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Preliminary validation of a 1MW oscillating wave surge converter WEC-Sim model

Pauline Laporte Weywada, Joao Cruz, Joshua Scriven, Matti Vuorinen, Tuula Maki

Abstract—**The MegaRoller project, funded under the European Union's Horizon 2020 research and innovation programme, aims to develop and demonstrate a novel Power Take-Off (PTO) solution for Wave Energy Converters (WECs). As part of the project, a custom fully-coupled wave-structure interaction WEC model based on the numerical simulation package WEC-Sim was developed. Essentially, the principal objective of the WEC-Sim model is to enable a detailed assessment of the distributed loads affecting the MegaRoller WEC system, in an effort to support the PTO design process. In order to accurately assess the influence of the distributed loading contributions over the WEC's prime mover, a number of novel features were conceptualised in the WEC-Sim model. This includes an advanced wave-by-wave control system implementation, the possibility of using a position dependent database of hydrodynamic inputs, and the capability to assess the influence directional spectrum in the estimated load patterns. This paper describes the development of the advanced WEC-Sim model, including a preliminary validation exercise and some initial investigations on the impact of each novel feature on the WEC's response.**

Keywords— **Fully-coupled load assessment, MegaRoller Numerical modelling, Oscillating Wave Surge Converter (OWSC), Power Take-Off (PTO), Validation, Wave energy.**

I. Introduction

EFFICIENCY and reliability are two key challenges for Power Take-Offs (PTOs). Waves generate slow and irregular oscillations, which require the handling of large alternating forces in order to extract wave power. The MegaRoller project aims to design, build and validate a generic high performance, cost-efficient and reliable 1MW PTO that can be integrated into Oscillating Wave Surge Converter (OWSC) designs. The development of the PTO for a 1MW OWSC device is underpinned by multiple software and hardware innovations. In this context, the knowledge of localised effects related to both the environmental conditions and the WEC response is of crucial importance to the design, implementation and integration activities to be completed. One of the consortium's key focus is therefore to increase the understanding of the wave-structure interaction problem, via the development of a distributed, fully-coupled, nonlinear WEC distributed loads model, suitable for performance, load and structural assessments from an early design stage up to the transition to detail design.

In this paper, the development of an advanced wave-structure interaction numerical model of a 1MW OWSC is presented. The model was developed in a customised version of WEC-Sim, introducing a range of nonlinearities (hydrodynamic and mechanic). These include:

- The implementation of an advanced, sub-optimal control strategy, where the real part of the mechanical impedance is controlled on a wave-by-wave basis.
- The possibility of using a database of hydrodynamic inputs (rather than a mean profile).
- The extension of the input wave generation capabilities to use directional spectra.

Additional features, in particular the consideration of structural deformations of the flap surfaces as a response to the distributed loads impacting the WEC, were also implemented in the model and are the focus of further studies - see [1].

An initial model based on the previous design iteration of the WaveRoller WEC was built, as experimental data were available for such design. A preliminary validation exercise was then conducted to assess model accuracy, comparing numerical estimates with the key outputs from a model testing campaign conducted by AW-Energy at Queen's University of Belfast (QUB). A range of regular and irregular wave tests were selected for initial comparisons, and the key results are summarised in this paper. A MegaRoller WEC model version was then developed, to allow initial estimates of key WEC metrics.

Ultimately, it is expected that the WEC-Sim model will contribute to the detailed understanding of the asynchronous loading affecting the MegaRoller WEC main sub-systems (namely its prime mover and PTO system), and therefore support the structural design of the 1MW MegaRoller WEC.

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This paper is organised in five main sections. Following this introduction (Section I), the load analysis model of the MegaRoller WEC is described in Section II, focusing on the upgraded features implemented for the purposes of the MegaRoller project. An initial case study is then presented in Section III, in the form of a pre-validation exercise related to the Queen's University of Belfast tests on an earlier WEC design. The results of preliminary investigations looking at the additional features in the WEC-Sim are then presented in Section IV. The investigations focused on the assessment of the influence of three novel features in the model on WEC performance: the control strategy, the use of a database of hydrodynamic coefficients (as an alternative to data related to a single, mean wetted profile) and the consideration of directional spreading. Finally, the recommended next steps, in particular regarding the connection to the design process, are detailed in Section V.

II. MEGAROLLER LOAD ANALYSIS WEC MODEL

A. *Technical description of the MegaRoller WEC*

Essentially, the MegaRoller WEC can be described as an OWSC with an innovative, modular PTO solution, where hydraulic piston pumps have an interface with the panel via a twin drivetrain located at each end of the WEC's prime mover (flap). The pistons pump hydraulic fluid inside a closed circuit, which is enclosed inside a hermetic structure and thus not exposed to the marine environment. The high-pressure fluids are fed into hydraulic motors that drive a generator. Finally, the electrical output from the generator is fed to the electric grid via a subsea cable (see Fig. 1).

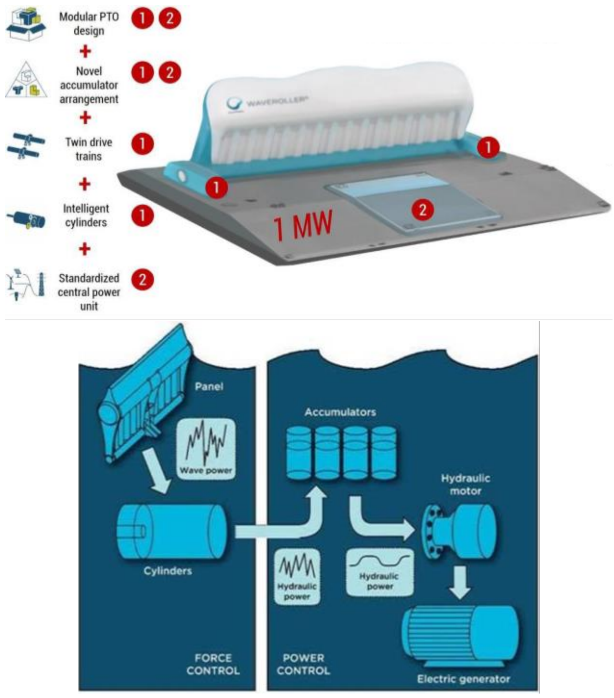

Fig. 1. 1MW OWSC device (top) and OWSC conversion process (bottom)

The device operates in nearshore regions at depths of between 8 and 20 metres. It is anchored to the seabed and, depending on mean depth and tidal range, it is mostly or fully submerged during operation. A series of devices can be deployed in an array to create a wave farm. Since the WEC is constructed as a modular individual unit, there is no technical upper limit to the number of devices that can be used in an array.

The target geometric and mass properties of the MegaRoller WEC prime mover (the flap) are summarised in TABLE I. The main dimensions of the WEC are illustrated in Fig. 2. Given the early stage of the design, the overall properties are generic and subject to further refinement.

TABLE I
KEY GEOMETRIC AND MASS PROPERTIES OF THE MEGAROLLER WEC PRIME MOVER (FLAP)

Property	Unit	Value
Volume	m^3	750
Mass	*kg*	250,000
Moment of inertia I_{yy}	kgm^2	5,000,000
Location of the centre of gravity[a]	*m*	5.3
Location of the bearings[a]	*m*	1
Location of the PTO[a]	*m*	3

[a]Locations (in metres) refer to vertical positions in the water column measured from the seabed.

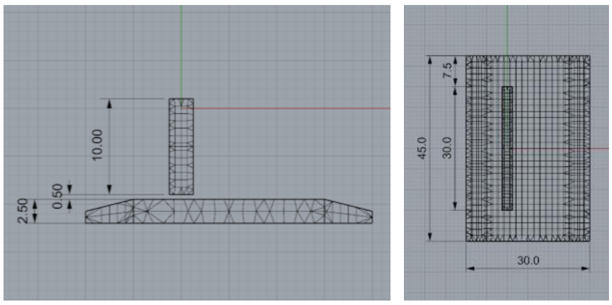

Fig. 2. MegaRoller WEC dimensions (in m) – side and top views. The red and green axis correspond to the x and z axis of the coordinate system, respectively (origin at water level)

B. *Overall description of the WEC-Sim model*

WEC-Sim (Wave Energy Converter SIMulator) [2] is an open-source WEC simulation tool, developed in MATLAB/Simulink using the multi-body dynamics solver SimMechanics. The WEC-Sim project is funded by the U.S. Department of Energy's Wind and Water Power Technologies Office, and the code development effort is a collaboration between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL).

In its original formulation, WEC-Sim has the ability to model WEC devices that involve rigid bodies, PTO systems and moorings. Simulations are performed in the time-domain by solving the governing WEC equations of motion in all relevant degrees-of-freedom, in a fully-coupled format (i.e. simultaneously accounting for all relevant load sources) – see e.g. [3].

A Simulink chart representing the multi-body structure implemented in WEC-Sim is illustrated in Fig. 3. At a high level, the base is connected to the seabed via a fixed constraint, and to the prime mover (the flap) via a pitching constraint (mimicking the bearings). Each PTO subsystem includes a translational PTO block, described further in Section C.

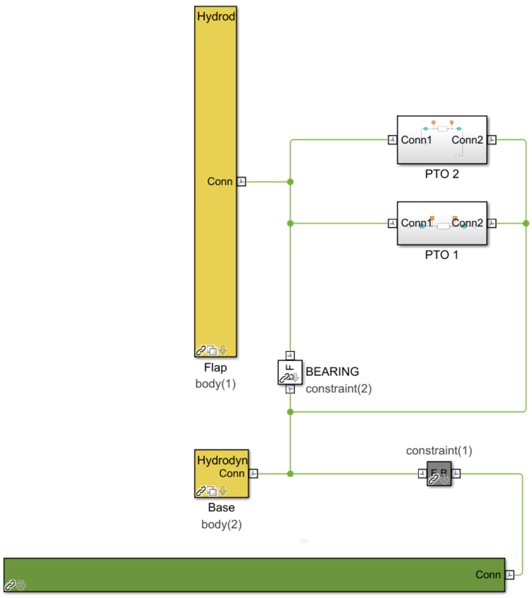

Fig. 3. Schematic of the MegaRoller WEC-Sim model

In WEC-Sim's native rigid body dynamics implementation, the hydrodynamic loading on the WEC does not affect the structural dynamics of wave-activated bodies. However, structural interactions could potentially be of significant relevance for the design of the WEC, if e.g. hydrodynamic loads excite fundamental frequencies of the structure, leading to potentially destructive effects. In order to assess the impact of the distributed loading contributions over the flap on the PTO system, an advanced structural dynamics module was developed and implemented in WEC-Sim. Such module is further described in Section D, and presented in more detail in [1].

The hydrodynamic coefficients and the wave exciting force associated with the main bodies were derived in NEMOH [4]. The derived hydrodynamic data include first-order (linear) and weakly nonlinear quantities (instantaneous hydrostatic and Froude-Krylov forces). In order to account for the change in hydrodynamic properties with the pitching motion of the flap, the WEC-Sim formulation was extended to enable the use of a database of hydrodynamic coefficients that depend on the flap's position (see also Section E).

Finally, directional spreading may generate asynchronous operation of the twin drivetrain, bringing a significant challenge for the PTO design. To address this, the WEC-Sim model was extended to enable the calculation of the wave exciting force on the WEC when a directional spectrum is used as an input. This additional feature is further described in Section F.

C. *PTO and control model: wave-by-wave damping optimisation*

The PTO forms part of a WEC's power conversion chain, usually being the primary system that converts the wave-induced motion into mechanical or electrical power [5]. For OWSCs such as the MegaRoller WEC, the electricity is converted from the back-and-forth movement of the bottom-mounted flap.

A Simulink chart representing the underlying PTO model implemented in WEC-Sim is illustrated in Fig. 4. At the inception of a WEC-Sim simulation, the wave input parameters are pre-processed to derive the free-surface elevation time-series at the location of the device. The resulting time-series is used to predict the zero up-crossing instants and the period of each passing wave, which in turn informs the selection of the appropriate PTO damping coefficient. The time-series of coefficients is saved in the $pto(1).cdatabase$ variable, which is then fed in the PTO model to derive the PTO torque at each instant.

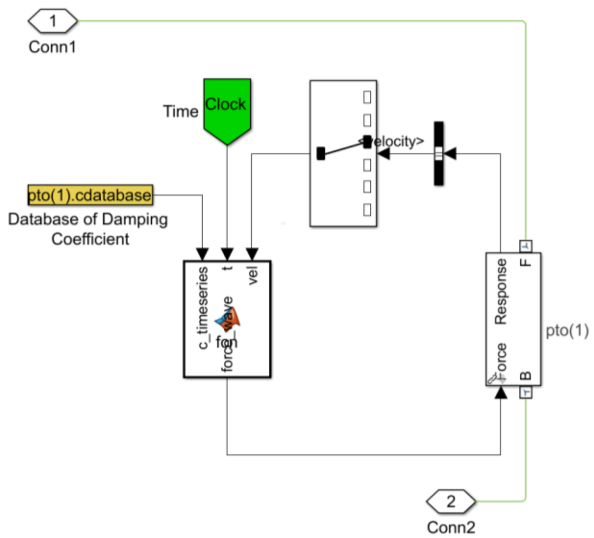

Fig. 4. Schematic of the MegaRoller PTO WEC-Sim model

One of the focus of the MegaRoller project is to develop an advanced PTO controller logic, in particular for power capture optimisation. In a preliminary step, a sub-optimal solution was implemented, where only the real part of the mechanical impedance is controlled. To assess the impact of a wave-by-wave PTO damping control algorithm, simulations comparing WEC-Sim outputs using this active strategy and those using a passive strategy (i.e. same damping coefficient throughout the sea state) were performed - see Section IV.A.

D. *Structural dynamic model*

In the existing rigid body dynamics implementation, the hydrodynamic loading on the WEC does not affect the internal structural dynamics, i.e. the prime mover shape remains unchanged throughout the simulation. In order to assess the impact of the distributed loading contributions over the flap on the PTO system, an advanced structural dynamics module was implemented in WEC-Sim. Following the approach used in other coupled hydro-elastic tools such as HydroDyn [6], a structural dynamic add-on using a Finite-Element (FE) solver is linked to WEC-Sim to enable a hydro-elastic time-domain analysis of WECs.

The structural dynamic add-on is developed using *Code_Aster* [7] as the FE solver. Two alternative approaches were considered:

- The FE solver is used as a post-processor, taking results from WEC-Sim and calculating distributed forces and displacements.
- The FE solver is coupled to WEC-Sim, updating the deformed shape at each time step to influence calculation of loads at the next time step.

The development of the module is described in detail in [1], along with some case studies illustrating results related to the different approaches.

E. *Database of hydrodynamic coefficients*

In the WEC-Sim structural model, each wave-activated body block contains the hydrodynamic properties that enable the calculation of the first-order hydrodynamic forces acting on the body. In its original formulation, the hydrodynamic properties are computed by a BEM flow solver (e.g. NEMOH) considering the device in its mean equilibrium position. In order to account for the change in hydrodynamic properties with the pitching motion of the flap, the WEC-Sim model of the MegaRoller WEC was extended to enable the use of an input database of hydrodynamic coefficients. These were derived from multiple BEM simulations, with the mean position of the flap at a range of pitch angles (referred to as "BEM angle"). In particular, simulations for angles ranging between -40 and +40 degrees were completed, with a 10-degree step.

During the WEC-Sim simulations, and when the database implementation is activated, the model calculates the hydrodynamic forces using the hydrodynamic coefficients derived at the BEM angle closest to the instantaneous angle at the current time-step (referred to as "current angle"). To avoid instabilities, a hysteresis approach was implemented. At each time step, the code compares the current angle to the range of BEM angles; a new BEM angle is then only selected if the difference between BEM and current angles is larger than 7.5 degrees (i.e. ¾ of the BEM angle spacing of 10 degrees).

Simulations comparing WEC-Sim outputs in terms of WEC performance without and with the proposed database implementation are presented in Section IV.B.

F. *Spread waves*

Historically, monochromatic (regular) or unidirectional (irregular) waves have been used in hydraulic models of coastal projects. In the original formulation of WEC-Sim (v3.0), the irregular waves are approximated to a linear superposition of regular waves of distinct amplitudes and directions, and are characterised in the frequency-domain by a wave spectrum. The general form of the unidirectional wave spectra $S(f)$ available in WEC-Sim is given by:

$$S(f) = Af^{-5}\exp(-Bf^{-4}) \tag{1}$$

where f is the frequency (in Hz), and A and B are coefficients that vary depending on the wave spectrum. Standard shape spectra available in WEC-Sim include the Pierson-Moskowitz (PM) spectrum, the two-parameter Bretschneider spectrum (BS) or the Joint North Sea Wave Project, JONSWAP (JS), spectrum.

However, real ocean waves are short-crested, having directional spreading which spreads or diffuses wave energy over many directions about a central angle of wave approach. Practically, the directional wave spectrum $S(f,\beta)$ can be modelled parametrically as the wave spectrum $S(f)$ times a function of angular spreading (f,β), usually called a spreading function, following:

$$S(f,\beta) = S(f)D(f,\beta) \tag{2}$$

The formulation of $D(f,\beta)$ must ensure that the total energy in the directional spectrum is the same as the total energy in the corresponding one-dimensional spectrum:

$$\int_0^\infty \int_{-\pi}^{\pi} S(f)D(f,\beta)\, d\beta df = \int_0^\infty S(f)df \tag{3}$$

In a preliminary step, a simple idealized cosine-squared spreading function $D(\beta)$ was implemented in WEC-Sim:

$$D(\beta) = \begin{cases} \frac{2}{\pi}\cos^2(\beta-\beta_0) & for\ |\beta-\beta_0| < \frac{\pi}{2} \\ 0 & otherwise \end{cases} \tag{4}$$

where β_0 is the direction of the incoming wave.

Simulations comparing WEC-Sim outputs in terms of WEC performance in a unidirectional and multidirectional input wave fields are presented in Section IV.C.

III. CASE STUDY: PRE-VALIDATION EXERCISE

The case study presented in this section aims to act as a preliminary validation exercise, comparing the WEC-Sim outputs built to replicate the previous design iteration, the WaveRoller WEC, against measurements from tank tests conducted at the Queen's University of Belfast facility between August 2017 and January 2018, using a previous design iteration of the WaveRoller WEC at a 1:36 scale.

The tank tests were conducted within the MaRINET2 project funded by the European Union Horizon 2020 Framework Programme, under grant agreement no 731084. The testing campaign concentrated on recording the loads at multiple locations, mainly on the foundation and the flap, under a wide range of design conditions of varying tides, sea states and wave directions.

In the following subsections, comparisons between tank measurements and WEC-Sim outputs are presented for a regular wave case (Section III.A) and for an irregular wave case (Section III.B).

A. Regular wave case

This subsection describes the preliminary comparison of the WaveRoller WEC-Sim model outputs with experimental data in regular waves using measurements from the tank tests. The multi-body WEC model for the system, although similar to that shown in Fig. 3, was adapted to use the properties of the previous design iteration of the WaveRoller WEC (single PTO and smaller dimensions). The target PTO profile (i.e. PTO torque vs. pitch velocity) was a Coulomb profile. However, the profile measured in the tank showed significant variation with respect to the targeted Coulomb profile, in particular for large waves. An averaged, smoothed profile based on the experimental measurements was therefore input instead of the target profile (see Fig. 5).

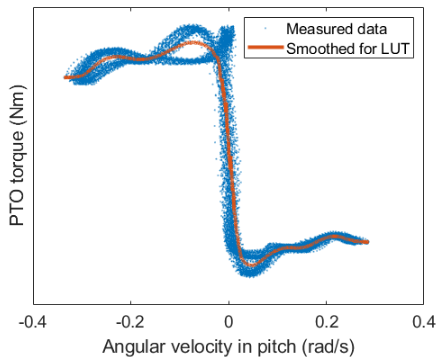

Fig. 5. PTO torque profile: torque value against flap angular velocity in pitch – as measured in the tank (blue) and as input in the WEC-Sim PTO model look-up-table (red)

The target input wave condition was a regular wave with a full-scale equivalent 2m wave height and 10s period, in a water depth of 14.5m. For validation purposes, the environmental input conditions were defined in the input file as the exact measured time-series of free-surface elevation.

Fig. 6 shows the time-series of flap motion and PTO torque extracted from the simulation output and experimental measurements.

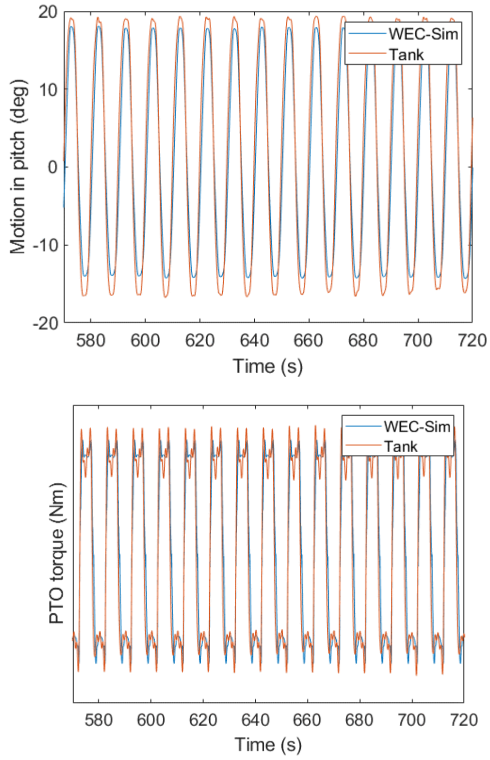

Fig. 6. Comparison of time-series of flap motion in pitch (top) and PTO torque (bottom) between tank measurement (red) and WEC-Sim estimates (blue) – 150s extract – full-scale equivalent – regular wave case

Fig. 7 illustrates the agreement between the two motion estimates, along with a linear fit of the scatter diagram (black line). The under-estimation of the amplitude of motion by WEC-Sim is likely to be related to uncertainties on the tank data, in particular potential inaccuracies in the wave and PTO force measurements, scaling effects (see e.g. [8]), and / or an under estimation of the drag force.

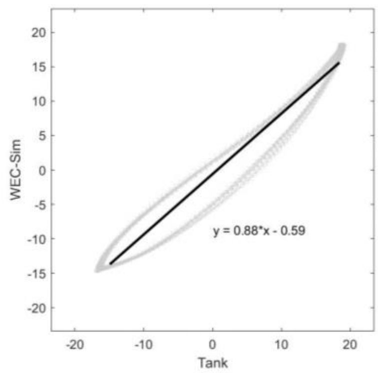

Fig. 7. Scatter diagram of pitch motion as measured in the tank (horizontal axis) and estimated in WEC-Sim (vertical axis) – regular wave case

B. Irregular wave case

This subsection describes the preliminary comparison of the WEC-Sim model outputs with experimental data in irregular waves, with 3.5m wave height and 10s wave period, in a water depth of 14.5m (full-scale equivalent).

Fig. 8 shows the time-series of flap motion and PTO torque extracted from the simulation output and experimental measurements. Overall, the WEC-Sim motion output matches reasonably well the tank measurements, despite the discrepancies in the PTO torque. The latter are more representative of experimental limitations, rather than numerical inaccuracies.

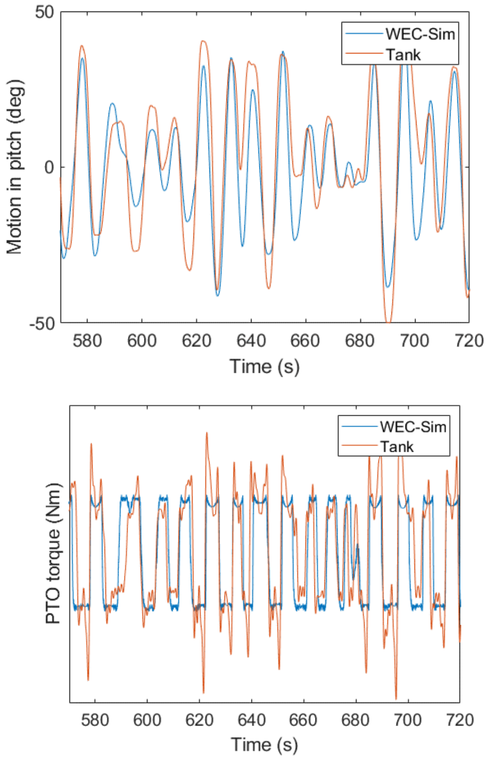

Fig. 8. Comparison of time-series of flap motion in pitch (top) and PTO torque (bottom) between tank measurement (red) and WEC-Sim estimates (blue) – 150s extract – full-scale equivalent – irregular wave case

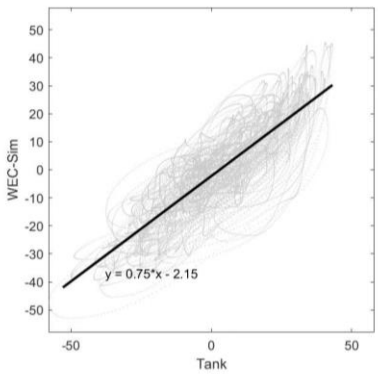

Fig. 9. Scatter diagram of motion in pitch as measured in the tank (horizontal axis) and estimated in WEC-Sim (vertical axis) – irregular wave case

Fig. 9 illustrates the agreement in pitch motion between the WEC-Sim simulation output and the signal measured in the tank. The black line corresponds to a linear regression fit of the scatter diagram. Considering the uncertainties associated with the models, in particular regarding the PTO torque profile and the approximation in the drag force implementation (see also Section III.A), the agreement is relatively good, with WEC-Sim overall under estimating the tank results by about 25%.

C. *Key outcomes of the pre-validation study*

The pre-validation exercise presented in this section shows an overall good agreement between the WEC-Sim outputs and the tank measurements related to the WaveRoller WEC. Moving forward, the MegaRoller project aims to focus on a larger WEC design, developing a PTO solution for a 1MW OWSC device. Building on the know-how derived from the WaveRoller WEC model, the MegaRoller WEC-Sim model needs to consider a number of additional features that address the added complexity of the upgraded WEC. In particular, the MegaRoller WEC-Sim model was initially customised to enable the following investigations, related to MegaRoller specific aspects:

- Influence of a wave-by-wave damping control strategy in the WEC response, moving away from the sea-state by sea-state control method previously used in WaveRoller.
- Assessment of the sensitivity of the larger MegaRoller flap to torsional loads when waves come from oblique headings, considering spread wave inputs in the WEC-Sim model.
- To address the potentially large range of pitch motion experienced by the WEC, the facility to use an input database of hydrodynamic coefficients was also developed.

Preliminary investigations that document the implementation of these features are presented in Section IV. Further developments conducted in the MegaRoller project, namely the impact(s) of structural deformation in the overall WEC and also the PTO response, are addressed separately in [1].

IV. PRELIMINARY INVESTIGATIONS

Following the validation of the initial WaveRoller model, and prior to conducting a detailed load assessment, preliminary investigations were conducted to quantify the influences of the novel WEC-Sim implementations on the WEC response.

The investigations focused on the assessment of the influence of the control strategy on WEC performance (Section IV.A), and the impact on the WEC's response of two additional features in the WEC-Sim model, namely the use of a database of hydrodynamic coefficients (Section IV.B) and the directional spreading (Section IV.C).

A. *WEC control strategy*

To assess the potential benefits of a wave-by-wave control strategy, where the PTO settings are optimised for each incoming wave, the WEC performance outputs using the sub-optimal option implemented (see Section II.C) were compared to those of a passive strategy, where the PTO damping coefficient is constant throughout the sea state.

Fig. 10 shows the resulting ratio of power matrix between both control strategies (sub-optimal mean absorbed power vs. passive). An average improvement over the overall matrix can be observed, in particular around the smaller and mid-range peak periods, where the improvements are more significant. However, it should be noted that a similar pattern on the PTO loads is also observed, with the ratio of RMS PTO force ranging approximately between 0.5 and 4.5.

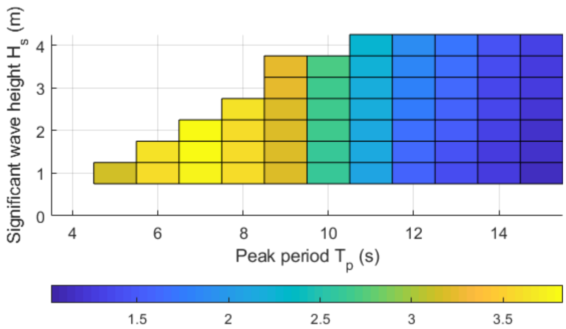

Fig. 10. Ratio of power matrices: sub-optimal control strategy vs. passive control strategy

To assess the overall impact of the control strategies in the performance of the WEC, the Mean Annual Energy Production (MAEP) was derived for the target deployment site, Peniche (Portugal). The corresponding scatter diagram can be found in Appendix. The MAEP results are summarised in TABLE II, showing an overall increase of approximately two-fold in the estimated MAEP between the passive and the sub-optimal control strategies. TABLE II also features the capacity factor of the WEC, derived as the ratio between the MAEP and the rated annual energy yield, assuming a power rating at 1MW. It is clear from TABLE II that control is a decisive factor in WEC performance, and that further optimisation work may be required, also quantifying the influence in the resulting PTO loading profiles.

TABLE II
MEAN ANNUAL ENERGY PRODUCTION (MAEP) AND CAPACITY FACTOR AT THE PENICHE SITE FOR THE PASSIVE AND SUB-OPTIMAL CONTROL STRATEGIES

Control strategy	MAEP (GWh/y)	Capacity factor
Passive	0.9	10%
Sub-optimal	1.7	19%

B. *Database of hydrodynamic coefficients*

This section focuses on the impact of using a database of hydrodynamic coefficients versus the original WEC-Sim formulation, where the hydrodynamic properties are only derived for the WEC's mean equilibrium position. In both cases, the simulations were run using the sub-optimal control strategy described in Section II.C.

Fig. 11 to Fig. 14 compare different key performance metrics between the original formulation of WEC-Sim ('*Baseline*') and the novel implementation with the database of hydrodynamic coefficients ('*Database*'). The metrics considered the mean mechanical absorbed power (Fig. 11), the root-mean-square (RMS) of motion in pitch (Fig. 12), the RMS PTO force (Fig. 13) and the RMS of PTO velocity (Fig. 14).

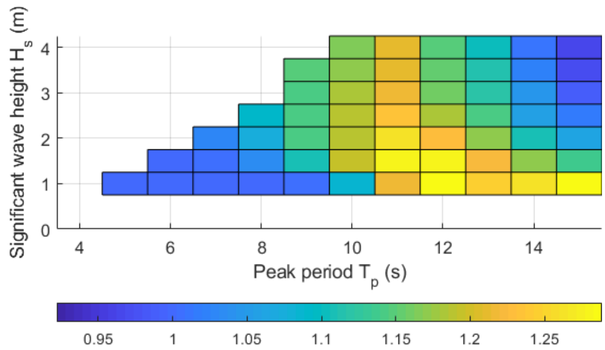

Fig. 11. Ratio of power matrices: '*Database*' vs. '*Baseline*'

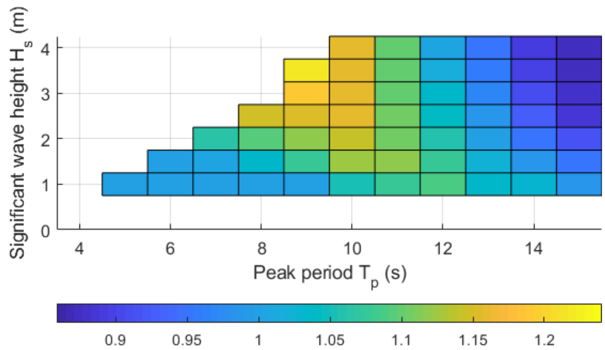

Fig. 12. Ratio of RMS angle: '*Database*' vs. '*Baseline*'

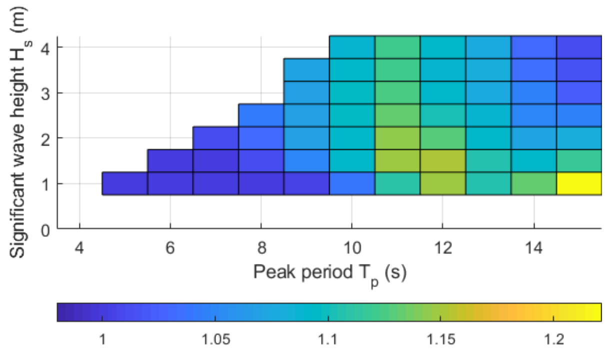

Fig. 13. Ratio of RMS PTO force: '*Database*' vs. '*Baseline*'

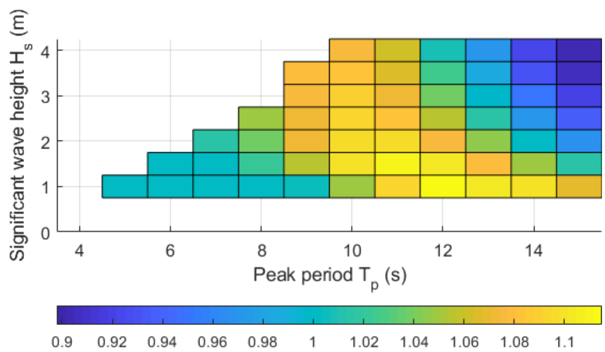

Fig. 14. Ratio of RMS PTO velocity: '*Database*' vs. '*Baseline*'

In waves of low periods and waves of high periods and heights, the impact of the database implementation remains limited (up to around 10%) in all metrics considered. On the contrary, an increase of more than 25% can be seen in waves of high periods and low heights, as well as in medium periods and heights.

Looking at time-series of motion in pitch (Fig. 15) and absorbed power (Fig. 16) for cases displaying a large difference in absorbed power (e.g. incident wave of 11.5s peak period and 1.75m wave height), it can be seen that the WEC's response remains overall fairly similar with or without the database option, but that peaks of larger motions observed when using the database (see e.g. at instant 1380s in Fig. 15) lead to large peaks of power absorption, leading to significant differences in the mean power estimates.

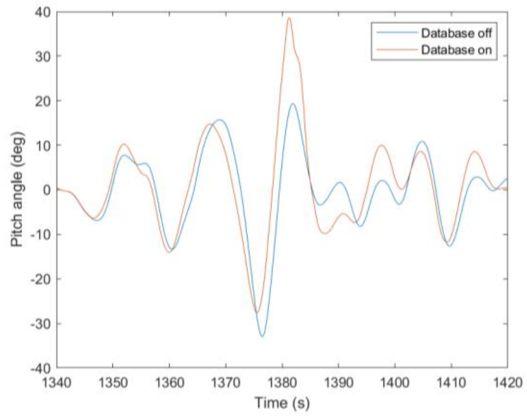

Fig. 15. Comparison of time-series of motion in pitch (in degree) between the '*Baseline*' case (no database, in blue) and the '*Database'* case (database on, in red) – 80s extract – incident wave of 11.5s peak period and 1.75m significant wave height

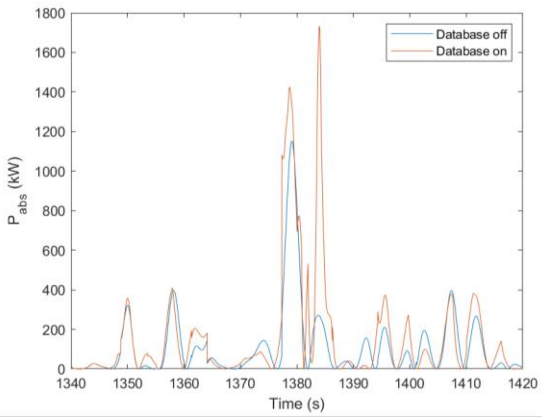

Fig. 16. Comparison of time-series of absorbed power (in kW) between the '*Baseline'* case (no database, in blue) and the '*Database'* case (database on, in red) – 80s extract – incident wave of 11.5s peak period and 1.75m significant wave height

TABLE III
MEAN ANNUAL ENERGY PRODUCTION (MAEP) AND CAPACITY FACTOR AT THE PENICHE SITE FOR THE BASELINE MODEL AND THE UPGRADED MODEL WITH DATABASE OF HYDRODYNAMIC COEFFICIENTS

Case	MAEP (GWh/y)	Capacity factor
Baseline	1.7	19%
Database	1.9	22%

To assess the overall impact of the database implementation in the estimated WEC performance, the MAEP for the Peniche site was also derived– see TABLE III. Overall, a 10% difference can be seen when comparing the MAEP obtained via the original formulation and that associated with a model that includes the database implementation. As a next step, a validation exercise can be conducted to assess the level of fidelity of the WEC response and loading estimates (see Section V).

C. *Directional spreading of the incident waves*

This section focuses on the impact of the directional spreading on different key performance metrics. Fig. 17 shows the ratio of mechanically absorbed power output of simulation over a range of sea states with a simple directional spreading function applied to the wave energy spectrum ('*Spread'*) by the output of simulations with no spread ('*Baseline'*).

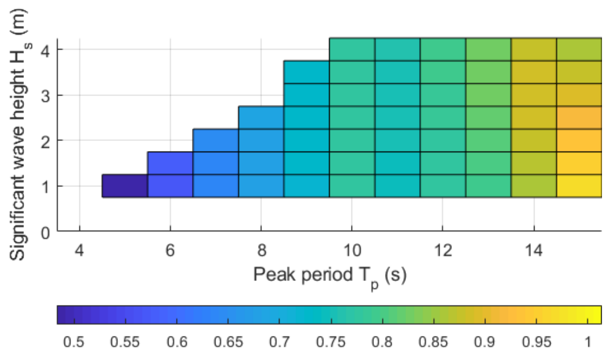

Fig. 17. Ratio of power matrices: '*Spread'* vs. '*Baseline'*

The directional spreading of the incident waves leads to a decrease in power performance, with less power absorbed in multidirectional waves compared to unidirectional waves. The reduction is of greater importance in small wave periods (40% decrease around 5s peak period). Similar to Section B, other metrics of interest included the RMS of motion in pitch, the mean PTO force and the RMS of PTO velocity. These showed a similar trend to Fig. 17. The systematic decrease in power performance also means a decrease in MAEP and capacity factor, as can be seen in TABLE IV. Overall, the directional spreading of the input wave leads to a reduction of c.17% in MAEP and capacity factor at the Peniche site.

TABLE IV
MEAN ANNUAL ENERGY PRODUCTION (MAEP) AND CAPACITY FACTOR AT THE PENICHE SITE FOR THE UNIDIRECTIONAL AND THE MULTIDIRECTIONAL INCIDENT WAVE CASES

Case	MAEP (GWh/y)	Capacity factor
Baseline	1.7	19%
Spread	1.4	16%

V. CONCLUSION AND NEXT STEPS

In this paper, a customised, advanced wave-structure interaction numerical WEC model implemented in the context of the MegaRoller project was introduced. The model will be used to support the PTO design process. In particular, the model will allow the assessment of the influence of distributed loading contributions over the WEC's prime mover, accounting for the interactions between the flap and the PTO load sources in a fully coupled manner.

A number of key innovative features aiming to improve the understanding of the nonlinear loading affecting the WEC on the twin drivetrains were conceptualised in the model, and presented in this paper. These included:

- The implementation of an advanced, sub-optimal control strategy, where the real part of the mechanical impedance is controlled on a wave-by-wave basis.
- The possibility of using a database of hydrodynamic inputs.
- The extension of the input wave generation capabilities to directional spectrum.

An initial validation exercise was conducted on the previous WaveRoller design iteration, comparing WEC-Sim outputs against measurements from tank tests conducted at Queen's University of Belfast. Overall, the comparisons showed a good agreement between the WEC-Sim outputs and the tank measurements.

Following the initial validation exercise, novel, custom features were implemented in WEC-Sim to reflect the upgrades in the MegaRoller WEC design. Preliminary investigations were conducted to assess the impact of these. In particular, the investigations assessed the power and MAEP estimates at the target site of deployment, Peniche (Portugal). As a next step, it is envisaged that a validation exercise of the numerical model will be conducted to assess the level of fidelity of the WEC response and loading estimates (noting that at least some of such effort may beyond the timeline of the MegaRoller project). The development of the novel functionalities will continue throughout the MegaRoller project, and in a wider context the activities are expected to provide guidance for modelling practices in the wave energy sector.

As an immediate next step, the model developed will be used in the MegaRoller project to conduct a load characterisation exercise, focusing on a range of performance, survivability and reliability metrics for critical design situations likely to affect the primary design of the MegaRoller WEC. The results of the load characterisation effort will directly inform the design of the MegaRoller PTO. Additional features, such as the structural dynamics module that accounts for flap deformations [1], shall also be included in such assessments.

APPENDIX

To define long-term representative conditions of the Peniche site, data from SWAN simulations covering the period between January 1997 and December 2006, i.e. 10 years were processed. The output data consisted of 6-hour averages of significant wave height H_s, energy period T_e, mean direction of wave propagation θ_0, peak period T_p, mean wave periods T_{m01} and T_{m02}, and wind speed and direction.

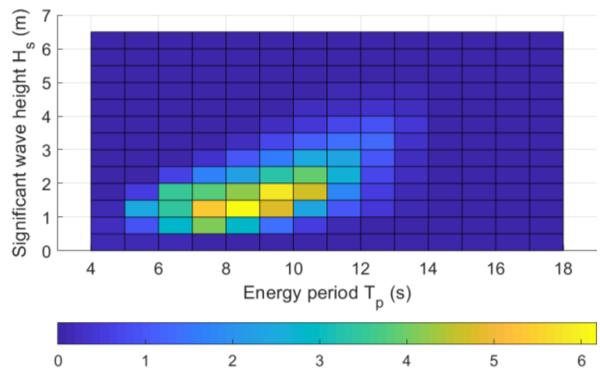

Fig. 18. Probability of occurrence of each Hs, Tp pair (39.4N, 9.3W, Jan 1997 – Dec 2006)

The coordinates of the data location of the Peniche site are 39.3894N and 9.3081E, which corresponds to a location estimated to be in the 12m depth contour. Using the full 10-year dataset, the long-term probability of occurrence of each H_s, T_p pair was derived and is shown in Fig. 18.

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