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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.

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

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Nomenclature

a	distance from the skirt to the bed [m]
A_{orif}	area of the orifice [m]
A_{OWC}	area of the OWC chamber [m]
b	device width or device base length [m]
B^*	turbine damping coefficient [m]
C_A	area coefficient [–]
c_g	group velocity [m s^{-1}]
c_i	phase celerity [m s^{-1}]
C_R	run-up coefficient [–]
C_S	significant run-up coefficient [–]
c_S	mass transport velocity or Stokes drift [m s^{-1}]
C_{max}	maximum run-up coefficient [–]
C_{WR}	capture width ratio [–]
e_b	base thickness [m]
e_{OWC}	OWC chamber wall thickness [m]
f	wave frequency [Hz]
g	gravitational acceleration [m s^{-2}]
H	wave height [m]
h	water depth [m]
H_I	incident wave height [m]
H_R	reflected wave height [m]
H_S	significant wave height [m]
H_T	transmitted wave height [m]
J	wave power per metre of eave front [kW m^{-1}]
k	wave number [–]
K_A	absorption coefficient [–]
K_R	refection coefficient [–]
K_T	transmission coefficient [–]
l_b	base sleeve length [m]
l_m	monopile length [m]
l_{OWC}	OWC chamber length [m]
l_S	skirt length [m]
m_{0C}	zero-order moment of the free surface oscillation at the OWC chamber [m^2]
m_{0I}	zero-order moment of incident wave [m^2]
m_{0P}	zero-order moment of the pressure drop at the OWC chamber [m^2]
$NRMSE$	normalised root mean square error [–]
P_m	mean pneumatic power [kW]
q	volumetric flow rate [m^3 s^{-1}]
R	run-up [m]
R^2	correlation coefficient [–]
RAO_C	free surface oscillation at the OWC chamber RAO [–]
RAO_P	pressure drop at the OWC chamber RAO [–]
S	steepness parameter [–]
S_i	spectral density [m^2 Hz^{-1}]
S_S	significant steepness parameter [–]
T	wave period [s]
T_E	energy wave period [s]
T_P	peak wave period [s]
T_Z	mean wave period [s]
$\bar{u}$	horizontal velocity [m s^{-1}]
Z	free surface oscillation of the OWC chamber [m]

Greek

$Ød_m$	monopile diameter [m]
$Ødo$	diameter of the orifice [m]
$Ød_{OWC}$	Chamber external diameter [m]
Δf	frequency band [Hz]
Δp	relative pneumatic pressure [Pa]
η	free surface oscillation [m]
λ	scale ratio [–]
ρ_a	density of air [kg m^{-3}]
ρ_w	density of water [kg m^{-3}]

Acronyms

AWACS	active wave absorption control system
DHI	Danish hydraulic institute
IRWA	incident and reflected wave analysis
JONSWAP	Joint North Sea Wave Project
MRE	marine renewable energy
OWC	oscillating water column
PT	pressure transducer
RAO	response amplitude operator
USC	University of Santiago de Compostela
UWL	ultrasonic water level
WEC	wave energy converter
WG	wave gauge

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 GnBH. 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 (Fig. 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