Numerical investigation of a new hybrid floating wind turbine concept

Beatrice Fenu, Mauro Bonfanti, and Giuliana Mattiazzo

Abstract—**In today's energy scenario dominated by the need to develop new methods of generating electricity, energy-intensive infrastructures are a promising solution towards energy self-sufficiency and environmental sustainability. Floating offshore wind turbine represents one of the major solution to exploit renewable energies. Currently, the increase of offshore wind market opens up the possibility of integrating different technologies to take advantage of marine energy potential, in particular wave energy. This work presents a new wave-wind hybrid floating platform with three Oscillating Water Columns (OWC) integrated in a floating offshore wind spar buoy. The design methodology is described showing the size of geometric characteristics of OWCs and the size of the energy conversion system. The hybrid system is investigated by a time-domain model that integrates the wind turbine model, the hydrodynamics of the floater, t he thermodynamics of the OWC air chambers, and the damping effect induced by the OWC air turbine. The thermo-aero-hydro coupled numerical framework is described to highlight the implementation of the thermodynamic model in WEC-Sim/MATLAB environment. Specifically, t he w ater column dynamics are solved as piston-rigid body representation, enabling the time-domain analysis of the OWC dynamic behaviour. Impulse turbines are considered as OWC Power Take-Offs (PTO). The resource scenario of Mediterranean Sea is considered as case study, in terms of both wind and wave conditions. The analysis focuses on the power extraction capabilities of the OWCs and on the impact of OWCs on the productivity of the wind turbine. Further developments on multi-objective design tools and on optimal PTO control design aiming power maximisation could be conducted for hybrid energy platforms based on this established numerical framework.**

Index Terms—**Hybrib platform, Oscillating Water Column, time-domain model, WecSim.**

I. Introduction

The integration of wave energy converters into floating wind turbine structures has gained considerable attention in recent years as a promising avenue for maximizing energy capture and enhancing the overall efficiency o f o ffshore r enewable e nergy s ystems. By combining the harnessing of wind and wave resources, this integrated approach holds great potential to unlock significant s ynergies a nd p rovide a m ore sustainable and reliable power generation solution. Overall, the development of a wide range of wave energy converters has shown promise in tapping into the vast potential of ocean waves. Several technologies are investigated numerically and experimentally, chasing the proof of concept and the numerical validation [1]–[4]. Among these technologies, oscillating water columns have emerged as one of the most successful options, owing to their mechanical and structural simplicity. OWCs combined into the FOWTs structure not only enable platform stabilization but also increase the quantity and quality of the energy to be harvested.

By integrating wave energy converters into floating wind turbine structures, renewable energy developers can benefit from optimized resource utilization, improved energy yield, and potentially reduced costs. However, challenges such as system design, control strategies, and the interaction between wind and wave devices need to be carefully addressed to maximize the benefits of this integrated approach. Zhang et al. [5] have made significant advancements in the field by developing a coupled numerical framework that models the time-domain behavior of a floating offshore wind turbine (FOWT) integrated with oscillating water columns (OWCs) on a semisubmersible platform. Their work addresses the complex interactions between the wind turbine, OWCs, and the floating structure, providing valuable insights into the performance and behavior of such integrated systems. In a related study, Sarmiento et al. [6] conducted experimental work to validate a novel semisubmersible structure that combines three oscillating water columns with a 5 MW wind turbine, confirming the feasibility and effectiveness of the integrated platform for both wind and wave energy harvesting. More recently, M'zoughi et al. [7] presented the integration of two or four OWCs within a barge platforms, demonstrating the feasibility and potential of utilizing multiple OWCs for wave energy conversion. An experimental investigation is conducted by Fenu et al. [8] to analyze the hydrodynamic behavior of a spar buoy wind turbine platform integrated with three cylindrical OWCs towards the influence of the wind loads on power production. Furthermore, the integration of OWCs into a barge platform is explored to highlight its potential as a strategy for active structural control [9]. The integration of different WECs is deepened by Li et al. [10] who investigates the dynamic response and performance optimization of a floating wind turbine and propose control strategies to enhance power production and mitigate interactions between the two systems. In addition, the integration of gyroscopes into a wind turbine submerged platform is found to have a stabilizing effect [11].

Dynamic response of floating marine systems are commonly analyzed in the frequency domain by a first order potential theory approach [12]. The integration of different working principle devices assumes the increase in the complexity of the system. Nonlinear

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effects have to be considered to well represent the hydrodynamic behavior of the platform and however, the linearity assumption is no longer valid. To overcome the difficulties of a full nonlinear time-domain analysis, different techniques could be applied. One of the possibilities to integrate non-linearities is to apply a spectral domain model, as presented in [13], [14]. Another approach in the study of wave energy converters involves utilizing a linear time domain model based on the Cummins equation [15], commonly known as the hybrid frequency-time domain model. This model combines elements of both frequency and time domains to provide a comprehensive understanding of wave energy conversion. This formulation of the resulting model allows for a detailed representation of the system dynamics and response. Although the initial model is linear, it also provides flexibility to incorporate nonlinear effects as loads [16]. In this study a linear time-domain numerical model is presented based on the Cummins equation, with the aim to model the wind turbine loads, the platform motion and the thermodynamic behavior of the air chambers of the OWCs.

The paper focuses on the numerical investigation through a time-domain model of a hybrid platform. Section II presents the time-domain model of the hybrid system dynamics and loads, including the thermodynamic representation of the air turbine of OWCs. Section III describes the power assessment procedure conducted to analyze the system performance. In Section IV, the design of the platform is described. In Section V the results are presented, highlighting the influence of the wind speed on the energy production of the wave energy converters. Conclusions are reported in Section VI.

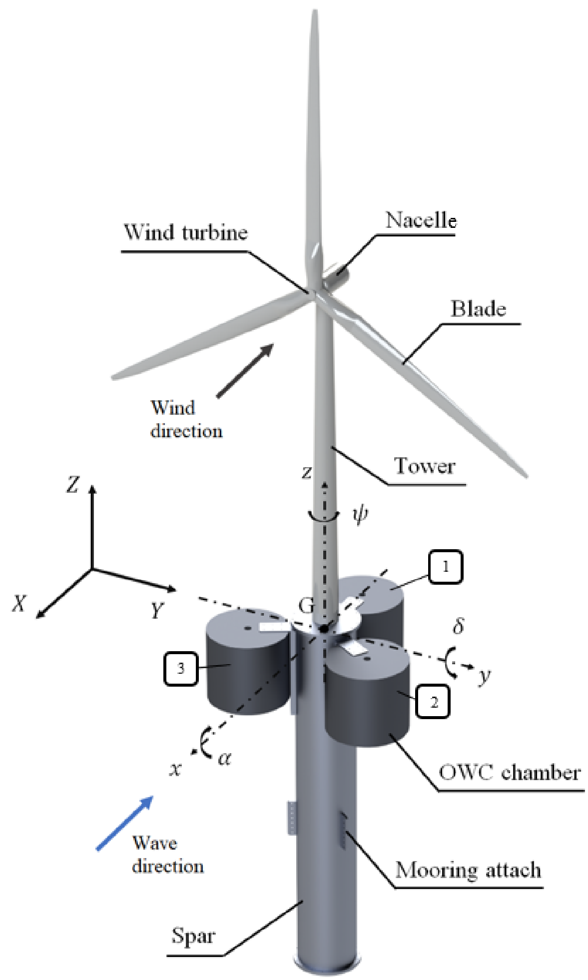


Fig. 1: Hybrid spar buoy integrated with 3 Oscillating Water Column and its reference system, wave and wind direction.

II. Coupled Numerical Model

In this section, we describe the proposed numerical model that couples aero-hydro-servo components, enabling dynamic time-domain analysis of hybrid FOWT-OWC platforms. Time-domain multi-body model of the hybrid system is developed in Matlab/WecSim workspace. The integration of the thermodynamic model describing the OWCs air chambers dynamics and the control actuation due to the air turbine are integrated using Simulink workspace. The wind turbine model is integrated following MOST implementation in WecSim tool [17]. Fig 1 shows the design layout of the hybrid platform.

A. Time domain model

The model solves rigid bodies' motion for the substructure motion in 3 DOF, which include the central spar buoy and the three air chambers, rigidly connected, and three water columns motion only in heave DOF, hypothetically assumed to be represented by a rigid piston [18]. The hydrodynamic coefficients of the multi-body system are obtained with OrcaWave software and implemented in WecSim as input. The potential flow theory is solved for each body and the interaction between the substructure and the water columns are considered only for heave motion.

The following model is based on linear wave theory, assuming the following hypothesis:

- The flow is considered as irrotational and incompressible and inviscid.
- harmonic oscillations of the hull for each DoF
- zero-forward-speed conditions [12].
- small wave amplitudes and body motions compared to the wavelength are considered.
- The diameter of the inner tube is much smaller then the wavelength, justifying the internal free surface representation as a rigid piston.

The equation of motion in time domain is written for a multi-body system,of $i-th$ bodies [19]

$$(\mathbf{M}_i + \mathbf{A}_i^{\infty})\,\ddot{\mathbf{X}}_i + \mathbf{B}_i\dot{\mathbf{X}}_\mathbf{i} + \mathbf{K}_i\mathbf{X}_i = \mathbf{F}_i^{\text{exc}} + \mathbf{F}^{\text{mo}} + \mathbf{F}^{\text{WT}} + F_i^{\text{OWC}} \tag{1}$$

where $\mathbf{M}_i$ is the inertia matrix of each body, $\mathbf{A}_i^{\infty} \in R^{n_D \times n_D}$ is the added mass contribution evaluated for infinite oscillation frequency, $\mathbf{B}_i \in R^{n_D \times n_D}$ is the radiation impulse response, $\mathbf{F}_i^{\text{mo}} \in R^{n_D}$ the mooring recall, $\mathbf{F}_i^{\text{WT}} \in R^{n_D}$ the forces associated to the wind turbine, and $\mathbf{F}_i^{\text{OWC}} \in R^{n_D}$ is the reaction forces due to the OWCs.

1) State space representation: The radiation forces $\mathbf{f}_R \in R^{n_D}$ arise from the motion of the hull through the water that results in inertia and friction components. These contributions can be obtained by solving state-space representation

$$\begin{aligned}\dot{\boldsymbol{\zeta}} &= \mathbf{A}_r\boldsymbol{\zeta} + \mathbf{B}_r\dot{\mathbf{X}}_f \\ \mathbf{f}_R &= \mathbf{C}_r\boldsymbol{\zeta} + \mathbf{D}_r\dot{\mathbf{X}}_f\end{aligned} \tag{2}$$

The vector $\boldsymbol{\zeta} \in R^{n_R}$ represents the state vector that approximates the radiation force contributions and n_R is the approximation order. The state space matrices $\mathbf{A}_r \in R^{n_R \times n_R}$, $\mathbf{B}_r \in R^{n_R \times n_D}$, $\mathbf{C}_r \in R^{n_D \times n_R}$ and $\mathbf{D}_r \in R^{n_D \times n_D}$ can be identified following the well-known approach described by Faedo et al. [20], leading a satisfactory approximation of the transfer function

$$\mathbf{H}_{\dot{X}_f R}(\omega) = \omega^2\mathbf{A}_R(\omega) + \mathrm{i}\omega\mathbf{B}_R(\omega) \tag{3}$$

which relates the body velocity to the resulting radiation force. Moreover, the incoming wave is considered directed along the x-direction leading the incident angle θ equal to zero. The excitation force is defined as a superposition of N_w wave components [21]

$$F_i^{\text{exc}} = \sum_{k=1}^{N_w} \Gamma_i(\omega_k, \theta)A_k \cos(\omega_k t + \phi_k + \phi_i(\omega_k, \theta)) \tag{4}$$

where the hydrodynamic excitation coefficient $\Gamma_i(\omega_k, \theta)$ depend on the array configuration and the resulting diffraction of the incident wave with an angle θ. ϕ_k and ϕ_i are the phases of each component. A_k are the amplitude of the waves described by their spectrum $S_\omega(\omega)$.

B. OWC model

To obtain the equation that describes the air pressure variation inside the chamber, the air volume variation due to free surface oscillation and the air mass flux through the chamber air turbine are related by means of thermodynamic relation. The model is based on the hypothesis: (1) air is an ideal gas, (2) adiabatic compression and decompression of the air and (3) isentropic processes.

$$\dot{p} = -\gamma_{\text{gas}}(p + p_{\text{atm}})(\frac{\dot{V}}{V} + \frac{\dot{m}_{\text{t}}}{m_{\text{c}}}) \tag{5}$$

where p is the pressure inside the air chamber, p_{atm} is the atmospheric pressure, γ_{gas} is a ideal gas coefficient and considered equal to 1.4, V is the volume of air inside the chambers and $\dot{V}$ its rate, and $\dot{m}_{\text{t}}$ and m_{c} are the mass flow rate of the air turbine and the air mass inside the air chamber, respectively. The volume flow rate is defined by the relative heave motion between the substructure $\dot{z}_{\text{spar}}$ and the water column $\dot{z}_{\text{OWC}}$ per the cross-sectional area of the air chamber S_{OWC}, following the relations

$$\dot{V} = \dot{z}_{\text{rel}}S_{\text{OWC}} \tag{6}$$

$$\dot{z}_{\text{rel}} = \dot{z}_{\text{spar}} - \dot{z}_{\text{OWC}} \tag{7}$$

The performance characteristics of a turbine define the relations between the mass flow rate and the pressure difference in the air chamber, which in turn influences the power extracted. The turbine characteristics can be presented in dimensionless form (neglecting the effect of the variations in Reynolds number and Mach number [22]). Defining the following relations

$$\Psi = \frac{p}{\rho_a\Omega^2 D^5} \tag{8}$$

$$\Phi = \frac{\dot{m}}{\rho_a\Omega D^3} \tag{9}$$

$$\Pi = \frac{P_t}{\rho_a\Omega^3 D^5} \tag{10}$$

where Ω is the rotational speed, D is the turbine rotor diameter and P_t the turbine instantaneous power output. The dimensionless coefficients represent respectively the pressure head, the flow rate coefficient and the aerodynamic torque. The air turbine efficiency can be defined as

$$\eta = \frac{\Pi}{\Psi\Phi} \tag{11}$$

The dynamics of the turbine/generator set is described by [23]

$$I\dot{\Omega} = T_{\text{turb}} - T_{\text{gen}}^{\text{em}} \tag{12}$$

where T_{turb} is the mechanical torque of the air turbine and $T_{\text{gen}}^{\text{em}}$ is the instantaneous generator electromagnetic torque. The air turbine geometry together with its rotational speed working range affect the power performances of the oscillating water column device [24]. Indeed, the turbine power output is proportional to Ω^3. The generated power can be expressed by Eq. 13

$$P_{gen}^{opt} = a\Omega^b \tag{13}$$

where a and b coefficients are characteristic of the air turbine. For avoiding the generator overpower, the following control law can be adopted to limit the rotational speed of the air turbine.

$$P_{gen}^{em} = min(P_{gen}^{opt}, P_{gen}^{rated}) \tag{14}$$

where P_{gen}^{rated} is the rated power of the generator.

III. Power performance assessment

The starting point of a design process is the analysis of resource energy potential in the specific site of installation. Following the purpose of the design of the hybrid system, careful consideration is given to selecting an optimal site for the design of the OWC air chambers. The analysis of the wave energy potential is performed in the perspective of obtaining the maximum about the energy performance of the wave energy converters device.

To evaluate the capabilities of the device effectively, it is essential to adopt a standardized performance measure. The annual average Capture Width Ratio (CWR) is a widely accepted non-dimensional performance parameter commonly used for comparing the energy performance of WECs based on different working principles. It is possible to assess and compare the

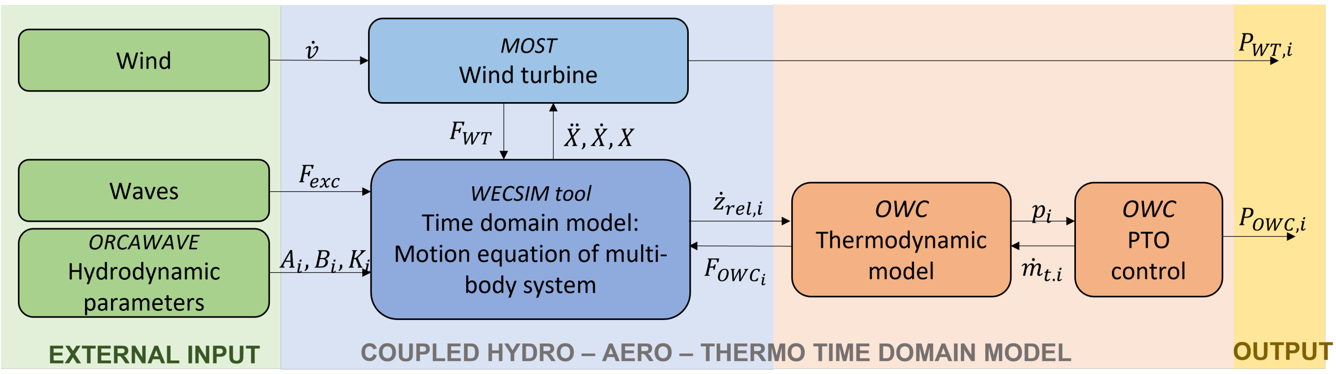


Fig. 2: Scheme of the coupled numerical framework combining the hydrodynamic model of the floating platform with the aerodynamic model of the wind turbine and the thermodynamic model of the Oscillating Water Columns

energy performances of different WECs [25] because the CWR represent a hydrodynamic efficiency, defined as the ratio between the power absorbed by the device and the wave power to a characteristic dimension B, typical for each type of WEC. Eq. 15 represents the CWR relation

$$CWR = \frac{P_e}{P_w B} \tag{15}$$

The initial step involves defining the parameter B. In the case of a circular configuration representing the horizontal cross-sectional area of the chamber of an OWC, the characteristic dimension B can be equated to the diameter of the air chamber [25]

$$B = \sqrt{\frac{4A_W}{\pi}} \tag{16}$$

where A_w is the maximum horizontal cross-sectional area of the device, assumed to be the main driver for the ability of a heaving device to absorb waves. The wave power is defined by the Eq. 17

$$P_w = \frac{\rho g^2}{64\pi} H_s^2 T_e \tag{17}$$

where ρ is the sea water density and g is the gravitational acceleration. H_s and T_e are characteristic of each wave and represent the significant wave height and the energetic wave period, respectively. The present definition of the wave power consider the hypothesis of deep water condition.

A. Case study: Pantelleria

For the interest of the research, reference is made to the studies previously carried out in Pantelleria [26] which represents one of the site with the highest specific productivity in the Mediterranean Sea from the point of view of the wind resource availability. The energy potential from the wave resource in the Mediterranean Sea is shown in the Figure 3. It can be noticed that the average power per unit crest map of exhibits its highest values in the North-West area of the Mediterranean Sea, while around the Island of Pantelleria the average power per unit crest is in the range of 4 to 6 [kW/m] [27].

The wave power is estimated by the analysis of the wave energy resource in Pantelleria [3]. The wave resource is represented by the scatter matrix of the main

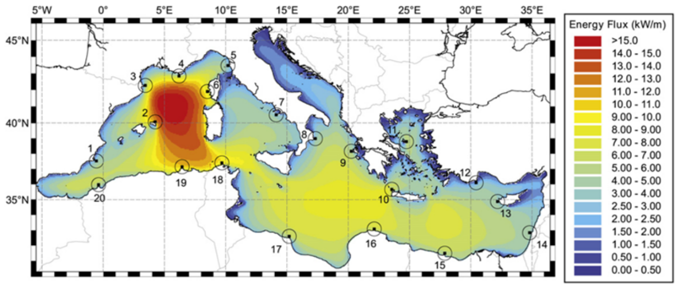


Fig. 3: Distribution of average power per unit crest in the Mediterranean [27].

wave characteristics, significant wave height H_s and energetic wave period T_e, depending on the percentage of occurrence.

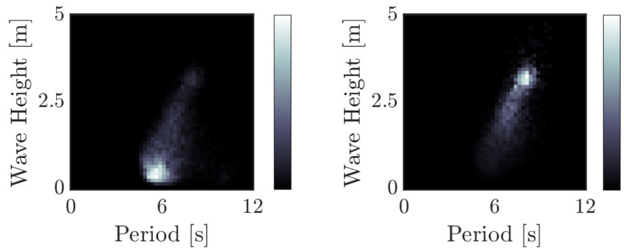


Fig. 4: Wave matrix of the occurence and energy of Pantelleria sea states

Figure 4 shows on the left the most occurring waves and on the right the most energetic waves. From an energetic perspective, it is observed that waves with higher periods and significant wave heights are more desirable. However, waves with lower periods and significant wave heights have a higher probability of occurrence. In the case study, the sea state with the highest occurrence is selected as the basis for sizing the wave energy converter (WEC) device, such as the dimension B, that is the chamber diameter.

IV. HYBRID PLATFORM DESIGN

In this chapter, the hybrid platform is described and the design the OWC air chambers integrated into the Spar buoy wind platform is presented. The spar buoy is a well-know floating platform concept. The present floating platform is the result of a techno economic optimization for the water depth of the coast of Mediterranean Sea [28]. The reference wind turbine is the 5MW NREL, developed and studied by Jonkman [29]. The wave energy converter is thought to be welded to the spar-buoy platform, forming a single rigid body. The sizing of the OWCs is performed to maximize the wave energy exploitation. Indeed, the power output is maximized in certain sea state condition, in particular when the characteristic parameter of the chamber is proportional to the wavelength [30]. So it is possible to obtain the diameter of the air chamber through the relation expressedn in Eq. 18

$$D_{design} \propto C\lambda \tag{18}$$

where λ is the wavelength and C is a proportional constant [30]. Similar considerations are taken about the height of the chambers. The resonance frequency of the chambers depends on their submerged height by the relation

$$\omega_{\text{res}} = \sqrt{\frac{g}{H_{\text{design}}(A(\omega)+1)}} \tag{19}$$

where g is the gravitational acceleration, A is the addedd mass dependent by the frequency and H_{design} is the height of the submerged part of the OWC air chamber. The height has to be tuned to the resonance frequency of interest, so that it is possible to excite the system specifically for an interesting wave period. The freeboard of the device, i.e. the height of the OWC air chamber above the water surface has to be high enough to prevent the sea water reaching the air turbine positioned in the upper part of the air chamber. The pneumatic power performances depend on of the area-ratio of the orifice cross-section of OWC system, i.e. the dimensionless ratio between the orifice area and the chamber water plane area, because directly influences the air flow speed in the OWC chamber. Therefore, the choice of a suitable orifice ratio in first hypothesis has been defined in the interval between $0.66\% < R_{\text{Orifice}} < 2\%$ following the studies of [31], [32]. The PTO system is integrated on the top surface of the OWCs and it is chosen accordingly to the previous considerations, modeling a biradial air turbine. Finding a universal rule that can fit every type of OWC wave energy conversion system is challenging, therefore an optimization process should be considered in future works. In the following, Tab. I summarizes the rules adopted for the design and the characteristics of the hybrid platform.

TABLE I: Summary of the main characteristic dimensions of the OWC air chamber

Symbol	Quantity	Unit
λ	Wave length	47 m
D_{design}	Air chamber diameter	19 m
H_{design}	Air chamber height	16 m
h	height above WSL	8 m
$R_{Orifice}$	Orifice ratio $= \frac{\text{Aair turbine}}{A_{\text{w}}}$	0.66 % - 2%

A. Hydrodynamics of the OWCs

In this Section the OWCs' heave motion response characteristics are investigated. Special attention is devoted to the heave resonant period of the converter, as it serves as a crucial indicator of the operational condition based on the working principle of the device. The resonant period mainly depends on the height of the OWC chamber, as explained in Section IV. It is tuned to be in the range between the most occurrent wave period and the most energetic wave period of the installation site wave resource, with the aim to maximize the wave power exploitation. In this context, the displacement Response Amplitude Operator (RAO) is calculated by the hydrodynamic solver and it reports the heave response. The displacement RAOs represents the amplitudes of the radiation potentials, obtained by solving the equation of motion for the body at first order in wave steepness. The equation of motion is solved for each water column, considered to behave like a rigid body. Fig. 5 shows the heave RAO results. As it can be seen, the resonant period is 7.5 [s] for the three chambers. Chamber 2 and 3 are located in wave front and present the same response, since the symmetry of the system in x-axis. Chamber 1 presents a slightly higher response, due to the asymmetry of the system in y-axis.

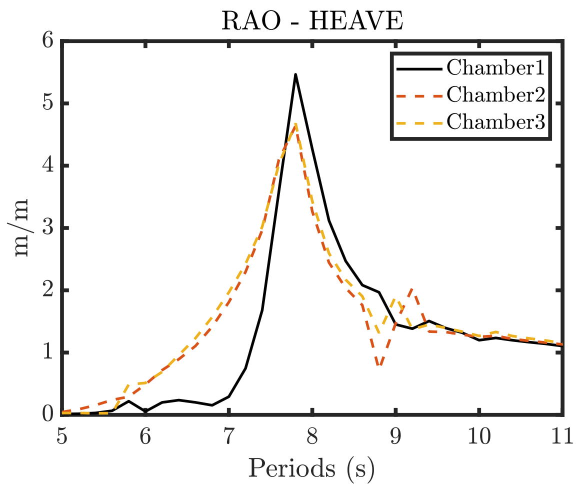


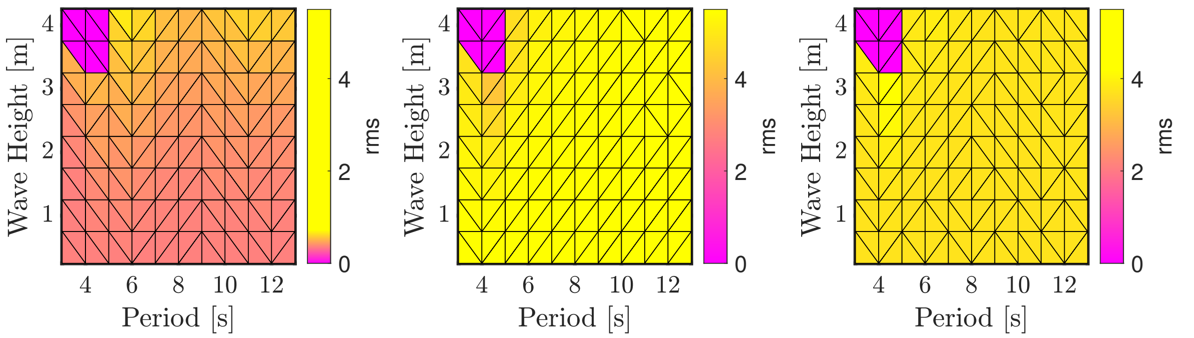
Fig. 5: Displacement RAO of the air chamber for heave motion

The highest power performances from the OWCs' water columns is expected to be in correspondence of the resonance period. The power outputs are shown in the following Section.

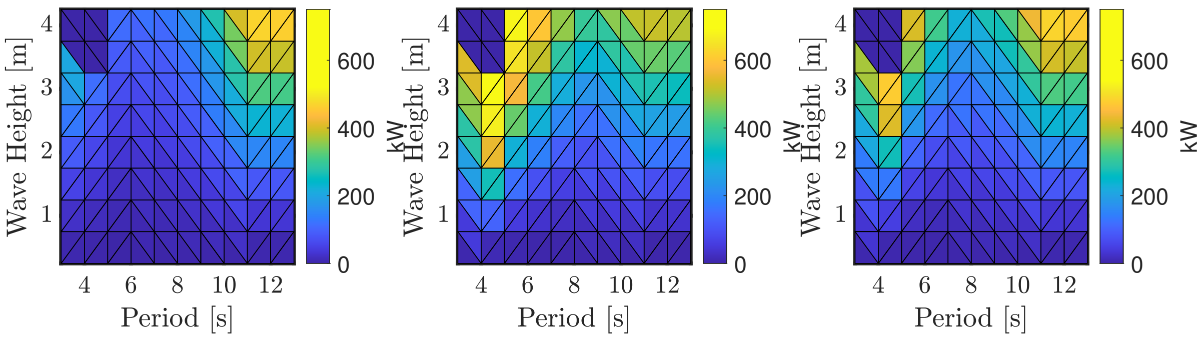
V. Results

In the present section the results of the power assessment of the hybrid system energy conversion is presented.

The power performance of the three OWCs are presented in different scenarios. The hybrid platform is considered to be exited by three significant wind speeds to analyze the influence of the hydrodynamic response of the system on the obtained power of the OWCs. For this purpose the wind turbine cut-in speed,



(a) RMS of the pitch motion in each sea states for cut in wind speed = 3 [m/s], rated wind speed = 11.4 [m/s], cut-off wind speed = 25 [m/s]



(b) Mean power by the OWCs for each sea states for cut in wind speed = 3 [m/s], rated wind speed = 11.4 [m/s], cut-off wind speed = 25 [m/s]

Fig. 6: Representation of correlation between the pitch motion of the wind turbine and the power output of the three OWCs for different wind loads

the rated wind speed and the cut-off wind speed characteristic of reference wind turbine are considered. For each wind speed, the system is excited by different wave loads, representative to the wave resource of Pantelleria (see Fig. 4). A summary of the wind and wave conditions is presented in Tab. II:

TABLE II: summary of wind and wave conditions performed

Wind speed	Quantity	Wave characteristics
Cut-in	3 [m/s]	Tp = 3-12s, Hs = 0.25-4.25 m
Rated	11.4 [m/s]	Tp = 3-12s, Hs = 0.25-4.25 m
Cut-off	25 [m/s]	Tp = 3-12s, Hs = 0.25-4.25 m

Statistical quantity, i.e. Root Mean Sqare (RMS), representative of the pitch motion are presented together with the mean power output of the OWCs' air turbines.

Fig. 6a clearly illustrates that pitch motion variations become more pronounced as wind speeds increase, particularly at the rated wind speed condition of 11.4 [m/s]. This condition aligns with the peak in the thrust force curve, which is characteristic of the selected wind turbine. The power output of OWCs air turbines exhibits sensitivity to the wave resource, aligning with expectations. As depicted in the Fig. 6b, it is evident that higher power outputs are achieved when encountering more energetic wave sea states. The relationship between wave energy and power generation is clearly demonstrated, emphasizing the importance of optimizing the utilization of wave resources for maximizing OWCs' power output. The influence of wind loads on the hybrid platform is evident, resulting in increased pitch motion. Notably, the OWCs demonstrate a higher power output as wind speeds escalate, particularly in conjunction with small wave periods ranging from 4 to 7 [s]. This correlation between wind speed, wave period, and power output highlights the significance of considering both wind and wave factors when optimizing the performance of the hybrid platform. By leveraging these interdependent variables, it becomes possible to achieve enhanced power generation from the OWCs within the system. In contrast, the analysis reveals that the pitch motion does not exhibit a significant influence in the presence of OWCs. Consequently, it can be concluded that the OWCs do not affect the motion of the wind turbine, thereby having no discernible impact on the wind power output. While the OWCs play a crucial role in wave energy conversion, their presence does not introduce any noticeable alterations to the motion dynamics of the wind turbine, allowing it to operate independently and maintain its expected power generation performance.

To better understand the power performance of the OWCs, the annual capture width ratio CWR_{ann}, calculated as the sum of each CWR per the occurrence, is presented in Tab. III.

VI. Conclusion

This paper presents a comprehensive time-domain investigation of a novel hybrid platform, which combines a spar buoy wind turbine platform with three

TABLE III: Annual Capture Width Ratio

CWR_{ann}	Values %
CWR at Cut-in	0.5
CWR at Rated	2
CWR at Cut-off	1

air chamber oscillating water columns. The primary objective is to analyze the hydrodynamic behavior of the integrated system and assess the power capability of the wave energy converter. The results obtained from the study demonstrate that the integration of OWCs does not exert any significant influence on the pitch motion of the hybrid platform. This finding indicates that the presence of the OWCs does not disrupt or alter the natural motion characteristics of the wind turbine platform. Therefore, the wind turbine can operate independently, maintaining its expected performance in terms of pitch motion. On the other hand, the analysis reveals that the power output of the OWCs is notably influenced by the wind speed. This correlation between wind speed and power generation highlights the importance of considering wind conditions when assessing the overall performance and power capability of the integrated system. Regrettably, the assessment reveals that the annual capture width ratio is relatively low, indicating that the hybrid platform's ability to harness the available wave energy is limited. Consequently, the energy produced by the system falls short and fails to make a substantial contribution to overall energy generation. To address this limitation, further research and development efforts should focus on optimizing the design of the hybrid platform to enhance power extraction capabilities and focus on stabilizing the wind turbine platform.

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