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Hydrodynamic response of the WEC sub-system of a novel hybrid wind-wave energy converter

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ABSTRACT

Multiple marine resources are usually available in the same area and synergies between the different users of these resources exist. Multipurpose platforms, which combine more than one of these renewable resources, have been proposed as a sustainable approach. One type of multipurpose platforms is the hybrid wind-wave systems, in which a single platform combines the exploitation of offshore wind and wave energy. In this paper a novel hybrid system that integrates an oscillating water column (OWC) wave energy converter (WEC) with an offshore wind turbine on a monopile substructure is considered. The main objective of this paper is to define and test a simplified version of the WEC sub-system of this hybrid energy converter. An experimental campaign was carried out to characterise the hydrodynamic response of a 1:37.5 scale model of the WEC sub-system under regular and irregular waves. On the basis of the data from the experimental campaign, the hydrodynamic response of the WEC sub-system is characterised in four steps: (i) through an incident and reflected wave analysis (IRWA), to characterise the interaction between the device and the waves; (ii) through the capture width ratio, to study the performance of the device; (iii) through response amplitude operators (RAOs) of the free surface elevation and pneumatic pressure inside the OWC chamber, to study the effects of the incident waves on the device response; and (iv) through the wave run-up on the device. The results from this multifaceted analysis lead to the proof of concept of this novel hybrid system, supporting its feasibility to be combined with offshore wind substructures; but also to characterise its behaviour and interaction with the wave field, essential to full understanding of the benefits of hybrid systems.

Keywords: Wave energy; Offshore wind; Hybrid wind-wave; Physical modelling; Hydrodynamic response

1. INTRODUCTION

The sustainable exploitation of multiple marine resources – e.g., marine renewable energies (MREs), food resources (fisheries and aquaculture), maritime transport and leisure among others - has a great potential for development [1-5] and, therefore, for playing a fundamental role in the future EU maritime policy [6, 7]. In the last decade, multipurpose platforms have been suggested as a means to a sustainable exploitation of certain maritime resources, which are usually available in the same area [8-12]. In this context and considering the strong synergies between offshore wind and wave energy, combined wind-wave systems are of particular interest [13, 14].

The combined exploitation of wave and offshore wind energy has been classified [13] into: co-located, hybrid and island systems, depending on the degree of connectivity between the offshore wind and wave energy sub-systems. Various technical reports have recently acknowledged that co-located marine energies and multipurpose platforms are real alternatives. Most of these reports stem from EU funded research projects [15-19] aimed at enhancing industrial and scientific collaboration towards a more sustainable energy supply. At present there are only a few scientific publications dealing with wind-wave systems. The characterisation of the combined resource and the assessment of the potential for the combination of both technologies [20-22], for example, through the co-location feasibility index (CLF) [23-25] and the assessment of co-located wind-wave technologies following a marine spatial planning approach, [26] has identified that the benefits of combining both technologies are greater when un-correlated resources are combined. Grid integration issues, including the grid balancing cost of combined electricity production are considered by [27-32]; [33-36] have shown how the shadow-effect of a co-located wind-wave farm affects the operation the overall cost of a combined farm. Different hybrid wind-wave energy converters are studied by [37], including a multi-Mega-Watt wind turbine and platform with an array of oscillating water columns (OWCs), which are a type of wave energy converter WEC. Some examples of hybrid wind-wave systems suggested previously are: the floating hybrid Poseidon by the Danish Floating Power Plant AS [38], the floating hybrid platform W2Power proposed by the Norwegian Pelagic Power AS [39], the fixed hybrid based on an oscillating body proposed by the German NEMOS GmBH. Other previous proposals of hybrid systems are those presented by: the Danish companies Wavestar AS [40], Wave Dragon AS [41] and LEANCON Wave Energy AS [42] and the UK company Wave Trader Ltd [43].

This paper deals with a novel hybrid system that integrates an OWC, with an offshore wind turbine on a monopile substructure. The hybrid wind-wave energy converter considered for this paper builds on that presented in [44], to define a new prototype for the WEC sub-system. On the basis of this assessment - together with the relevance of synergies, such as the shadow effect, it was identified that

there was a lack in the literature of evaluation methods to fully represent the hydrodynamic response of a WEC sub-system for hybrid wind-wave energy converters.

The set of methods proposed in this paper tackles the characterisation of the hydrodynamic response of a WEC sub-system by means of physical modelling following a four step approach. First, the interaction between the device and the wave field – a critical element to understand the implications of the shadow effect – is characterised with an incident and reflected wave analysis (IRWA) method. Secondly, the capture with ratio is used to study the performance of the OWC. Thirdly, the response of the two main parameters affecting the performance of the OWC, namely the free surface elevation and the pneumatic pressure inside the OWC chamber, is characterised by means of the response amplitude operator (RAO). Finally, the run-up coefficient is used to study the wave run-up at the front of the device.

This article is structured as follows. The hybrid wind-wave energy converter is described in Section 2. The physical model, experimental set-up, experimental programme, and the data analysis techniques are described in Section 3. The results are presented in Section 4 and their discussion in Section 5. Finally, conclusions are drawn in Section 6.

2. THE HYBRID WIND-WAVE ENERGY CONVERTER

2.1. Hybrid concept

The prototype of the WEC sub-system considered for this work builds on the hybrid concept presented in [44], where an OWC type of WEC is mounted on a bottom-fixed offshore wind substructure. The first configuration (Figure 1a) integrates a cylindrical OWC chamber around a monopile substructure. The chamber is fixed to the monopile, opened at the base and connected at the upper part to an air turbine - e.g., a Wells or an impulse turbine. The monopile is the most extensive type of offshore wind substructure system, with diameters ranging from 4 m to 6 m depending on the type of wind turbine and the water depth, offshore wind turbines used together with monopiles range from 3 MW to 7 MW and have a hub height between 70 m and 100 m over the mean sea level. Moreover, the water depth for monopile mounted wind farms ranges from 10 m to nearly 30 m [45].

A jacket-frame type of substructure is considered for the second configuration (Figure 1b). The free space inside the jacket foundation is used to install a conical shaped OWC chamber, to optimise the space inside the substructure. As in the previous configuration, the chamber is fixed to the substructure with the bottom open. Jacket-frame substructures for offshore wind are a type of foundation system designed to reach deeper waters than traditional systems – e.g., monopiles of gravity-base structures. This type of substructure usually consists of tubular lattice towers which are

designed to be deployed at water depths ranging from 20 m to up to 50 m, and usually supports turbines of 5 MW [46].

Figure 1: Conceptual representation of a hybrid wind-wave energy converter considering an OWC as WEC sub-system for two different configurations: (a) as a hybrid mounted on a monopile and (b) as a hybrid mounted on a jacket frame

2.2. The OWC WEC sub-system

Based on the hybrid concept from the previous section, a prototype for a WEC sub-system combining an OWC and a monopile was initially defined in the framework of a new patent [47], with patent number WO2016185189A1. The patent defines a novel hybrid wind-wave energy converter, where the WEC sub-system has the capability to self-adapt to different wave heights and tidal ranges as well as to the direction of the incident waves. Figure 2 shows a schematic representation of one of the possible configurations of the prototype. The figure shows different views of the device, where some of the components and parts of the device are indicated. The proposed device is formed by – note that the numbers shown in brackets refer to the ones in the figure:

1. a chamber (1);
2. a substructure system, (2) to link the device to the seabed – i.e., usually the substructure system will be shared with a wind turbine;
3. a ballast tank (3), defined as part of the hull of the chamber between the inner (7) and external walls of the chamber;
4. a skirt (4) or extension at the bottom of the chamber;
5. one or more air turbines (5) which act as the OWC power take off turning the electric generator to produce electricity;

6. a security and control system comprising pressure relief valves (6); and
7. a set of bulkheads (8) that give structural strength and divide the internal part of the chamber into separate segments (9).

Figure 2: Schematic representation of one of the configurations of the prototype showing its different parts. A front view of the device is at the top-left, a rear view of the device at the top-right, a top view in the bottom-left and a perspective view in the bottom-right. Clarification for the meaning of the different numbers can be found in the text (reproduced from [47])

2.3. Development of the hybrid system

Once an initial version of the hybrid wind-wave prototype was designed, the next phase in the development process requires the validation of the prototype, so the different systems and sub-systems proposed in the patent application can be optimised and assessed in detail. The development of the hybrid system requires a multi-stage approach [48, 49]; in particular, for the prototype considered in this work, a three-step approach is suggested. The first step focuses on the proof of concept of the device, and on the definition of a set of methods to evaluate, optimise and assess the performance of this and future iterations of the model. The second step uses these tools to run an optimisation process of the device – this optimisation focuses on increasing the hydrodynamic performance of the device, reducing the loads on the substructure and testing the performance of the proposed sub-systems. Finally, the third step involves a complete detailed techno-economic assessment of the updated prototype from the optimisation phase.

This paper deals with the first step, by characterising the hydrodynamic response of the device. An experimental campaign defines and tests a simplified version of the WEC sub-system. The results

145 from the experimental campaign are used to: (i) set the reference for future evaluations of different
 146 prototype configurations, and (ii) define a set of methods to characterise the hydrodynamic response
 147 of the device.

148 3. MATERIALS AND METHODS

149 3.1. Physical model

150 A physical model based on a simplified version of the hybrid prototype was built. The 1:37.5 scale
 151 model (Figure 3) was designed considering the limitations of the experimental facility and various
 152 sources [50-52]. The most important characteristics and dimensions of the model are presented in
 153 Table 1.

154

155

156

Figure 3: Schematic representation of the model

157 The scale model was designed considering a geometrically undistorted model – i.e., the scale ratio
 158 for both the vertical and horizontal lengths is the same ($\lambda_L = 37.5$) – and the Froude similitude. The

scale ratio was selected in accordance with: (i) the diameter of various full-scale monopile substructures; (ii) the dimensions of the experimental facility; (iii) the water depth and wave conditions tested. The offshore wind turbine was not included in the scale model of the WEC sub-system as it does not have an impact on the hydrodynamic response of the WEC sub-system.

Table 1: Model characteristics and dimensions

Parameter		Dimension
<i>OWC Chamber</i>		
Model scale	λ	1/37.5
Chamber shape	-	Semi-cylindrical
Chamber material	-	Polyester and methacrylate
PTO	-	Perforated discs
Chamber external diameter	$\varnothing d_{OWC}$	$64.5 \times 10^{-2} \text{ m}$
Chamber length	l_{OWC}	$43.2 \times 10^{-2} \text{ m}$
Skirt length	l_s	$9.3 \times 10^{-2} \text{ m}$
Distance from the skirt to the bed	a	$31.4 \times 10^{-2} \text{ m}$
Chamber draught		$26.2 \times 10^{-2} \text{ m}$
Water depth	h	$53.3 \times 10^{-2} \text{ m}$
Chamber wall thickness	e_{OWC}	$0.3\text{-}0.5 \times 10^{-2} \text{ m}$
Inner chamber water plane area	A_{OWC}	0.1532 m^2
<i>Monopile</i>		
Monopile shape	-	Cylindrical
Monopile material	-	PVC
Monopile external diameter	$\varnothing d_m$	$16.0 \times 10^{-2} \text{ m}$
Monopile length	l_m	1.0 m
<i>Base plate</i>		
Base shape	-	Square
Base Material	-	Stainless-steel
Base length	b	$64.5 \times 10^{-2} \text{ m}$
Base thickness	e_b	$0.3 \times 10^{-2} \text{ m}$
Base sleeve length	l_b	$9.0 \times 10^{-2} \text{ m}$

The model was built in polyester, PVC, methacrylate and stainless-steel. The OWC chamber was built in 3-5 mm thickness polyester with marine finish. It has a frontal panel made of polyester and methacrylate with 5 mm thickness which was fixed to the rest of the chamber using an epoxy resin. The monopile was built using a PVC pipe with an external diameter of 160 mm. Finally, a 3 mm stainless steel square base was used as the main support for the model. The damping induced in the OWC chamber of the full-scale prototype by an impulse turbine can be modelled by means of an orifice [51, 53, 54]. To study the influence of the turbine-chamber coupling [55] three different turbines (orifice diameters) were considered. For this purpose, a system of perforated discs, one per orifice was

used. The main characteristics of the perforated discs can be found in Table 2. Here, the diameter of the orifices was defined by the area coefficient (C_A), as the ratio between the area of the orifice (A_{orif}) and the area of the OWC chamber (A_{owc}), ranging between 0.5% and 2% of A_{owc} [56].

$$C_A = \frac{A_{orif}}{A_{owc}} \quad (1)$$

Table 2: Characteristics of the perforated disc used to model the PTO damping

Perforated disc code	ϕd_o	C_A
Ø30 mm	3.06×10^{-2}	0.48%
Ø44 mm	4.39×10^{-2}	0.99%
Ø51 mm	5.14×10^{-2}	1.35%

3.2. Experimental set-up and testing programme

The experimental campaign was carried out in the wave-current flume of the University of Santiago de Compostela (USC), which has a total length of 20 m, a height of 0.95 m, a width of 0.65 m and a variable water depth between 0.20 m and 0.60 m. Waves are generated with a piston type wave-maker, from the Danish hydraulic institute (DHI), which is equipped with an active wave absorption control system (AWACS) to absorb reflected waves. The paddle has a maximum stroke of 0.60 m, being normally positioned at the middle point with a partial stroke of ± 0.30 m. The reference system adopted to define the experimental set-up has been as follows: the axis Ox , is the longitudinal axis that passes through the mid plane of the flume, with $x = 0$ at the wave-maker and positive direction towards the model; axis Oz , vertical, with positive direction upwards and $z = 0$ at the free-surface in repose; and axis Oy , perpendicular to the flume, with positive direction such that the trihedral $Oxyz$ has positive orientation. The model was positioned with the centre of the monopile at $x = 10.9$ m and the water depth was fixed at 0.533 m – i.e., corresponding to a prototype water depth of 20 m at the scale of 1:37.5.

Nine conductive wave gauges (WGs) were used to measure the displacement of the free surface along the flume and three ultrasonic water level (UWL) sensors to do it inside the OWC chamber (Figure 4). Five of the WGs were positioned along the centreline of the flume: the first one (WG1) was located at $x_1 = 2.525$ m to record the wave generation; the next three (WG2, WG3 and WG4) at $x_2 = 8.55$ m, $x_3 = 9.35$ m and $x_4 = 9.75$ m, to record the data for a reflection analysis; and the last one (WG9) at $x_9 = 11.55$ m, to record the transmitted wave. The remaining four wave gauges were positioned: three aligned with the front of the monopile (WG5, WG6 and WG7) at $x_{5-7} = 10.813$ m and $y_5 = 0.197$ m, $y_6 = 0$ m and $y_7 = -0.142$ m respectively, to measure the run-up at the monopile; the final

one (WG8) at $x_8 = 10.9$ m and $y_8 = -0.207$ m, to record the run-up at the front of the OWC chamber. The three UWL sensors - *LUV31* from *Omega* - were attached to three respective 1" NPT shafts which were built with the model. The three UWL sensors (UWL1, UWL2 and UWL3) were positioned at $x = 11.05$ m and $y_1 = 0.15$ m, $y_2 = 0$ m and $y_3 = -0.15$ m. In addition, the differential pneumatic pressure between inside and outside the chamber was measured by means of a differential pressure transducer (PT) - *LPM / LPX 5480* from *GE Druck*. Data from the different instruments positioned along the flume and on the model were acquired with the DHI hardware and software, at a sampling frequency of 20 Hz.

Figure 4: Experimental Set-up

The experimental programme was defined for a range of wave conditions and the three different orifice sizes. A site in 20 m of water depth, close to the port of A Guarda (NW Spain), was considered for selecting the wave conditions. Figure 5 shows the scatter diagram for this selected reference site, and Table 3 its main characteristics. The methodology followed to generate these wave conditions can be seen in [57]. Note that even though the impact of the tidal level on the energy extraction of an OWC has been proved to be relevant in the case of fixed OWC systems (e.g., [58]), this has not been considered for this experimental campaign as the proposed prototype has the capability to adapt to the tidal level by adjusting the relative position of the OWC to the mean water level.

222 The tests were structured in five different series, two for regular waves (Series A and Series B),
 223 two for irregular waves (Series C and Series D) and one to test the repeatability of the previous four
 224 series (Series R) [48, 49, 52]. Series A defines regular linear wave tests by combining three wave
 225 heights ($H = 0.75, 1.25$ and 1.75 m, in prototype values) and eight wave periods ($T = 7, 8, 9, 10, 11, 12,$
 226 13 and 14 s, also in prototype values). Series B defines regular non-linear wave tests by combining six
 227 wave heights ($H = 1.75, 2.25, 2.75, 3.25, 3.75$ and 4.25 m, in prototype values) and the same eight
 228 wave periods as for Series A. The non-linear free surface elevation considered for Series B was
 229 determined as explained in Appendix A. The duration of the regular tests was defined to last for at
 230 least 100 waves for Series A and 50 waves for Series B. Note that the lowest wave height on Series B
 231 ($H = 1.75$ m) was tested for comparative purposes with Series A.

Figure 5: Scatter diagram of the selected reference site

Table 3: Characteristics of the selected site

Selected reference site data	
Location	A Guarda (NW Spain)
Latitude [UMT]	29 T / 508,250 m E
Longitude [UMT]	29 T / 4,640,000 m N
Water depth	20.170 m
Predominant climate	Atlantic
Annual mean power	25.67 Kw/year
Resolution in period	1 s
Resolution in height	0.5 m

235 The hydrodynamic response of the device under irregular waves was studied in Series C, which is
 236 defined for seven different sea states and a Joint North Sea Wave Project (JONSWAP) spectrum. Series
 237 D defines six JONSWAP [58] sea states with the same significant wave height and different peak wave

periods, to study the effect of the wave period on the response of the device (Table 4). The duration of all the irregular wave tests was selected to match 60 minutes at prototype scale.

Table 4: Wave conditions for the two irregular waves series (Series C and D) (prototype data)

Sea state code	H_S	T_E	T_Z	T_P
Series C				
C01	1.25 m	6.70 s	5.58 s	7.81 s
C02	1.75 m	7.88 s	6.57 s	9.19 s
C03	2.25 m	8.82 s	7.35 s	10.29 s
C04	2.75 m	8.98 s	7.48 s	10.47 s
C05	3.25 m	9.37 s	7.81 s	10.93 s
C06	3.75 m	9.86 s	8.22 s	11.51 s
C07	4.25 m	10.33 s	8.61 s	12.05 s
Series D				
D01	2.25 m	7.50 s	6.25 s	8.75 s
D02	2.25 m	8.50 s	7.08 s	9.92 s
D03	2.25 m	9.50 s	7.92 s	11.08 s
D04	2.25 m	10.50 s	8.75 s	12.25 s
D05	2.25 m	11.50 s	9.58 s	13.42 s
D06	2.25 m	12.00 s	10.00 s	14.00 s

Finally, the repeatability tests (Series R) were structured in three subgroups, one for each of the regular waves series (RA and RB) and a final one for irregular waves (RC). Series RA is defined by combining two wave heights ($H = 0.75$ and 1.75 m, in prototype values) and three wave periods ($T = 8, 10$ and 12 s, also in prototype values). Series RB is defined by combining two wave heights ($H = 1.75$ and 3.25 m, in prototype values) and the same three wave periods as for Series RA. Finally, Series RC is defined for three sea states with $H_S = 1.25$ m and $T_P = 6.70$ s, $H_S = 2.25$ m and $T_P = 8.82$ s, and $H_S = 3.25$ m, and $T_P = 9.37$ s, in prototype values. Each of the wave conditions defined for the three subgroups was repeated for five consecutive tests. The mean values of the two indicators from the statistical analysis of the data from the repeatability series – i.e., the correlation coefficient (R^2) and the normalised root mean square error ($NRMSE$), obtained as explained in Appendix B – can be found in Table 5.

The time series of the free surface elevation from the wave gauges at their different positions along the flume, the free surface elevation from the ultrasonic water level sensors inside the OWC chamber and the differential pneumatic pressure between inside and outside the OWC chamber from the pressure transducer are presented in Figure 6 as an example of a regular waves test.

259 **Table 5:** Mean values of the correlation coefficient (R^2) and the normalised root mean square error ($NRMSE$) for the
 260 recorded data from the wave gauges (WG), ultrasonic water level (UWL) sensor and pressure transducer (PT) from the
 261 repeatability test series

	WG	UWL	PT
<i>Series RA</i>			
R^2	0.994	0.992	0.999
$NRMSE$	6.18%	6.21%	2.05%
<i>Series RB</i>			
R^2	0.996	0.979	0.995
$NRMSE$	4.34%	10.18%	3.53%
<i>Series RC</i>			
R^2	0.991	0.983	0.995
$NRMSE$	2.60%	5.14%	1.55%

263 **Figure 6:** Recorded data from the free surface elevations along the flume, the oscillation of the water column and the
 264 pressure drop inside the OWC chamber during part of a test ($H = 0.75$ m, $T = 12$ s, $B^* = 107.52$)
 265
 266

3.3. Data analysis

An incident and reflected wave analysis (IRWA) method [59, 60], was used to characterise the incident and reflected waves. Data series from the central group of wave gauges (WG2, WG3 and WG4) were used as input for the method. Based on the incident and reflected wave heights and on the transmitted wave height obtained from the wave gauge in the lee of the model (WG9), the reflection and transmission coefficients (K_R and K_T) can be defined for regular waves [50] as

$$K_R = \frac{H_R}{H_I}, \quad (2)$$

$$K_T = \frac{H_T}{H_I}. \quad (3)$$

and for irregular waves as

$$K_R = \sqrt{\frac{m_{0R}}{m_{0I}}}, \quad (4)$$

$$K_T = \sqrt{\frac{m_{0T}}{m_{0I}}}, \quad (5)$$

where m_{0i} is the generic zero order moment,

$$m_{0i} = \int_{f_{min}}^{f_{max}} S_i(f) df \quad (6)$$

S_i is a generic power spectral density, and the respective incident, reflected and transmitted zero order moments (m_{0I} , m_{0R} and m_{0T}) can be obtained by replacing S_i with the power spectral density of the respective incident, reflected and transmitted waves.

Based on the incident wave height or the incident power spectral density, obtained from the IRWA, the mean power for the incident waves per metre of wave front, J , can be defined for regular waves as

$$J = \frac{\rho_W g H_I^2 c_g}{8}, \quad (7)$$

and for irregular waves

$$J = \rho_W g \sum_{i=1}^N S_i(c_g)_i \Delta f, \quad (8)$$

where ρ_W is the water density; g the gravitational acceleration; H_I the incident wave height; N is the number of frequency components or bands (for each Δf), and S_i and $(c_g)_i$ are the spectral density and the group velocity for the i -th band, respectively. The group velocity is given by

$$(c_g)_i = n_i c_i, \quad (9)$$

where

$$n_i = \frac{1}{2} \left(1 + \frac{2k_i h}{\sinh(2k_i h)} \right), \quad (10)$$

where h is the water depth, k_i the wave number for the i -th frequency band and c_i is the phase celerity,

$$c_i = \frac{\omega_i}{k_i}, \quad (11)$$

where ω_i is the angular frequency of the i -th band, obtained from the dispersion relationship,

$$\omega^2 = g k_i \tanh(k_i h). \quad (12)$$

The mean pneumatic power of the OWC converter, P_m , during a test is given by

$$P_m = \frac{1}{t_{max}} \int_0^{t_{max}} \Delta p q dt, \quad (13)$$

where Δp is the relative pressure between the chamber and the atmosphere, q is the volumetric air flow rate through the chamber's orifice, t is time and t_{max} is the duration of the test. The relative pressure is measured directly from the differential pressure sensor data and the volumetric air flow is determined assuming conservation of mass and from the velocity of the free surface inside the inner chamber multiplied by the water plane area of the inner chamber [51, 61]. The velocity of the free surface is obtained by numerical differentiation of the mean of the free surface elevation data recorded with the three ultrasonic water level sensors (UWL1, UWL2 and UWL3).

The efficiency of an OWC is commonly defined as the ratio between the pneumatic power absorbed by the air turbine, P_m , and the wave power incident on the device – i.e., the incident wave power per metre of wave front, J , times a relevant dimension, b , in m – known as the capture width ratio (C_{WR}),

$$C_{WR} = \frac{P_m}{Jb}. \quad (14)$$

The Response Amplitude Operator (RAO) is widely used to study the relationship between the incident wave and the magnitude of the output of some of the characteristic parameters of a WEC. In this paper, the RAO is used to compare the relation between the amplitude of the incident wave; and the amplitude of the surface oscillation and the pneumatic pressure inside the OWC chamber. The oscillation of the free surface inside the OWC chamber is obtained from the mean of the three ultrasonic water level sensors and the relative pneumatic pressure from the differential pressure transducer data (PT). For regular waves the RAO operator for the translation motion of the chamber's free surface oscillation in heave (RAO_C) can be rewritten as

$$RAO_C = \frac{H_C}{H_I}, \quad (15)$$

where H_I is the incident wave height and H_C is the chamber's free surface oscillation height. A similar approach is followed for the RAO of the pneumatic pressure (RAO_P), however, this time it must be divided by the water density (ρ_w) and the gravitational acceleration (g) to make the RAO non-dimensional

$$RAO_P = \frac{1}{\rho_w g} \frac{H_P}{H_I}, \quad (15)$$

where H_I is the incident wave height and H_P is the variation of the pneumatic pressure height.

The evaluation of wave run-up at the front of the monopile (WG6) and at the middle of the frontal face of the OWC chamber (WG8) is carried out by means of the so called wave run-up coefficient, which can be defined for regular waves [62] as

$$C = \frac{R}{H_I}, \quad (16)$$

where R is the wave run-up and H_I is the incident wave height.

Among all the different run-up values commonly used to evaluate the irregular waves run-up over a structure – i.e., the maximum run-up (R_{max}), the run-up exceeded by 2% of the crest ($R_{2\%}$), the average of the highest 1/10 of the run-ups ($R_{1/10}$), the average of the highest 1/3 of the run-ups or significant run-up (R_S) and the mean run-up ($\bar{R}$) – two have been selected to define the maximum and significant run-up coefficients (C_{max}) and (C_S) respectively

$$C_{max} = \frac{R_{max}}{H_{SI}}, \quad (17)$$

$$C_S = \frac{R_S}{H_{SI}}, \quad (18)$$

where H_{SI} is the incident significant wave height.

The hydrodynamic response of an OWC depends not only on the wave conditions (wave height and period) but also on the damping that the air turbine exerts on the system [63, 64]. In order to quantify this influence, a dimensionless damping coefficient can be defined, following [58], as

$$B^* = \frac{\Delta p^{1/2}}{q \rho_a^{1/2}}, \quad (19)$$

where Δp is the relative pressure between the chamber and the atmosphere, q is the volumetric air flow rate through the chamber's orifice and ρ_a is the air density. The damping coefficient represents the ratio between the square root of the pressure drop and the volumetric flow rate, which for a given chamber geometry depends only on the orifice diameter ($\varnothing do$) – i.e., the smaller the orifice diameter, the larger the damping. Following [54], the damping coefficients for the three orifice diameters tested ($\varnothing do = 30, 44$ and 51 mm) are $B^* = 208.52, 107.12$ and 76.38 respectively.

331 4. RESULTS

332 4.1. Incident and reflected wave analysis (IRWA)

333 An incident and reflected wave analysis (IRWA) was performed with data from the experimental
 334 campaign to obtain the incident and reflected wave heights and to characterise the reflection and
 335 transmission coefficients (K_R and K_T). The results corresponding to the three damping coefficients
 336 tested under regular and irregular waves are summarised in Figure 7 and Figure 8 respectively.

337

338

339 **Figure 7:** Variation of the reflection and transmission coefficients (K_R and K_T) with the wave steepness (S) for
 340 regular waves (Series A and B); and for different values of the wave period (T) and damping coefficient (B^*) (prototype
 341 data)
 342

343 It is clear that the coefficients (K_R and K_T) are mainly driven by the wave period and to a small
 344 extent by the wave steepness (S for regular waves and S_S for irregular waves, see Appendix C) and the
 345 turbine damping (B^*). Data are mostly well grouped except for the two smallest periods ($T = 7$ and 8
 346 s) in regular waves and the sea state with the smallest wave height in the irregular waves Series C (H_S

347 = 1.25 m and $T_P = 7.81$ s); which show more scattered results and sometimes a different
 348 behaviour - e.g., the larger and intermediate damping coefficients values ($B^* = 208.52$ and 107.12).
 349 The reflection coefficient (K_R) shows a reduction in the reflection when the wave period increases. In
 350 general, the reflection coefficient increases with the wave steepness, with the exception of the smallest
 351 wave period ($T = 7$ s) in regular waves. The influence of the wave steepness on the reflection
 352 coefficient becomes more pronounced for larger wave periods. In addition, it can be observed that the
 353 reflection coefficient increases when the damping coefficient increases.
 354

Figure 8: Variation of the reflection and transmission coefficients (K_R and K_T) with the significant wave steepness (S_S) for irregular waves (Series C and D) and for different values of damping coefficient (B^*) (prototype data)

355

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357

358

359 The transmission coefficient (K_T), in contrast with the reflection coefficient, increases with the
 360 wave period and decreases when the wave steepness increases, the effects of the latter becoming more
 361 pronounced for larger wave periods and for irregular waves. The variation of the transmission
 362 coefficient with the damping coefficient is very small, except for smaller values of the wave steepness

363 ($S < 0.02$) for regular waves and ($S_s < 0.015$) for irregular waves, where a small increase in the
 364 transmission is observed when the damping coefficient increases.

365 4.2. OWC performance

366 The performance of the hybrid device is evaluated with the capture width ratio (C_{WR}), shown in
 367 Figure 9 for the three values of the damping coefficient versus wave steepness (S) and in Figure 10
 368 versus the significant wave steepness (S_s) for regular and irregular waves, respectively. In addition,
 369 Figure 11 shows the C_{WR} matrix.

Figure 9: Variation of the capture width ratio (C_{WR}) with the wave steepness (S) for regular waves (Series A and B); and for different values of the wave period (T) and damping coefficient (B^*) (prototype data)

374 From Figure 9 and Figure 10 it can be observed that the damping coefficient, above all, is the
 375 parameter that influences the C_{WR} most. The best performance is obtained, in general, for the
 376 intermediate damping value ($B^* = 107.12$). However, the largest damping value ($B^* = 208.52$) shows a
 377 better performance for lower steepness values ($S < 0.02$) and large wave periods ($T > 10$ s) for regular
 378 waves and low significant wave steepness ($S_S < 0.015$) for irregular waves, the C_{WR} decreasing less
 379 markedly with decreasing wave steepness for the other damping values. In addition, Figure 9 shows
 380 that, the higher the wave steepness, the lower the C_{WR} .
 381

382
 383 **Figure 10:** Variation of the capture width ratio (C_{WR}) with the significant wave steepness (S_S) for irregular waves
 384 (Series C and D) and for different values of damping coefficient (B^*) (prototype data)

Figure 11: Variation of the capture width ratio (C_{WR}) with the wave height (H) and wave period (T), or C_{WR} matrix, for regular waves (Series A and B) and for different values of the damping coefficient (B^*) (prototype data).

Figure 11 shows the performance or C_{WR} matrix for regular waves, a means to better understand the influence of the different parameters on the performance. The C_{WR} is represented in terms of the wave height (H) and period (T) for each of the three damping coefficient values (B^*). An area of best performance is found for the three damping values for the lower wave periods ($T < 10$ s) showing a maximum efficiency at ($T = 8$ s). The smallest damping value ($B^* = 76.38$) shows a better performance for larger values of the wave height ($H > 3$ m), and the larger damping ($B^* = 208.52$) shows a better performance for large wave periods ($T > 10$ s) and low wave heights ($H < 3$ m). The influence of the damping coefficient over the C_{WR} is higher than that of the wave height or period.

4.3. Device response

The response amplitude operators (RAOs) for the free surface oscillation and pressure drop inside the OWC chamber (RAO_C and RAO_P respectively) are represented for the three values of the damping coefficient versus the wave steepness (S) in Figure 12 and versus the wave frequency (f) in Figure 13.

Figure 12: Variation of the response amplitude operator (RAO) for the free surface elevation and the pressure drop inside the OWC chamber (RAO_C and RAO_P respectively) with the wave steepness (S) for regular waves (Series A and B): and for different values of the wave period (T) and damping coefficient (B^*) (prototype data).

In Figure 12 it can be clearly seen that both RAOs are mainly driven by the damping coefficient (B^*) and the wave steepness (S). Data are, in general, well grouped except for the smaller wave period ($T = 7$ s) and values of the RAO of the free surface oscillation of the OWC chamber with small wave steepness ($S < 0.02$) and the smaller damping coefficient ($B^* = 76.38$). Both RAOs show opposite behaviours, when the RAO of the free surface oscillation decreases, the pressure drop RAO increases and vice versa. The higher the damping coefficient and the higher the wave steepness (S), the lower the free surface oscillation RAO (RAO_C). Therefore, the higher the damping coefficient and the higher the wave steepness, the higher the pressure RAO (RAO_P).

Figure 13: Variation of the response amplitude operator (RAO) for the free surface elevation and the pressure drop inside the OWC chamber (RAO_C and RAO_P respectively) with the wave frequency (f) for regular waves (Series A and B); and for different values of the wave height (H) and damping coefficient (B^*) (prototype data).

Figure 13 shows the traditional representation of the measured values for both RAOs against the wave frequency (f); the following observations may be drawn: First: the free surface oscillation inside the OWC chamber RAO (RAO_C) converges to 1 for the lower frequencies for the middle and smaller damping coefficient values ($B^* = 107.12$ and 76.38) – i.e., meaning that the amplitude of the free surface oscillation inside the OWC chamber equals the incident wave amplitude, reducing the efficiency of the device as observed in Figure 8. Secondly, for the large damping coefficient ($B^* = 208.52$) values of RAO_C do not converge. This lack of convergence for lower frequencies explains why the CWR matrix for the same damping coefficient value shows better efficiency values for higher wave periods. Thirdly, values of RAO_C increase when both the wave period and the damping coefficient decrease. Fourthly, the pneumatic pressure inside the OWC chamber RAO (RAO_P) converges for larger frequencies and increases its divergence as the wave frequency decreases, showing, in general, its

maximum value for wave periods around ($T = 8$ s) – i.e., this maximum in the pressure drop amplitude is shown at the same wave period where the maximum efficiency is found (Figure 11). Finally, values of $RAOP$ increase when both the wave period and the damping coefficient increase.

4.4. Run-up

An analysis of the run-up at the part of the device facing the incoming waves was performed with data from the experimental campaign, to characterise the run-up coefficient (C_R) for regular waves and the significant and maximum run-up coefficients (C_S and C_{max}) for irregular waves. The results at the front of the monopile are summarised in Figure 14 and Figure 15 for regular and irregular waves, respectively. In addition, those at the middle of the frontal face of the OWC chamber are presented in Figure 16 and Figure 17 for regular and irregular waves, respectively.

It is apparent that the run-up coefficient, at both positions in the model, is influenced, above all, by the wave steepness (S) for regular waves and the significant wave steepness (S_S) for irregular waves, and to a lesser extent by the damping coefficient (B^*). Data are mostly well grouped, with low scatter in both the regular waves run-up coefficient (C_R) and the irregular waves significant run-up coefficient (C_S); however, the irregular maximum run-up coefficient (C_{max}) has more scatter and much larger values in average.

For regular waves, the run-up coefficient (C_R) shows, in general, values equal or larger than 1 for wave steepness values larger than ($S > 0.02$) – i.e., the run-up equals or exceeds the amplitude of the incident wave. Therefore, the higher the wave steepness (S) and the higher the damping coefficient, the higher the run-up coefficient. Furthermore, comparing the run-up at both positions in the model, it can be clearly seen that it is higher at the mid-point of the OWC front than at the monopile. Nevertheless, when looking at the irregular waves run-up a clear difference is evident. On the one hand, the significant run-up coefficient (C_S) presents the same behaviour as the regular run-up coefficient (C_R). On the other hand, the maximum run-up coefficient (C_{max}) shows a completely different behaviour. Although, the significant steepness (S_S) is still clearly the parameter that influences the C_{max} , followed by the damping coefficient (B^*), average values of C_{max} are now in the range 0.7 and 2.6.

Figure 14: Variation of the run-up coefficient (C_R) at the front of the monopile with the wave steepness (S) for regular waves (Series A and B); and for different values of the wave period (T) and damping coefficient (B^*) (prototype data)

Figure 15: Variation of the significant and maximum run-up coefficients (C_s and C_{max}) at the front of the monopile with the significant wave steepness (S_s) for irregular waves (Series C and D) and for different values of damping coefficient (B^*) (prototype data)

Figure 16: Variation of the run-up coefficient (C_R) at the middle of the frontal face of the OWC chamber with the wave steepness (S) for regular waves (Series A and B); and for different values of the wave period (T) and damping coefficient (B^*) (prototype data)

Figure 17: Variation of the significant and maximum run-up coefficients (C_S and C_{max}) at the middle of the frontal face of the OWC chamber with the significant wave steepness (S_S) for irregular waves (Series C and D) and for different values of damping coefficient (B^*) (prototype data)

5. DISCUSSION

In this work, a novel concept of a hybrid wind-wave energy converter, where an OWC is considered for the WEC sub-system, was first introduced. Then, the prototype for a possible configuration of the WEC sub-system was described. A comprehensive series of physical model tests were carried out to tackle the first part of the development of the hybrid device. A simplified version of the WEC sub-system prototype was defined and tested in order to set the reference for future evaluations of different prototype configurations and to define a set of methods to characterise the hydrodynamic response of the device.

The parameters investigated to characterise the hydrodynamic response of the hybrid device were the wave height and wave period; and the damping coefficient, which quantifies the damping exerted

by the air turbine on the motion of the free surface inside the oscillating water column chamber. The turbine damping was modelled by a number of orifices of different diameters made on a series of exchangeable disks, each of the orifices diameters corresponds to a value of the damping coefficient for given wave conditions. In total, 315 tests were performed, considering regular and irregular wave conditions, structured into five different test series. The hydrodynamic response of the device was characterised by considering four different sets of analysis techniques: (i) an incident and reflected wave analysis, to determine the reflection and transmission coefficients (K_R and K_T); (ii) the analysis of the capture width ratio (C_{WR}), to study the efficiency or ratio between the pneumatic power output of the OWC and the incident wave power; (iii) the analysis of the RAOs of the free surface oscillation and the pressure drop inside the OWC chamber (RAO_C and RAO_P respectively), to study the relationship between these fundamental components of the OWC power output with the incident wave; and (iv) the analysis of the run-up coefficient at different positions in the front of the model.

The reflection analysis identified the wave period as the parameter that influences the wave reflection and transmission coefficients most – i.e., much more so than the wave steepness and the turbine damping coefficient. As the wave period increases the reflection coefficient decreases – note that this behaviour is the opposite to that observed for a coastal structure extending down to the seabed but similar to the one observed for other WECs, e.g., [65, 66] – and the transmission coefficient increases. In addition, a similar influence but to a lesser degree has been identified for the damping coefficient, with the reflection coefficient increasing and the transmission coefficient decreasing when the damping coefficient increases. The IRWA shows that the WEC sub-system interacts with the wave field by transmitting between 12% and 37% of the incident wave power and reflecting between 23% and 71%. This interaction is a key input to understand the implications that the ‘the shadow effect’ may have at a larger scale – i.e., at the wind farm scale.

The analysis of the hybrid device performance showed that the damping coefficient is the parameter that most affects the capture width ratio, highlighting the importance of the fundamental role of the turbine-chamber coupling when designing an OWC device. For the wave conditions and damping coefficient values tested, the intermediate damping coefficient value ($B^* = 107.12$) is the one that shows, in general, the highest values of the C_{WR} , although the highest damping coefficient value ($B^* = 208.52$) shows better values of the C_{WR} for large wave periods and low wave heights – i.e., lower values of the wave steepness ($S < 2 \times 10^{-2}$) for irregular waves and significant wave steepness ($S_s < 1.5 \times 10^{-2}$) for irregular waves. Furthermore, maximum efficiency values are found for the three damping coefficient values at the wave period of ($T = 8$ s) for regular waves and for the peak periods between 7 s and 10 s for irregular waves.

The analysis of the main parameters that influence the power output of an OWC – i.e., the pneumatic pressure inside the chamber, and the free surface oscillation inside the chamber – was carried out by means of the RAO. Both RAOs show a strong relationship with the wave steepness and the damping coefficient, when both the damping coefficient and the wave steepness increase, the free surface oscillation RAO decreases and the pneumatic pressure RAO increases. The free surface oscillation RAO converges to 1 for lower wave steepnesses and the intermediate and the smaller damping coefficients, this does not occur for the highest damping coefficient, which, explains the increased efficiency for this particular damping and wave steepness values. Furthermore, the pressure drop RAO presents a more or less uniform behaviour, converging for lower wave periods and showing a maximum at ($T = 8$ s), which coincides with the wave period at which the maximum efficiency is found.

The analysis of the run-up coefficient at the front of the monopile and at the middle of the frontal face of the OWC chamber shows larger run-ups at the face of the OWC chamber and a direct relationship of the run-up coefficient and the wave steepness, and to a smaller degree with the damping coefficient. The run-up increases when both the wave steepness and the damping coefficient increase. In addition, from the analysis of the irregular run-ups it was noticed that while the significant run-ups present a similar behaviour to the regular waves run-ups, the maximum run-ups show values on average between 1.5 and 2 times larger and a stronger dependence on the wave steepness.

6. CONCLUSIONS

In this work the hydrodynamic response of the WEC sub-systems of a novel hybrid wind-wave energy converter was successfully assessed by means of an intensive physical model test campaign. Based on the results of the experimental campaign, the two main objectives of this paper were achieved: (i) to prove the concept of the proposed WEC sub-system, showing its feasibility to be combined with offshore wind substructures; and (ii) to propose and apply a set of methods for assessing the hydrodynamic response of the WEC sub-systems of hybrid devices, which allows the complete characterisation of the performance of the device and its interaction with the wave field.

Based on the results from this work it is clear that the proposed WEC sub-system constitutes a viable solution to be considered as a hybrid wind-wave energy converter; notwithstanding, certain issues require further work – e.g., the increased loads on the substructure. Thus, the results of this work are but an initial step towards the development of the proposed prototype.

Previous research on either hybrid or WEC devices was mostly focused on individual parameters, such as the efficiency or the RAOs. Notwithstanding, to completely characterise the hydrodynamic response of a hybrid system's WEC sub-system the classical approach is not enough, and novel

558 parameters must be considered. This work defines a comprehensive set of methods based on four main
559 pillars: (i) the interaction between the device and the wave field, (ii) the OWC efficiency, (iii) the
560 response of the two main parameters driving the efficiency of the OWC – the free surface oscillation
561 and the pressure drop inside the OWC chamber – to the incident wave field, and (iv) the wave run-up
562 at the front of the device. This set of methods allows the behaviour of the WEC sub-systems to be fully
563 characterised and will constitute a starting point for future research to further evaluate the effects of
564 this behaviour at a larger scale pneumatic – e.g., the behaviour of a hybrid wind-wave farm. In addition,
565 this work also serve as a reference case for future iterations in the development of the prototype, and
566 for the validation of complex numerical models.
567

568 NOMENCLATURE

569	a	= distance from the skirt to the bed [m]
570	A_{orif}	= area of the orifice [m]
571	A_{OWC}	= area of the OWC chamber [m]
572	b	= device width or device base length [m]
573	B^*	= turbine damping coefficient [m]
574	C_A	= area coefficient [--]
575	c_g	= group velocity [$m\ s^{-1}$]
576	c_i	= phase celerity [$m\ s^{-1}$]
577	C_R	= run-up coefficient [--]
578	C_S	= significant run-up coefficient [--]
579	c_S	= mass transport velocity or Stokes drift [$m\ s^{-1}$]
580	C_{max}	= maximum run-up coefficient [--]
581	C_{WR}	= capture width ratio [--]
582	e_b	= base thickness [m]
583	e_{OWC}	= OWC chamber wall thickness [m]
584	f	= wave frequency [Hz]
585	g	= gravitational acceleration [$m\ s^{-2}$]
586	H	= wave height [m]
587	h	= water depth [m]
588	H_I	= incident wave height [m]
589	H_R	= reflected wave height [m]
590	H_S	= significant wave height [m]
591	H_T	= transmitted wave height [m]
592	J	= wave power per metre of eave front [$kW\ m^{-1}$]
593	J_{WEC}	= wave power per unit width of the WEC [kW]
594	k	= wave number [--]
595	K_A	= absorption coefficient [--]
596	K_R	= reflection coefficient [--]
597	K_T	= transmission coefficient [--]
598	l_b	= base sleeve length [m]
599	l_m	= monopile length [m]
600	l_{OWC}	= OWC chamber length [m]
601	l_S	= skirt length [m]
602	m_{0C}	= zero-order moment of the free surface oscillation at the OWC chamber [m^2]
603	m_{0I}	= zero-order moment of incident wave [m^2]
604	m_{0P}	= zero-order moment of the pressure drop at the OWC chamber [m^2]
605	$NRMSE$	= normalised root mean square error [--]
606	P_m	= mean pneumatic power [kW]
607	q	= volumetric flow rate [$m^3\ s^{-1}$]
608	R	= run-up [m]
609	R^2	= correlation coefficient [--]
610	RAO_C	= free surface oscillation at the OWC chamber RAO [--]

611	RAO_P	= pressure drop at the OWC chamber RAO [--]
612	S	= steepness parameter [--]
613	S_i	= spectral density [$\text{m}^2 \text{Hz}^{-1}$]
614	S_S	= significant steepness parameter [--]
615	T	= wave period [s]
616	T_E	= energy wave period [s]
617	T_P	= peak wave period [s]
618	T_Z	= mean wave period [s]
619	$\bar{u}$	= horizontal velocity [m s^{-1}]
620	Z	= free surface oscillation of the OWC chamber [m]
621	<i>Greek</i>	
622	$\varnothing d_m$	= monopile diameter [m]
623	$\varnothing d_o$	= diameter of the orifice [m]
624	$\varnothing d_{owc}$	= Chamber external diameter [m]
625	Δf	= frequency band [Hz]
626	Δp	= pneumatic pressure drop [Pa]
627	η	= free surface oscillation [m]
628	λ	= scale ratio [--]
629	ρ_a	= density of air [kg m^{-3}]
630	ρ_w	= density of water [kg m^{-3}]
631	<i>Acronyms</i>	
632	<i>AWACS</i>	= active wave absorption control system
633	<i>DHI</i>	= Danish hydraulic institute
634	<i>IRWA</i>	= incident and reflected wave analysis
635	<i>MRE</i>	= marine renewable energy
636	<i>OWC</i>	= oscillating water column
637	<i>PT</i>	= pressure transducer
638	<i>RAO</i>	= response amplitude operator
639	<i>USC</i>	= University of Santiago de Compostela
640	<i>UWL</i>	= ultrasonic water level
641	<i>WEC</i>	= wave energy converter
642	<i>WG</i>	= wave gauge
643		

644 SUPPLEMENTARY MATERIALS

645 The research materials supporting this publication may be accessed at
646 <http://hdl.handle.net/10026.1/11373>. If you have any question regarding these research materials,
647 please contact the corresponding author of this paper.
648

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653 APPENDIX A. NON-LINEAR WAVE MODEL

654 For this work, the non-linear free surface $\eta(x, t)$ is defined using an algorithm suggested by
 655 Fenton [67] implemented using also [68, 69]. First the wave number is calculated using the Newton's
 656 method for a residual error of 1.00×10^{-5} .

$$\begin{aligned} f(k) = \left(\frac{k}{g}\right)^{1/2} c_S - \frac{2\pi}{T(gk)^{1/2}} + C_0(kh) + \left(\frac{kH}{2}\right)^2 \left(C_2(kh) + \frac{D_2(kh)}{kh}\right) + \\ \left(\frac{kH}{2}\right)^4 \left(C_4(kh) + \frac{D_4(kh)}{kh}\right) + \dots = 0, \end{aligned} \quad (20)$$

657 where: k is the wave number, T the period, h the mean water depth, H the wave height, c_S the “mass
 658 transport velocity” or “Stokes drift velocity” – for laboratory experiments in tanks with closed ends,
 659 as is the case, a value $c_S = 0$ can be considered – and the coefficients C_n which can be found in [67].

660 The algorithm following Newton's Method is:

$$k_0 = \frac{4\pi^2}{(gT^2)} \left(1 - \frac{4\pi\bar{u}}{(gT)}\right). \quad (21)$$

661 From $n=0$ (and $n=1, 2 \dots$ as appropriate)

$$k_{n+1} = f(k_{0,1,2,\dots,n}) - \frac{\delta f(k_{0,1,2,\dots,n})}{\delta k}. \quad (22)$$

662 The algorithm stops if $k_{n+1} - k_n < 0.000001$

663 Once the value of k is known, with d , H and T as known variables, the wave length λ can be
 664 obtained from, Equation 23 and the wave celerity c from Equation 24:

$$k = \frac{2\pi}{\lambda}, \quad (23)$$

$$c = \frac{\omega}{k} = \frac{\lambda}{T}. \quad (24)$$

665 Finally, the free surface is obtained from Equation 25 – where $\epsilon = kh/2$ – is the wave steepness
 666 and t is also known:

$$\begin{aligned}
k \eta(x, t) = & kh + \epsilon \cos(k(x - ct)) \\
& + \epsilon^2 B_{22} \cos(2k(x - ct)) \\
& + \epsilon^3 B_{31} (\cos(k(x - ct)) - \cos(3k(x - ct))) \\
& + \epsilon^4 (B_{42} \cos(2k(x - ct)) + B_{44} \cos(5k(x - ct))) \\
& + \epsilon^5 (-(B_{53} + B_{55}) \cos(k(x - ct)) \\
& + B_{53} \cos(3k(x - ct)) + B_{55} \cos(5k(x - ct)))
\end{aligned} \tag{25}$$

667 APPENDIX B. STATISTICAL INDICATORS

668 The correlation coefficient (R^2) and the Normalised Root Mean Square Error ($NRMSE$) defined
669 by Equation 26 and Equation 27 respectively was used to compare the different recorded time series
670 for the repeatability tests.

$$R^2 = \frac{(\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y}))^2}{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_i - \bar{y})^2} \tag{26}$$

671 where x_i and y_i are the equivalent data points from the two different data sets, of length N ; and $\bar{x}$ and
672 $\bar{y}$ are their respective arithmetic averages. This coefficient gives an idea on how identical are the series
673 compared, being 1 when both series are identical.

$$NRMSE = \frac{1}{x_{max} - x_{min}} \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2}, \tag{27}$$

674 where x_{max} and x_{min} are the maximum and the minimum values of the reference data set – i.e., the
675 maximum height values of the physical model dataset. The maximum height of the signals was used
676 over the average due to the sinusoidal nature of the data.

677 APPENDIX C. WAVE STEEPNESS

678 The wave steepness parameter (S) used to analyse the results for regular waves is defined as

$$S = 2\pi \frac{H}{gT^2}, \tag{28}$$

679 where H is the wave height, g is the acceleration of gravity (9.81 m/s^2) and T is the wave period. For
680 irregular waves, the significant steepness parameter is defined as

$$S_S = 2\pi \frac{H_S}{gT_P^2}, \tag{29}$$

681 where H_S is the significant wave height, g is the acceleration of gravity and T_P is the peak wave period.

682

683

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