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Development and assessment of a new geometry for CECO wave energy converter

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Abstract— **CECO is a wave energy converter (WEC) of the oscillating body type equipped with an inclined PTO and able to absorb simultaneously the kinetic and the potential wave energy. The outcomes of recent studies are described in the paper to provide an overview on the present status of knowledge about this WEC. A detailed numerical study was carried out to overcome identified issues and optimize its geometry for the conditions typical of the North Atlantic Coast of the Iberian Peninsula. The enhanced geometry was then tested on a geometric scale of 1/25 at the wave basin of the Faculty of Engineering - University of Porto, Portugal. The conclusions obtained supported the design of the new geometry, which is prepared for rougher wave conditions and presents a better hydrodynamic performance than the original one for the target sea conditions. Finally, the next research steps are briefly described.**

Keywords—**inclined PTO, numerical modelling, wave power, performance assessment, physical modelling.**

I. Introduction

OCEAN waves are one of the most promising sources of marine renewable energy due to the vast resource available worldwide, estimated to be approximately 2.11 TW (Gunn and Stock-Williams, 2012). However, its exploitation is considered technologically challenging and uneconomical nowadays. Hence, research is still needed to optimize the wide variety of harvest technologies, namely to increase their efficiency and robustness in the extremely harsh marine environment, which induces *e.g*. mechanical wear, corrosion, fatigue and large loadings that have a direct impact on the reliability of those technologies (Thies *et al*., 2011 and 2012).

On the other hand, the variability of the wave resource in different time scales, including intra- and inter-annually (Ramos *et al*., 2017, 2018), is critical in the development of wave energy converters (WECs), since it is challenging to reach sufficiently high wave energy conversion efficiencies under such unsettledness.

In the future, WECs are expected to supply significant amounts of renewable energy to the worldwide electricity grids, contributing with its share to the target of 337 GW of ocean energy by 2050 (OES, 2015). This would represent an important step towards becoming less dependent on the fossil fuels for electricity generation. However, to reach that stage, significant technology innovation is needed, to reduce both capital (CAPEX) and operational expenditure (OPEX) and to enhanced energy production (Chang *et al*., 2018). Cost-effective, reliable and high-performance WECs will lead to reduced levelized cost of energy (LCoE) and will allow attaining the industry target values, increasing the wave energy competitiveness against other sources of renewable energy (Tran and Smith, 2017).

To overcome issues associated to the intermittency and variability of wave resource, a complete understanding of the performance characteristics of the WECs is required together with the development of solutions to adjust their hydrodynamic response to the changing characteristics of the ocean environment. The modification of mass and geometry (*e.g*., Chen *et al*., 2019) of the WEC and/or the control of its power take-off (PTO) system (*e.g*., Wang *et al*., 2018) are alternatives for the adjustment of WEC response.

To mitigate the technical and financial risks related to the development of WECs, guidelines for structured test programmes were established (Heller, 2012), linked to the technology readiness levels (TRL). Those test programmes consist of five phases, with increasing complexity, where experimental testing is applied in parallel with numerical modelling. This composite modelling approach is justified by the fact that experimental testing is often expensive and difficult to carry out. However, extensive testing is always required prior to the deployment of a commercially operating WEC.

The most typical numerical models used to simulate the hydrodynamic responses of WECs and their performance in converting ocean wave energy are based on the Boundary Equation Methods (BEM) and the Navier Stokes

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Equation Methods (NSEM). In spite of the ability of NSEM models (fully non-linear) to reproduce directly viscous effects of boundary layer separation, turbulence, overtopping, wave energy dissipation and breaking, BEM models, based on potential flow theory, are usually preferred at initial and intermediate stages of the development of a WEC (*e.g.*, De Andres *et al.*, 2013, Pastor *et al.*, 2014), due to the very good relation between accuracy and computational costs, since at those stages a large number of variables is investigated, systematically.

In fact, up to the TRL 4, it is of paramount importance the characterization of both the wave power harvested and the conversion efficiency over a broad range of conditions and WEC's setups, so as to optimize design variables (*e.g.*, power take off (PTO) damping, geometry and dimensions of the WEC, inclination and submergence level). This task require time-efficient numerical tools.

Frequency-domain BEM models are very cost-effective and the most frequently applied tool to model the response and assess the performance of WECs. Nevertheless, since these models are unable to account for nonlinearities (Li and Yu, 2012), their use is only advocated if those are not relevant for the problem in analysis. On the contrary, time domain BEM models capture some of the nonlinearities of the problem and also deal with non-analytical effects in the interaction between waves and WEC (*e.g.*, articulations, joints and moorings), except for viscous flow separation, wave breaking and overtopping. Hence, time domain BEM models are suitable to simulate operational conditions, for which, waves are relatively small in height and, the non-viscous hydrodynamic forces are controlled by radiation and diffraction components.

A large number of WECs was developed and optimized to harvest wave energy along one main oscillation mode, often the heave (Richardson and Aggidis, 2013). On the other hand, the concept of a free-floating WEC with an oblique motion was already proposed by Salter and Lin (1995) and its key advantages, in comparison to a vertical motion concept, were demonstrated by Payne *et al.* (2015).

The novel wave energy converter CECO was idealized to convert, simultaneously, the kinetic and the potential energy of ocean waves in electricity, from the translational motions of a floating mobile part in relation to a reference structure, along an inclined axis. The experimental proof of concept of the device was carried out at the Hydraulics, Water Resources and Environment Division, of the Faculty of Engineering of the University of Porto, Portugal (Rosa-Santos *et al.*, 2015). Since then, numerous numerical studies were carried out to get more insight on its response under the action of wave and to optimize its performance (*e.g.*, López *et al.*, 2017a,b,2018; Ramos *et al.*, 2017,2018; and Rodríguez *et al.*, 2018, 2019).

This paper presents and discusses recent outcomes on the development of CECO, and describes some numerical studies carried out to optimize its geometry, to improve the efficiency of this WEC for wave conditions typical of the North Atlantic coast of the Iberian Peninsula. For the selected geometry, a new physical model study of CECO, on a geometric scale of 1/25, was conducted, for several wave conditions and different PTO damping levels.

The conclusions obtained so far supported the design of the new geometry of CECO that is prepared for rougher wave conditions and presents a hydrodynamic efficiency of more than twice the original one, for the target wave conditions. The new experimental data and conclusions will be the starting point for the future developments of CECO wave energy converter.

II. CECO WAVE ENERGY CONVERTER

A. CECO concept

The wave energy converter CECO explores the relative motions between its floating part and a reference support structure to generate electricity, Figure 1. The floating part is composed of 2 lateral mobile modules (LMMs) attached to a central sliding frame, which has translational motions along an inclined axis under the action of ocean waves. The sliding frame travels through a set of low friction guiding bearings that only allow motions in 1-degree of freedom. The electrical generator is installed inside the supporting structure, which is fixed to the sea bottom in this work. At full-scale, a jacket or monopile foundation, comparable to those used in offshore fixed-bottom wind turbines, might be used to support CECO.

CECO can be classified as a floating-point WEC of the oscillating type. The most distinctive characteristic of this WEC is the oblique motion of its floating part, described by the vertical angle (α) established between the direction of motion of its floating part and the horizontal reference

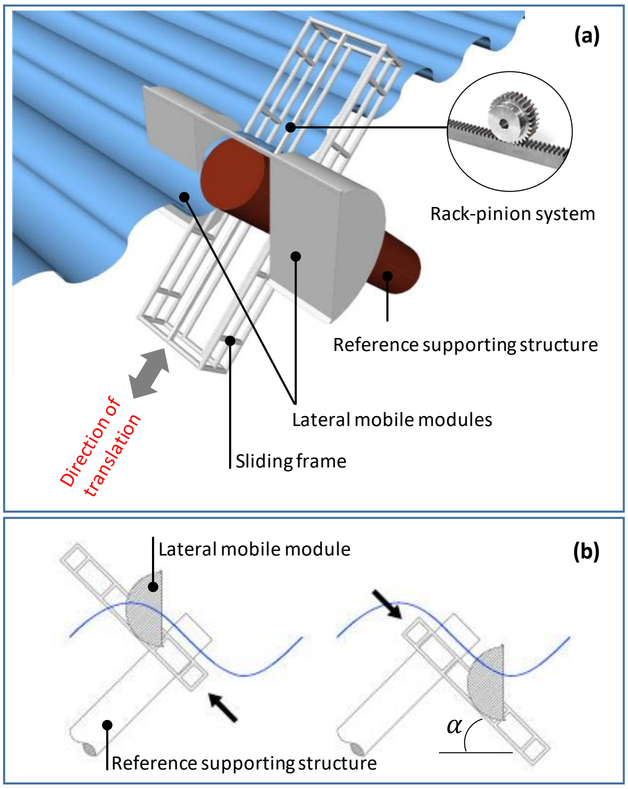

Fig. 1. Main components of CECO WEC (a) and its motion under the action of waves (b).

plane (Figure 1), and the flat vertical face of its two LMMs opposing the propagation of waves (in the original design of CECO). These characteristics give this WEC the ability to capture simultaneously the potential and kinetic energy of waves, not favouring any of those components.

The inclined PTO of CECO is categorized as a direct-mechanical drive system and comprises a rack-pinion mechanism that drives an electric generator. The rack is fixed to the floating part and oscillates together with it along the inclined axis, while the pinion is connected to the generator (fixed inside the reference supporting structure). Therefore, during the conversion of wave energy, the rack drives the pinion that, in turn, rotates the shaft of the generator. In order to adjust the rotational speed and torque, a gearbox may be used in-between the pinion and the electric generator (Rodríguez *et al*., 2018).

The compatibility with other marine energy harnessing technologies can result in a number of potential synergies in construction, operation and maintenance costs, but also in the use of the same physical space and infrastructures and in a more uniform combined electrical power output. Besides the flexibility of installation, the other strengths of CECO are: the scalability, the simple wave-to-wire energy conversion schema resulting in less energy losses and the different options to adapt and fine-tune its hydrodynamic response to incident waves, eventually in real-time (Rosa-Santos *et al*., 2015).

The performance of CECO depends on parameters such as the geometry, mass and dimensions (*i.e*., volume) of the LMMs, its orientation (heading) in relation to the direction of waves, the inclination of the PTO system, the submergence level of the LMMs or the damping associated to the PTO system. Hence, several design variables may be considered in the project of a CECO unit for a particular site and to extend its range of high operational efficiencies to a large variety of sea conditions.

B. Conclusions from previous R&D works

Several studies were carried out in the last six years to assess and improve the performance of CECO, using both physical model tests and numerical simulations (time and frequency domain models). This research effort led CECO to TRL 4 and ongoing work is expected to move this WEC to the next TRL. This section reviews the most significant findings of previews research works, which are the basis of the optimization studies described in this paper.

Rosa-Santos *et al*. (2019) shown that the PTO inclination influences the response of CECO significantly, namely by affecting its hydrostatic and hydrodynamic parameters (*e.g*., hydrostatic restoring coefficients, radiation damping, added mass, wave excitation forces), which directly impact the natural oscillation period and the response amplitudes, *i.e*., the amount of wave power that may be harvested for a given sea state. Each PTO inclination was found to have its specific optimal operating conditions. In general, the intermediate inclinations of 30º and 45° were considered the best ones, *i.e*. they were associated to the highest values of absorbed power for the majority of the tested sea states (Lopez *et al*., 2018). Moreover, it was possible to analyse in detail the three-energy conversion stages of CECO and to discuss the important influence of the damping associated to the PTO on the wave power absorption and subsequent conversion into electricity, for a wide range of sea states (Lopez *et al*., 2017b). In addition, it was found that the PTO damping, in the experimental tests, depends significantly on the wave conditions (Rodríguez *et al*., 2019).

The power matrix determined for the tested CECO unit (Ramos *et al*., 2017, 2018; Lopez *et al*., 2018) shown that the captured wave power is sensitive to wave characteristics, namely the significant wave height (H_{mo}) and peak wave period (T_P). This parameter was found to increase with H_{mo} and reaches its maximum for values of T_P in the range of 10 to 13 s. The relative capture width was higher for the smaller values of H_{mo} and for T_P up to 14 s. In addition, the water depth was found to have a relatively low impact on the captured wave power.

The performance of CECO converting wave energy in the Atlantic coast of the Iberian Peninsula was assessed for a period spamming 10 years (from 2005 to 2014), at three operating water depths, using as reference the parameters (Ramos *et al*., 2017; López *et al*., 2018): captured energy, CE, and captured energy efficiency, CE_{Eff}. Both the inter- and intra-annual variability of the resource were considered in the analysis and significant differences observed along the years and between the summer and the winter months.

The assessment along the Atlantic coast of the Iberian Peninsula allowed concluding that the tested CECO unit has a higher performance under milder wave conditions, *i.e*., the southern locations of the area of study, where the values of the captured energy efficiency are considerably higher, despite the lower resource available. In addition, for a fixed location, it was concluded that CE_{Eff} values are much higher during the summer months, when the wave conditions are milder, while CE presents higher values for winter conditions. In fact, the optimum range of operation of the tested CECO unit is more typical of mild to moderate wave conditions, but not suitable for the highly energetic wave conditions present at the northern locations of the area of study, namely during the winter, where the bulk of wave energy is spread in the range of 9 to 16 s of T_P and H_{mo} above 1.5 m. It was also concluded that CECO absorbs more power for a PTO inclination of 30° and an operating water depth of 30 m, considering the wave climate present in the area of study (Rosa-Santos *et al*., 2019).

In summary, past research has shown promising results in terms of the performance of CECO capturing incident wave energy, both in terms of the captured energy and the captured energy efficiency, with annual values exceeding, in some sites, 600 MWh and 35%, respectively. The results also highlighted limitations of the tested WEC harnessing wave energy under more energetic sea states, providing valuable insights for the optimization study presented in this paper, the most relevant being the need to redesign the geometry of the floating part of CECO to adapt it to sites with energetic wave conditions (>25 kWhm^{-1}).

In fact, despite the possibility of adjusting the response of CECO by varying its PTO inclination and damping, this WEC was not optimized for the energetic wave conditions characteristic of the northern locations of the Atlantic coast of the Iberian Peninsula.

III. Numerical Optimization

C. Definition of the target sea state for optimization

The wave resource characterization done by Ramos *et al.* (2017, 2018) for the Atlantic coast of the Iberian Peninsula shown that in the northern part, the bulk of wave energy is concentrated in the range of H_{mo} = 1.5 ~ 5 m and T_P = 9 ~ 16 s. Furthermore, it can be concluded that the maximum values of the average annual wave energy resource are concentrated around two characteristic sea states: one with T_P = 10 s and H_{mo} = 1.5 m and the other with T_P= 14 s and H_{mo} = 2.5 m, both with about the same amount of mean annual energy. The mean annual occurrence frequency of the first sea state is approx. 19% (1737 hours/year), while for the second one is approx. 5% (442 hours/year). As for that location the level of wave energy for both sea states is quite similar (around 15 ~ 20 MWh/m), the criterion for choosing the target sea state for CECO optimization was the occurrence probability. So, the selected sea state was defined by T_P = 10 s and H_{mo} = 1.5 m.

D. Geometry optimization

The original geometry of CECO presented a high wave energy conversion performance in the experimental proof of concept phase (Rosa-Santos *et al*., 2015) that was found to depend on several parameters, *e.g*., the WEC's setup (*i.e*., LMMs and reference supporting structure), the shape and dimensions of the LMMs and of the reference supporting structure (RSS), the spacing between the RSS and LMMs, the submergence of the LMMs, the PTO slope angle and characteristics (*e.g*., size, gear ratio, rpm), the mechanical losses, the type of electric generator and associated losses, the water depth and wave characteristics at the installation site, among others.

A comprehensive optimization of CECO would require, therefore, systematic variations of all those parameters and the corresponding numerical simulations and experiments for each resulting case. This procedure would be extremely time-demanding and possibly would lead to a significant number of optimized solutions.

In the present work, the optimization of the geometry of the LMMs is fully described, since it is considered to be one of the most relevant variables impacting the performance of CECO. In effect, the hydrodynamic efficiency depends mainly on the submerged WEC geometry, specifically the shape of the LMMs. On the other hand, the other design variables are more prone to have higher changes in future due to technological evolution, namely when moving from model-scale to full-scale, and hence it is assumed that they do not need to be fully optimized at the current TRL stage of CECO.

In the hydrodynamic optimization process of CECO, to limit the number of variables to be changed, the following design restrictions were initially assumed:

- The original layout (two LMMs and a fixed cylinder as RSS);
- The main characteristic dimensions (approx. 4.0 m x 4.5 m x 8.0 m);
- The PTO inclination angle (45º and 30º);
- The submergence of the LMMs (around 50%);
- The target sea state (T_P = 10 s and H_{mo}=1.5 m).

The optimization of the LMMs geometry was performed using a frequency domain model (Rodríguez *et al*., 2019). Since, in general, for a given WEC, its best performance in terms of absorbed power is obtained at resonance and with the theoretical optimum damping (B_{PTO}), the goal was to find resonant floating structures at the peak period of the target sea state.

Differently from the 1-dof heaving WECs, for which the resonant period is essentially a function of the waterplane area and mass, for a WEC with an inclined PTO, finding the natural period of oscillation is more complex due to the strong influence of the inclination. For the assessment of the power performance of the selected geometric shapes, an index denominated pure hydrodynamic efficiency was adopted,

$$\eta_H = \frac{P_{opt}}{JB} \tag{1}$$

where P_{opt} represents the maximum power absorbed by the WEC under the assumption that at each regular wave component of the selected sea state, the WEC operates at its theoretical optimum PTO damping (B_{PTO}), and JB the incident wave power corresponding to the total width of the LMMs. This efficiency index represents the theoretical limit for the maximum power absorption in a given sea-state and allows assessing the hydrodynamic performance of CECO independently of the given (or arbitrarily chosen) PTO damping.

Due to the large number of possibilities for a systematic variation of the geometries of the LMMs, the process was performed heuristically considering the original geometry of CECO as the reference. The modelled alternative shapes included variations in the orientation of the original semi-cylindrical shape of the LMMs, quarter-cylinder, boxed and triangular shapes, as well as combinations of those basic geometries, among other alternatives, Figure 2.

The numerical results demonstrated that although the original geometry of CECO was intuitively idealized, its performance was among the best of all tested alternatives. From the hydrodynamic point of view, more than thirty LMMs' geometries resulted from the heuristic variations of the original shape and PTO inclination.

The natural periods of oscillation for most of the tested geometries were between 5 and 7 s for a PTO inclination of

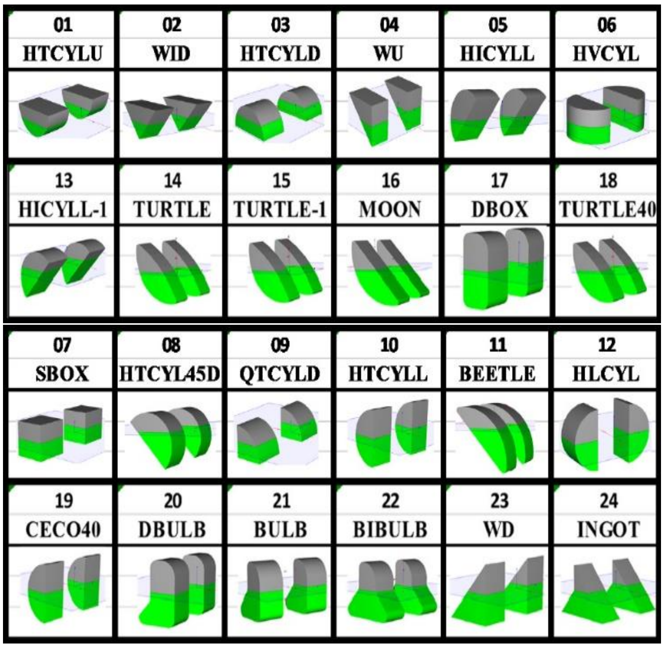

Fig. 2. Examples of geometries considered in the numerical optimization of the LMMs.

45º, *i.e.*, below the target resonant wave period (10 s). To achieve that resonant period for a PTO inclination of 45º, the LMMs geometry needs to have simultaneously a small waterplane area and a large submerged volume. Hence, the resultant geometries (*e.g.*, geometric shapes 20 - 24 in Figure 2) were quite unconventional for WECs and did not provide good hydrodynamic performances. It is important to note that the original CECO had a resonant period of around 8 s for a PTO inclination of 45º. In order to obtain higher resonant periods, the original PTO inclination was decreased, according to the findings of previous studies. A 30º inclination was considered enough for the geometries that displayed natural periods of around 7 to 8 s (at the 45º case). In terms of hydrodynamic efficiency, the shape that provided the best performance at the target sea state was the nº. 18, Figure 2. For the sake of comparison, the original geometry was also analysed considering the inclinations of 30º and 45º (the original design), Figure 3.

The main characteristics of the original (for 45º and 30º of inclination) and optimized (for 30º of inclination) LMMs shapes of CECO are presented in Table 1. The performance of those geometric shapes was assessed through the mean maximum absorbed wave power and the hydrodynamic efficiency at the target sea states.

The maximum available WEC power (in kW) for the target sea states are shown in Figure 4. This maximum WEC power was represented by a frequency-domain function in which ordinates are the absorbed power at each regular-wave frequency component of a given sea state spectra under the assumption that the optimum PTO damping is provided for each component. The amplitude of the wave for the computation of the absorbed power at each frequency is the amplitude of the associated regular wave component. Although the applied approach does not represent a real design condition, it provides the maximum available power that could be ideally absorbed

TABLE I
MAIN CHARACTERISTICS OF CECO: ORIGINAL AND OPTIMIZED SHAPES.

Characteristics	Original	Optimized
PTO inclination angle (º)	45º / 30º	30º
Overall length (m)	4.00	9.52
Overall width (m)	14.68	14.00
Overall height (m)	8.00	9.87
Draught (m)	4.63	5.29
Waterplane area (m²)	36.00	56.70
Mass (t)	139.04	298.44
Natural period (s)	8/10	10
Max. Power @ T_P= 10 s , H_{mo}= 1.5 m (kW)	30.1/53.3	63.7
η_H (T_P= 10 s, H_{mo}= 1.5 m)	0.29/0.52	0.64
Max. Power @ T_P= 14 s, H_{mo}= 2.5 m (kW)	41.7/ 77.4	93.3
η_H (T_P= 14 s, H_{mo}= 2.5 m)	0.12/0.22	0.27

by the WEC in an irregular sea. The performance assessed using such approach is very convenient and practical since it is independent of any PTO damping value (otherwise, arbitrarily chosen).

The optimized geometry (30º inclination) performs quite better than the original CECO design (45º inclination), Figure 4. In fact, the absorbed power and hydrodynamic efficiencies are more than twice those of the original CECO design at the selected sea states, Table 1. In regular waves, both the original and the optimized geometry performed quite well in a relatively broad range of frequencies. However, for the original CECO at 45º of PTO inclination, the lower periods were privileged. When the PTO inclination is set at 30º, the original CECO geometry still presents a good performance in a broad band of periods, but the better performances are situated around the period of 10 s. Such enhancement has resulted in a substantial increase of the absorbed power and of the hydrodynamic efficiencies for the irregular wave conditions.

In spite of the improved performance of the original geometry of CECO when the PTO inclination is modified to 30º, the optimized geometry (30º inclination) still performs better than the original one, especially for the higher wave periods. Furthermore, it should be mentioned that due to its smoother shape, the optimized geometry is expected to present substantial less viscous losses. Since the numerical tool used at this stage is based on potential

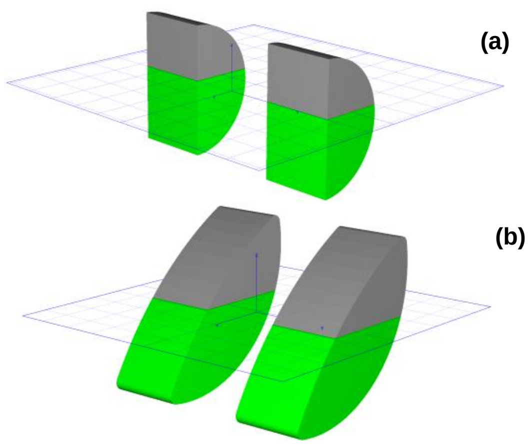

Fig. 3. CECO's geometries: (a) original (b) optimized.

(non-viscous) theory, the above statement could not be verified, but should be investigated later by means of CFD (NSEM) studies or experimental tests.

The frequency-domain model allowed a broad study of alternative geometries for CECO, however the results for a given geometry, *e.g.*, the optimized shape, should be taken from a qualitative (or comparative) perspective. In fact, it is important to investigate the influence of nonlinearities in CECO response, for instance, using the model Ansys® Aqwa™ (Ansys, 2016). This will allow to assess the impact of non-viscous nonlinearities on the results of the applied frequency-domain (linear) model. Moreover, the viscous effects (*e.g.*, drag and friction forces) should be assessed by CFD tools based on the Reynolds Average Navier-Stokes equations or physical model experiments.

The CFD numerical tools can be used to simulate the full hydrodynamic problem (considering waves and viscosity simultaneously), but require a very high computational effort, especially if the 3D complexity of a full CECO unit is considered. Moreover, experimental results for selected test conditions are required to validate the results.

The above conclusions supported the construction of a scale model of the new (enhanced) CECO WEC (Figure 5), prepared for the more energetic stretches of the Atlantic coast of the Iberian Peninsula.

IV. PHYSICAL MODEL STUDY OF CECO

E. *Introduction*

The experimental study of the new CECO geometry was carried out at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto (FEUP), Portugal. The wave basin used is 28 m long, 12 m wide and 1.2 m deep. The selected sea states were generated in the basin with a multi-element piston-type wave generation system,

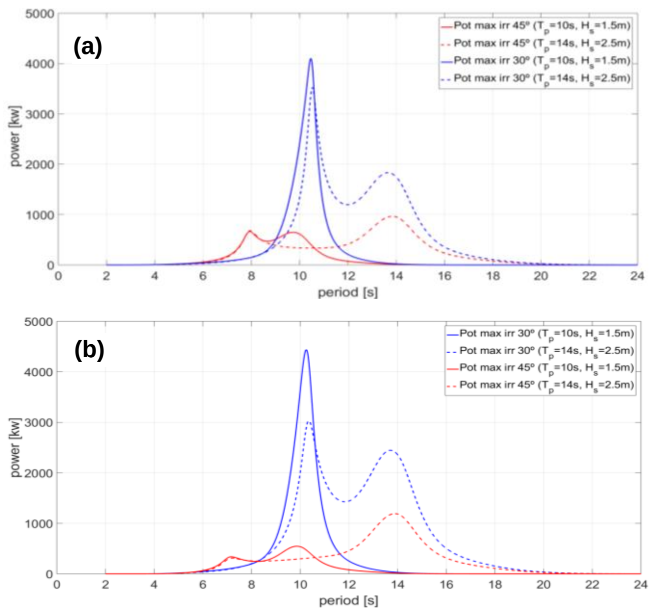

Fig.4. Transfer functions of (maximum) power for CECO: (a) original and (b) optimized.

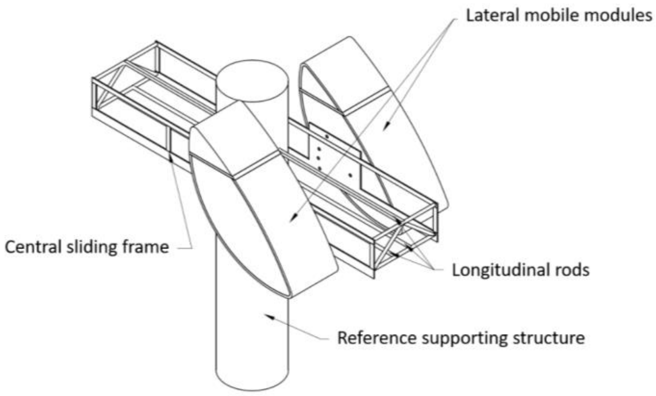

Fig.5. Optimized geometry of the CECO wave energy converter. Identification of main components.

controlled by a HR Wallingford, UK, wave synthesizer and also equipped with a dynamic wave absorption system. A dissipative beach was installed at the opposite end of the wave basin to minimize the reflection of incident waves.

The experimental equipment used consisted of: resistive wave gauges to measure the water free surface elevation (accuracy of ± 0.4 mm), a *Qualisys* motion capture system composed of three digital infrared cameras and capable of measuring the motions of floating bodies in their 6 degrees of freedom (*i.e.*, surge, sway, heave, roll, pitch and yaw) without contact with the model (accuracy of ± 0.5 mm for translational motions and ± 0.1º for rotational motions), and a system to measure directly the instantaneous power output of the PTO during the tests.

A sampling frequency of 40 Hz was selected to avoid aliasing in data spectral analysis and provide a satisfactory accuracy to parameters estimated based on time domain analysis. Wave conditions were calibrated before the tests with CECO, at the location where it was to be installed.

F. *Physical model of CECO*

The physical model used is a scaled-down reproduction of the enhanced CECO geometry on a scale of 1:25, selected in accordance to the dimensions of the wave basin (water depth) and the wave conditions selected for the study. The main differences to the previous experimental studies (*e.g.*, Rosa-Santos *et al.*, 2015, Marinheiro *et al.*, 2015) are mainly in the geometry of the LMMs, as it was improved to reach higher efficiencies under energetic sea states. The physical model was built and tested based on the Froude-similitude criteria.

The dimensions of the LMMs are presented in Table 1. Its maximum expected excursion was 25.0 m. The reference supporting structure was a cylinder with a diameter of 5.0 m that housed the PTO system. All the dimensions are provided in full-scale values. A set of bearings were applied to minimize friction and guide the main rods through the RSS, as this was very important for the operation and performance of the device, Figure 6.

Reproduction of PTO mechanisms in physical models is not straightforward since the technologies suitable for full-scale devices are difficult to downscale. In this study, a

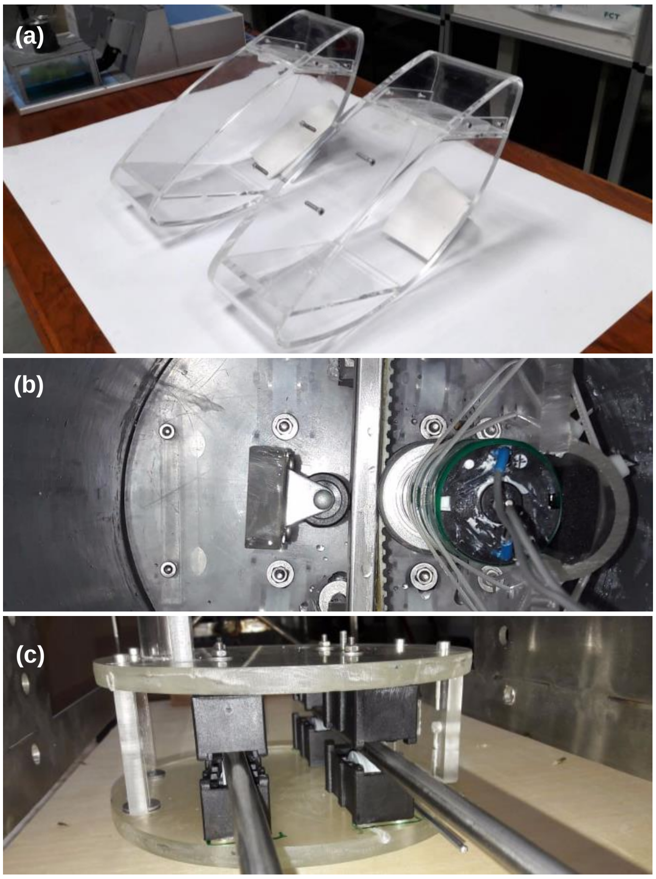

Fig.6. Physical model of CECO: (a) LMMs, (b) PTO housed inside the reference supporting structure and (c) guiding system.

small DC motor, working as generator, was used, which had the advantage of allowing the simulation of different PTO damping levels. The induced PTO damping forces simulate the electrical loads associated to the extraction of energy from ocean waves, to produce electricity. Three PTO damping levels were analysed and some tests were done without the PTO installed. The PTO rotates in both directions, in accordance to the upward and downward motions of the LMMs.

Two different approaches were applied to determine the instantaneous power absorbed, one was based on the direct measurement of the electric potential difference produced by the PTO (method 1), and the other was based on the motions experienced by CECO mobile part during the tests and the PTO performance curves (method 2). Those curves relate the damping force introduced in the system with its velocity (for the conditions tested). Both methods are described in detail by Marinheiro *et al*. (2015).

G. *Test conditions*

The performance of the new CECO unit was analysed for fifteen regular and five irregular wave conditions, three PTO damping levels (Ω), and two inclination of the PTO system (α), Table 2. The range of wave heights and wave periods were selected based on the sea conditions along the Atlantic coast of the Iberian Peninsula.

The irregular waves were generated using the filtered white noise technique for a sequence length of 2^{11}-1 pulses.

TABLE II

TESTING CONDITIONS OF THE PHYSICAL MODEL STUDY

α	Ω	waves	H/H_{mo}	T/T_P
30º	10; 42; 100; S/PTO	Regular	1.0	7; 9.5; 10; 10.5; 11; 12; 13; 14.5
			1.5	10; 10.5; 11; 13
			2.0	10; 11;14.5
	10; 42; 100; S/PTO	Irregular	1.5	7; 10; 13
			2.5	14.5
			3.5	14.5
45º	10; 100 S/PTO	Regular	1.0	7; 9.5; 10; 10.5; 13; 14.5
			1.5	10
			2.0	10; 14.5
	10; 100 S/PTO	Irregular	1.5	7; 10; 13
			2.5	14.5
			3.5	14.5

Regular wave conditions: wave height - H and wave period - T.
Irregular wave conditions: significant wave height - H_{mo} and peak wave period - T_P.

Each sea state was defined by a JONSWAP spectrum (peak enhancement factor of 3.3) and reproduced by about 260 waves. This number is justified by the comparative nature of the study and intends to ensure that tests had durations

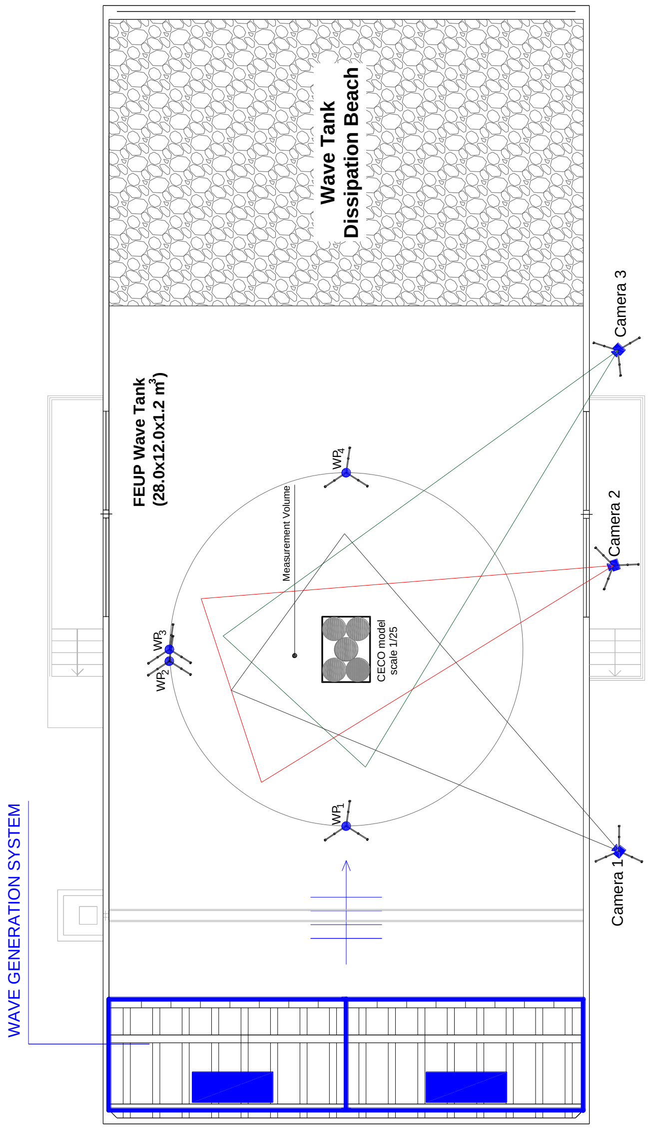

Fig. 7. Physical model set-up in the wave tank of FEUP.

long enough to allow a representative assessment of CECO response. The same temporal sequence of waves was used in the tests having the same peak wave period. Tests with regular waves were carried out for about 150 waves.

In this study, the submersion level of the LMMs was set equal to 50% of their total height. The water depth in the experimental facility was 0.8 m, which corresponds to 16 m water depth in full scale (*i.e.*, prototype). The physical model set-up in the wave tank is presented in Figure 7.

H. Experimental results

For an initial analysis of the hydrodynamic performance of the new CECO geometry in waves, the time series of motions of this WEC without PTO are analysed in regular waves. The wave conditions correspond to those of the target sea states of the intended installation site (*i.e.*, T = 10 s & H=1.50 m and T=14.5 s & H=2.00 m). Figure 8 shows the behaviour of CECO for the 45º inclination while Figure 9 presents the results for the 30º inclination ("surge" refers to the translational motion along the nominal inclination (α) of the sliding frame, Figure 1, and "heave" refers to the motion perpendicular to "surge").

In theory, "heave" motion is restricted, however, due to installation tolerances and misalignments, motions in this direction have also been observed, but with neglectable amplitudes (Figure 8). On the other hand, in few test cases, particularly, those for the more energetic and long waves, "heave" motions were significant (Figure 9). These heave motions may be caused by the bending of the sliding frame (Figure 1), observed during some of the experimental tests with very energetic waves. To avoid this issue, a stronger sliding frame should have been adopted, however, since this solution would have substantially affected the testing schedule, the tests continued without modifications in the structure. Notice, that since deformation is also one mean of energy dissipation, it is believed that greater "surge" excursions could have been obtained if deformation would have not been allowed.

The responses of CECO in surge show that the slope of 45º is more adequate for the 10 s waves, while the 30º slope performs better for the 14.5 s waves. In terms of response-to-wave amplitude ratio (Response Amplitude Operator – RAO) for surge, these tendencies become clearer (Figure 10). Each point in the figures represents the experimental result of a single test. Different points with same marker at the same period, represent different tested wave heights.

Figure 10a shows that the resonant period of surge for the 45º slope is around T = 10 s, which is higher than that experimentally reported for the original CECO's geometry (T = 8 s). Furthermore, the achieved RAO amplitudes are considerably higher than those of the original geometry (López *et al.*, 2017, Rodríguez *et al.*, 2019), confirming that the new design is more suitable than the original one for the target sea state of 10 s. In addition, as expected from classical spring-mass-dashpot oscillating system, the increase in damping makes the resonant amplitudes to decrease and the resonant periods to shift to lower periods, however, still with better performance than the original geometry of CECO wave energy converter.

For the 30º inclination, the behaviour of the surge RAO is more difficult to assess due to the presence of more than one peak in the RAO and the more marked difference in the amplitudes between the conditions without and with PTO. As the highest measured RAO was at T = 14.5 s, and no other tests were performed above this wave period, we can certainly confirm that the effect of reducing the slope was to shift the natural period of the surge motion to, at least, around 14.5 s. Therefore, for the 30º inclination, the new CECO geometry performs quite better for the longer waves – achieving RAOs around 7.0, while, for instance, for the same set-up, at T = 10 s, the RAOs are less than half this value.

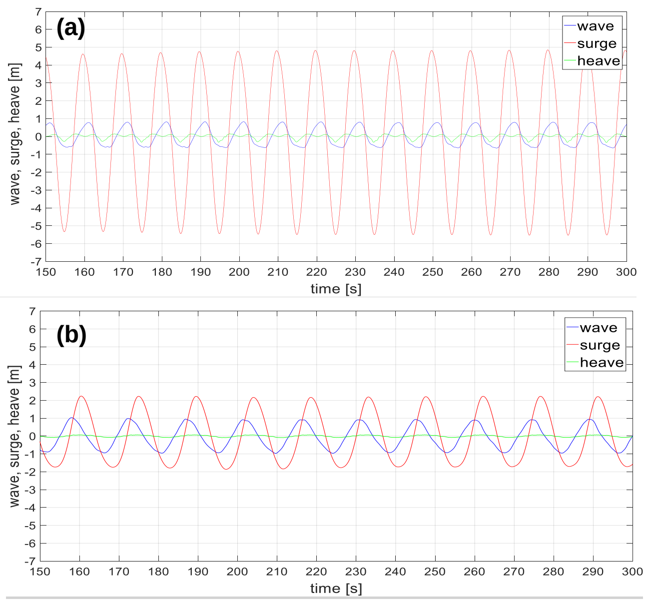

Fig. 8. CECO motions in regular waves for the 45º inclination: (a) T = 10 s & H = 1.50 m (b) T = 14.5 s & H = 2.00 m.

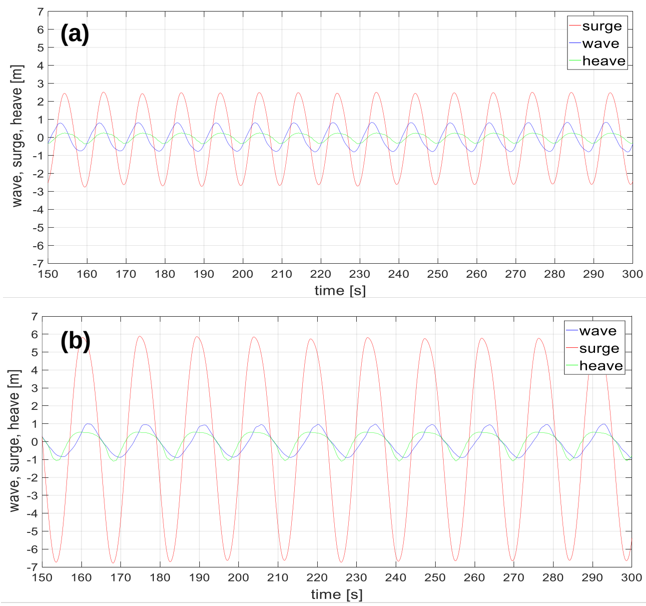

Fig. 9. CECO motions in regular waves for the 30º inclination: (a) T = 10 s & H = 1.50 m (b) T = 14.5 s & H = 2.00 m.

The experimental results have confirmed the tendencies predicted by the frequency domain (linear) model, namely the increase of the natural period for the new geometry and the shift to larger natural periods related to a decrease in the inclination angle. Nonetheless, quantitatively, there are important differences between the predicted and the experimental values of the natural periods. For instance, the numerical model predicted for the new geometry, at the inclination of 45º, a natural period around 7 s, so that to achieve 10 s, a reduction in the PTO inclination to 30º was necessary. On the other hand, according to the experimental results, for the 45º PTO inclination, the new geometry displayed a natural period of 10 s, while for the 30º inclination, the natural period shifted to more than 14.5 s. The differences between the numerical and experimental results must be further investigated. On one side, the numerical model applied could be oversimplifying the hydrodynamic forces. Indeed, due to the characteristics of the new CECO geometry, even small excursions of the LMMs can trigger significant changes in the submerged geometry (which may directly affect the hydrodynamic loads). However, on the other hand, uncertainties in the experimental set-up (*e.g.*, deformations due to bending or clearances) may affect the measured motions. All these effects will be investigated in future research works, but do not invalidate the qualitative conclusions obtained.

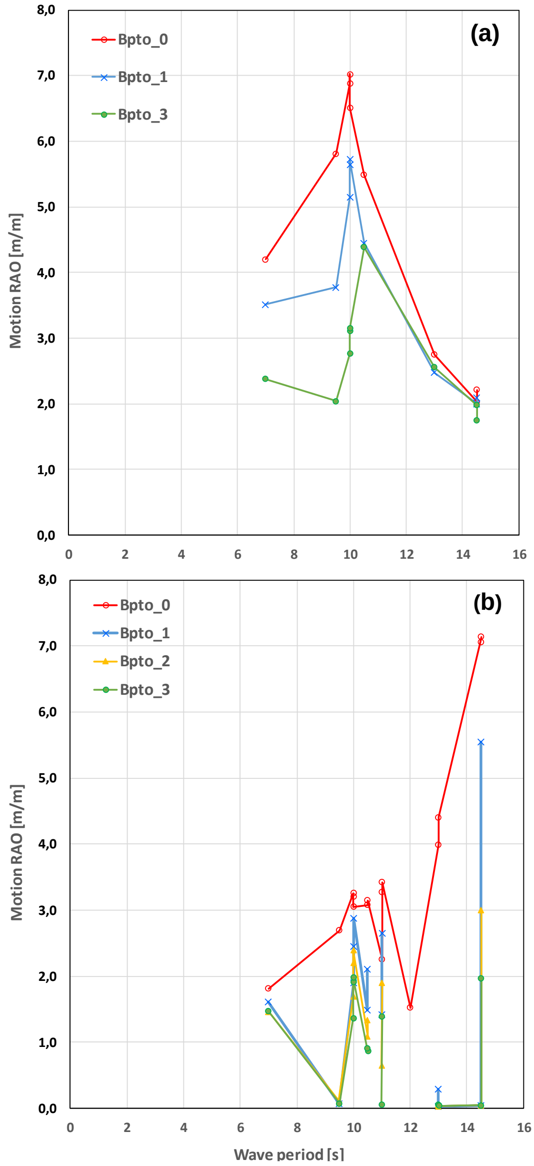

Fig. 10. Experimental RAO of CECO for different damping levels: (a) 45º inclination, (b) 30º inclination.

The hydrodynamic performance of the new geometry has been also assessed in irregular waves for the condition without damping. Figure 11 compares the motion spectra for the two tested inclinations of CECO for the target sea condition, *i.e.*, $T_p = 10$ s and $H_{m0} = 1.50$ m, with the response spectra of the original CECO geometry for a sea state with the same peak period, but with a higher significant wave height. It is quite clear that the new geometry at the 45º inclination is, by far, the more advantageous in terms of converting wave excitation in WEC motions for that sea state. On the other hand, for the sea state, $T_p = 14.5$ s and $H_{m0} = 2.50$ m, the 30º inclination performs significantly better than the 45º inclination (Figure 12).

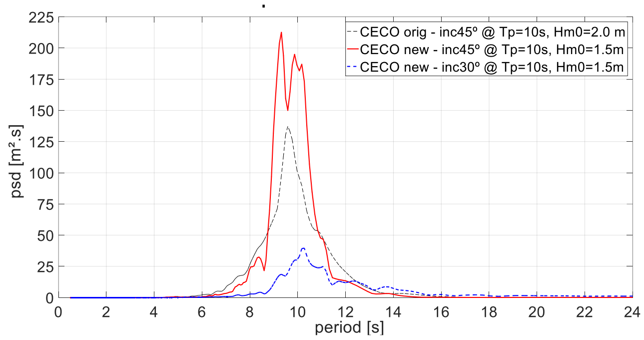

Fig. 11. Experimental motion response spectra of CECO without PTO damping.

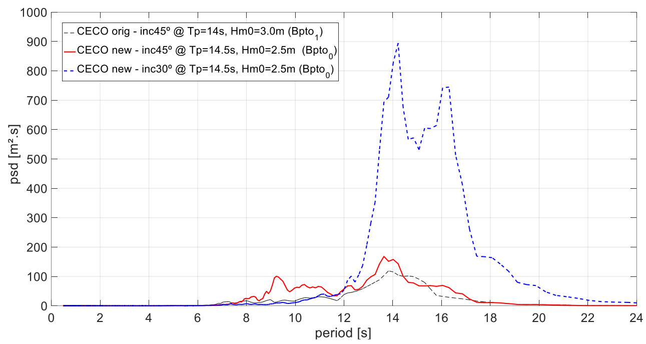

Fig. 12. Experimental motion response spectra of CECO for long waves.

Although power computations from the experimental data of the new CECO geometry are not available yet, in terms of hydrodynamic performance, the experimental results have shown that the new geometry is able to convert wave energy in motions more efficiently than the original one, as predicted by the numerical model. Nevertheless, further analyses are required to address the quantitative differences between the numerical predictions and the experimental measurements.

V. Conclusion

Outcomes of recent studies were described to provide an overview on the present status of knowledge about the

CECO wave energy converter and identify present issues and challenges. The numerical study carried out resulted in a new geometric shape for the LMMs, optimized for the wave conditions typical of the North Atlantic coast of the Iberian Peninsula. It also predicted, for the new geometry, a higher natural period of oscillation and a hydrodynamic efficiency of more than twice the original one, for the target wave conditions.

The new geometry was tested on a geometric scale of 1/25 at the wave basin of the Faculty of Engineering of the University of Porto, Portugal. The conclusions obtained so far support the design of the new geometry, nevertheless further research is still required to address and understand the quantitative differences noticed between the numerical predictions (obtained with a linear numerical model) and the experimental measurements.

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