW floating wind array [MAG].

Initial estimates of water depth and annual average wave power were taken from Marine Scotland online Interactive National Marine Plan (https://marinescotland.atkinsgeospatial.com/nmpi/) and Marine Energy Atlas (www.renewables-atlas.info). Following initial site selection, RESOURCECODE datapoint 277698 was identified as being within the boundaries of the Magnora ScotWind Site. A full set of data was downloaded from RESOURCECODE database [RES] to get a more accurate estimate of annual average wave power and produce a site scatter diagram. This site scatter diagram was used to select appropriate sea states for tank testing and modelling. Water depth across the site varies from 106-125 metres, so a water depth of 100m is assumed for this project. Estimates of the annual average incident wave energy at this site vary according to which wave models were used to estimate this. The annual average of 61kW/m calculated from RESOURCECODE is used.

3 MODELLING

3.1 *Common basis for physical and numerical modelling*

Some high-level assumptions or simplifications have been required in the project in order to design suitable experiments and numerical models to answer the priority questions. It is acknowledged that the MWAP project is not designing a full-scale platform for production, but rather designing a set of tests which can inform next steps in the development of a platform suitable for mounting multiple wave energy absorbers.

The air spring component of the pressure differential absorber has been replaced with a linear mechanical spring in both the tank test and the numerical model with spring rate chosen to give an appropriate natural frequency at target submergence.

At the moment, only resistive PTO control is included but subsequent work may explore reactive control and wave-by-wave control strategies such as Optimal Velocity Tracking [STO].

Various cases will be considered and analysed to different levels of accuracy in either the physical or numerical modelling.

The high-level question which this project aims to answer is how the power performance of many absorbers on a platform compares to that of multiple single WECs. In this case, what is the comparative performance of 9 absorbers on a platform versus 9 isolated WECs? As

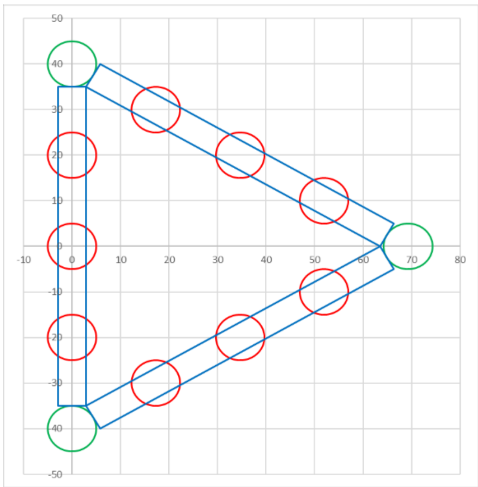

Fig. 4. Basic schematic of absorbers arrangement on the platform.

mentioned in earlier sections, there may be significant techno-economic advantages to developing a versatile or hybrid platform containing many absorbers, and so power-performance alone will not determine the commercial viability of a MWAP-style technology.

The platform designed for this project has not been optimized or directly scaled from a full-scale design, but instead has been developed as a useful experimental tool, allowing conclusions to be drawn on some fundamental questions.

The tank test model is 1:50 scale in order to appropriately match the tank water depth of 2m with that at the sample deployment site. It's acknowledged that various scale effects may influence the realism of model testing at this scale (such as viscous flow effects, correct scaling of inertia of a full-scale system, friction, stiction in PTO components etc.) so emphasis for data analysis will be placed on comparative performance between different configurations and not absolute figures.

Full scale designs for an MWAP-style technology are not publicly available, and so the most appropriate design has been chosen within this project to allow questions to be answered, provide initial conclusions and better inform future full-scale design.

The basic design of the WECs has come from AWS, but the experimental implementation has required design compromises, again suitable for tank testing but not representative of a full-scale design.

3.2 Platform and absorber build

The experimental design of the MWAP overcame a number of challenges in order to replicate the behaviour of the pressure differential wave converters at the selected scale, while also ensuring that they can be re-configured on the platform to allow different absorber arrangements and control strategies to be tested.

The baseline design parameters and sizing for the WECs and the platform were provided by WES, using a submerged pressure differential from the WES programme, and features of common triangular floating wind platforms under development.

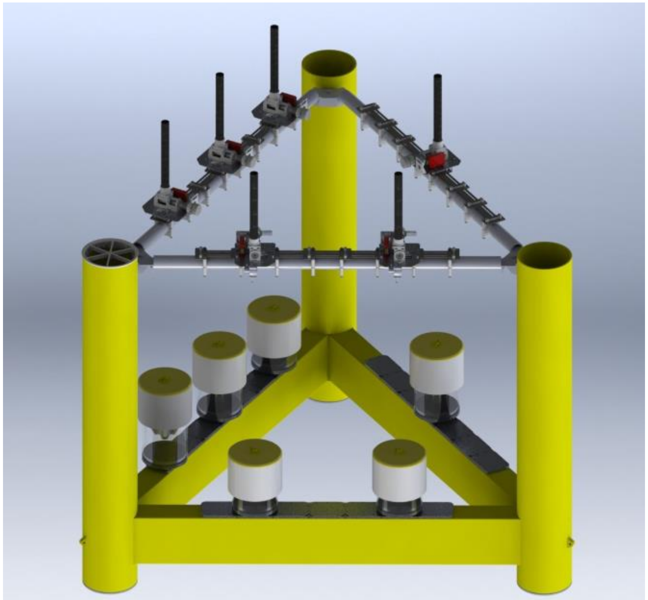

Fig. 5. SolidWorks 3D model of platform showing different arrangements of 1, 2 or 3 absorbers on each side. PTO components and instrumentation attached to upper beam (high above waterline).

A baseline configuration of 9 absorbers on the horizontal lower beam is shown in Fig. 1, with equal spacing between the 3 absorbers on each side and the vertical corner columns. Subsequent tests could focus on variations of this, as illustrated in Fig. 5. Fig. 5 also illustrates the upper beams added to the physical model, which allow for mounting of the PTO block equipment well above the water line.

The PTO block and control system were developed in order to be consistent with the requirement of a reconfigurable system. The instrumentation on the platform consists of one PTO block unit per absorber, connected through a custom control box and to the tank data acquisition system.

The key components of each PTO block are:

1. A mechanical spring designed to replicate absorber air spring response,
2. A motor drive and torque transducer to measure absorber response (mechanical power) and apply PTO control force,
3. A string potentiometer to measure absorber position.

The PTO block unit utilizes a brushless motor to deliver the control force on the absorber motions and allows virtually any control strategy to be specified within the limits of hardware. For example, FloWave are working on Optimal Velocity Tracking control on another wave energy research project and this could feasibly be implemented and tested using these PTO units. It also makes it feasible for a MWAP system with an interconnected air system to be simulated in tests with a software in the loop representation of air transport between absorbers.

However, in this initial testing campaign, the intention is only to model spring forces associated with each

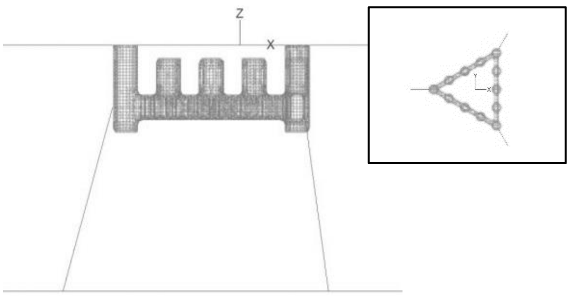

Fig. 7. Image from ORCAFLEX modelling showing TLP-style mooring analysed. Inset: plan view.

individual absorber's air system (supplied by the mechanical spring) and simple resistive (i.e. linear damping) PTO forces (delivered by the motor drives).

During tests, measurements of the position, velocity and torque out can be measured for each absorber. In-line load cells are also used to measure mooring loads while testing the MWAP with the taut complaint and TLP-type moorings. Qualisys is also being deployed to track the supporting platform's motions in all degrees of freedom.

The platform itself is a specially constructed rigid aluminium frame, with a machined surface on the top face of each lower horizontal beam. Holes in this top face enables multiple absorbers to be attached in a variety of positions. These holes also allow for air to pass from the absorbers, as they are compressed, into the hollow beam and corner column, venting to atmosphere reducing impact of residual air on system dynamics as discussed earlier in the paper.

The structure of each absorber comprised a mix of specially printed 3D features and common sizes of water hydraulic pipework. They were sealed against water ingress using an in-house fabricated rolling seal, using silicon rubber. Multiple materials were evaluated for the seal, covering varying degrees of pliability and compliance. Confirmation of the final sealing material will be available following extensive tank testing, ensuring longevity of the seal.

3.3 Mooring design and build

As discussed in earlier sections it is intended that platform tests and simulations will be conducted with three different restraint types:

1. With a rigid mounting frame attached to the tank floor
2. With a TLP-style mooring (see Fig. 6)
3. With a taut compliant mooring allowing platform to move more freely (see Fig. 7)

To support doctoral research being carried out at FloWave on use of mooring analysis software to design tank scale moorings, design of the TLP-style and compliant taut moorings has been done directly at 1:50 scale using ORCAFLEX, with the platform's hydrodynamic parameters across a range of frequencies determined using the ORCAWAVE potential flow solver.

The environmental design basis used in these analyses consists of the more energetic EuropeWave sea states.

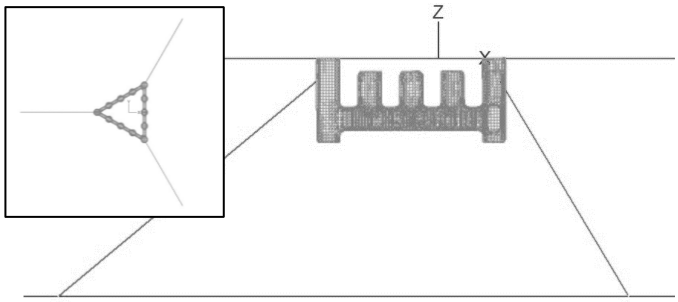

Fig. 6. Image from ORCAFLEX modelling showing 'compliant' mooring layout analysed. Note additional compliance in this case is provided by springs attached at line termination point (see Fig. 8). Inset: plan view.

Notionally these sea states are 1:25 scale, but when treated as 1:50 scale they are reasonably representative of the larger sea states frequently encountered at potential MWAP deployment sites.

Mooring design simulations have been done for the 9-absorber configuration of the platform in a notional survival state that assumes the absorber are locked in their mean positions. The actual survival mode for a full-scale MWAP may need to consider different absorber positions.

An iterative approach has been taken to determining appropriate design for each of the TLP-style and taut compliant moorings. The full parameter space and constraints considered in ORCAFLEX simulations are listed below:

- Parameter space
  - Number of lines: Three or six, forming three clusters of two lines each.
  - Angle between lines in cluster arrangement
  - Mooring stiffness: Determined by the choice of rope and/or inclusion of springs.
  - Seabed footprint: Varied declination angles to represent the maximum anchoring dimensions of the FloWave circular tank with the current platform geometry.

- Constraints
  - Limiting the minimum line tension to avoid snatch loads.
  - Limiting the peak tension loads to the capacity of the load cell instrumentation that will be used to measure mooring loads during tests.
  - Ensuring the feasibility of installation in the FloWave circular tank.
  - Using standardized and readily available materials and components.

Based on the analyses done, the layouts shown in Fig. 6 and Fig. 7 have been identified for testing in the tank.

In installation of both mooring options, individual mooring lines (HMPE lines) will be laid and instrumented as shown in Fig. 8 with line angles specified according to respective designs. In the case of the compliant taut moorings, springs are added at tank side terminations of lines to soften their axial stiffness.

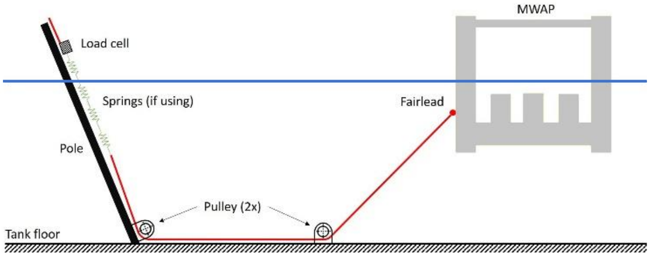

Fig. 8. Schematic of mooring implementation in the tank with waterline in blue.

3.4 Outline testing plan

FloWave Ocean Energy Test Facility at the University of Edinburgh is used for tank testing and is conducted in compliance with the IEC 62600-103 Pre-Prototype Testing [IEC]. Testing will consist of both regular and irregular sea states, including:

1. Three sweeps of 10 regular waves at a constant steepness,
2. 12 irregular, long-crested sea states, defined with Pierson-Moskowitz spectra.

The regular wave sweeps will each be run at 12 directions in 30° intervals around the full circumference of the model, allowing for characterisation of the behaviour of all absorbers.

To select the most appropriate irregular sea states, the occurrence scatter for the Magnora ScotWind site was initially compared to the full-scale equivalent of the 19 irregular sea states previously calibrated at 1:25 as part of the EuropeWave programme. Of these EuropeWave sea states, 5 were selected to be used in this project. 7 other sea state conditions were identified to provide coverage of the frequently occurring conditions in the reference scatter.

The 12 irregular sea states will each be run at 0°, 30° and 60° relative to the defined orientation of the platform, to understand the influence of directionality and whether different patterns in absorber performance emerge due to wave direction.

A sweep of PTO damping values (with the same value specified for all absorbers) will also be undertaken in these regular and irregular tests to understand how system performance is affected by PTO control. The frequency sweeps at one damping value will be repeated at the end of the campaign to monitor changes in absorber behaviour.

These tests will be initially run for a platform with 9 absorbers and for each of the three mooring configurations outlined above. Subsequently, the fixed platform will be tested with only 3 absorbers.

3.5 Numerical Modelling

In parallel with the physical model build, numerical models for various MWAP and solo WEC configurations are being developed covering:

1. The single WEC case
2. 9 absorbers on the platform
3. 9 WECs with no platform

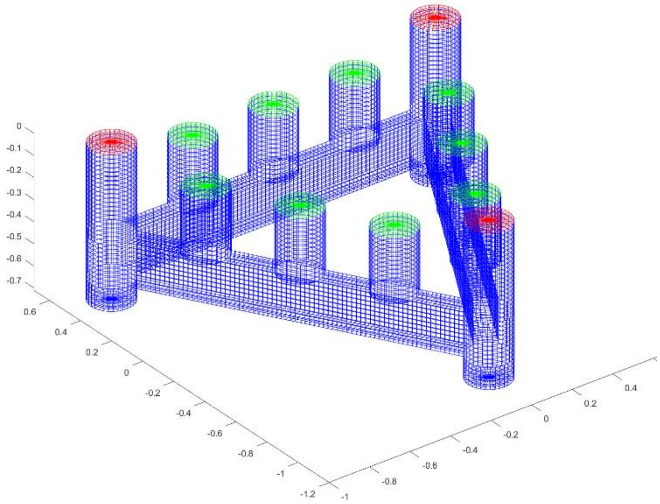

Fig. 9. Boundary element panels for WAMIT analysis of 9 WEC platform case, where generalized modes are applied to absorber surfaces shown in green.

A relatively light approach to numerical modelling is being taken at this stage with the focus initially on solving the equations of motion representing the system dynamics for each configuration in the frequency domain.

Based on the solution of the frequency-domain equations of motion, system dynamics and power production are being examined for the:

1. Unconstrained system, using the raw frequency-domain solution of the equations of motion; and
2. Constrained system, with instantaneous power and motion constraints handled very approximately using the approach proposed by [MAC]. This essentially involves constructing time series of the system's motion, velocity and power production from the frequency-domain solution based on specified sea-state realisations and capping each one according to specified constraints.

The approach to setting up the equations of motion and determining hydrodynamic coefficients for each configuration is essentially the same as the one adopted in [TAG] but for volume changing absorbers rather than point absorbers. Added mass, radiation damping, and excitation force parameters are determined using WAMIT across the range of frequencies of interest, and WAMIT's generalized modes functionality is used to handle individual absorber volume changing (essentially "heave") modes of motion. An example of the boundary element panelization used in a WAMIT analysis for 9 absorber case is shown in Fig. 9.

For the case of 9 absorbers on a platform, the only one of the numerically modelled configurations initially being tested in the tank, it is intended that terms covering additional damping will be added to the equations of motion and be calibrated with tank measurements. The added damping is likely to be representative of tank scale viscous damping and mechanical system damping.

How well the calibrated model can replicate the system response and power capture measured across tank tests for this platform configuration will then be assessed in full.

A full comparison between various test configurations and mooring options discussed earlier in this paper will be undertaken to understand how absorber performance is affected by the configuration in which the absorbers and the platform are deployed.

Some initial exploratory time-domain modelling is also proposed to understand:

1. The extent to which nonlinear system effects would be better handled with time-domain models, such as constraints or platform stability issues of the type identified by [SOU] for MWAP systems using volume changing absorbers.
2. How feasible it is to model multi-degree of freedom systems with the complexity of the 9-absorber system in the time domain.

In follow on work, such models may also be required to handle more sophisticated wave by wave control strategies such as model predictive control or optimal velocity tracking control.

4 CONCLUSION/FUTURE WORK

The project covered in this paper is part of a larger study by Wave Energy Scotland to understand the options for combining floating offshore wind and wave energy projects, and the potential benefits to both sectors of doing so. This paper describes the motivation, methodology and tools used to determine the relative power performance of wave energy devices mounted on a floating offshore wind style platform. The project started in October 2022, with wave tank testing carried out in June 2023. Results of the testing are not available at the time of preparing this paper.

Final results of another part of the wider study looking at the techno-economic opportunities of combining floating wind and wave were published in May 2023 [WES1]. Conclusions from that report may influence additional cases to be considered within this MWAP project in the future.

Data from the tank testing campaign will be used to validate the numerical model which can then be used to extrapolate to other platform configurations not tested in the tank. It is expected that analysed results of the initial tank testing will also help to identify behaviours of the absorbers on the platform which cannot be replicated in the frequency domain numerical model. Options for development of a time domain model will be considered in the future when results of this MWAP project are available and the number of possible cases has been reduced. Based on initial results, the MWAP may also be optimized somewhat before being modelled in the time domain, ensuring that any new model more accurately represents an anticipated full-scale embodiment of an MWAP.

The list below presents the topics which are expected to be explored more thoroughly following this initial investigation of the MWAP.

- Physical modelling:
  - Tank testing different numbers of WECs on the platform, and investigating the impact of asymmetry
  - Implementation of a different control strategy to all WECs
  - Along with the numerical model, determine scaling effects and implications of testing at 1:50 scale
  - Further understanding of the implementation of a mechanical spring to replicate the air spring in a real submerged pressure differential system
- Mooring design:
  - Understand changes in platform motions and absorber power performance as a result of changing mooring compliance
  - Improve mooring design to be more reflective of a true full-scale system, considering component availability and seabed characteristics
- Numerical modelling:
  - Validation of model based on tank test results
  - Detailed comparison between WEC cases given in Section 3.5
  - Investigation of different numbers or different sized absorbers on the platform
  - Development of a model for asymmetrical cases
  - Optimisation of the number or arrangement of WECs on the existing platform design
  - Investigation of options for time domain modelling of the MWAP, including system constraints and PTO control
- Other future work outside of the MWAP project:
  - Engagement with the floating wind sector to understand motivations or reservations about the integration of wave energy into their projects
  - Progress detailed full scale design of MWAP, understanding accurate design parameters and build costs
  - Investigation of improvements to the MWAP using a co-design approach, taking account of the platform, WEC, mooring and PTO control in the design optimisation

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