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An assessment of the trade-off between energetic efficiency and structural integrity in Wave Energy Converters

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A computational tool is developed to investigate the trade-off between the energetic response and the structural integrity in Wave Energy Converters (WECs) for irregular waves. The computational model takes into account the environmental parameters and the properties of the WECs, and calculates the extracted wave power and the accumulated fatigue damage in a specific incident sea state. The hydrodynamic and the structural problems are solved using analytical and structural-finite element models, respectively. The methodology is exemplified for a specific bottom-fixed Oscillating Water Column with an optimal configuration and different energetic content sea states. The results reveal the importance of taking into account the trade-off between the extracted wave power and the accumulated fatigue damage to support decision-making in the predesign stage to provide better solutions for marine renewable energy applications. In the framework of the structure monitored using Internet-Of-Things, this computational tool can lead to a digital twin within the context of structural integrity.

Keywords: Accumulated fatigue damage, analytical models, digital twin, extracted wave power, finite element models, irregular waves, wave energy converters.

1. Introduction

The wave energy is being investigated as an alternative to fossil fuels (Falcão, 2010; Ozkop and Altas, 2017). In this sense, a number of authors have focused on investigating the hydrodynamic performance of Wave Energy Converters through numerical models (Teixeira and Didier, 2021; Trivedi and Koley, 2021; Gang et al., 2022; Trivedi and Koley, 2023) and experimental approaches (Howe et al., 2020; Liu et al., 2022; Rodríguez et al., 2023). Notwithstanding, wave energy conversion technology is not competitive yet. In this context, several authors have tried to find optimal designs from an energetic point of view focused on numerical or analytical models (Falcão et al., 2012; Gomes et al., 2012; López et al., 2014; Jalón et al., 2016; Jalón and Brennan, 2017; Ezhilsabareesh et al., 2021) and experimental methods (Shih and Liu, 2022); however, not so many have focused on exploring the relationship between the optimal designs of WECs and their long-term reliability.

In this context, the main research objective of this paper is to investigate the trade-off between the energetic response and the structural integrity of WEC systems in irregular waves. For this purpose, a methodology is developed by coupling analytical and finite-element (FE) models to integrate the simulation process through a highfidelity computational tool. This computational tool can lead to a digital twin within the context of structural integrity, including the simulation, learning, and management (Chiachío et al. (2022)).

The proposed methodology is exemplified for a particular bottom-fixed Oscillating Water Column (OWC) system with an optimal configuration and specific environmental conditions. The available wave power, the power extracted from the incident sea states, and the accumulated fatigue damage are analyzed and compared.

2. Methodology

2.1. *Simulation process*

For this paper, a computational tool is developed to integrate the simulation process of the energetic response and the structural integrity of WECs in irregular waves. The simulation model solves the hydrodynamic problem with analytical models, whereas the structural problem is solved using a structural FE model. A schematic view of the simulation process is depicted in Fig. 1.

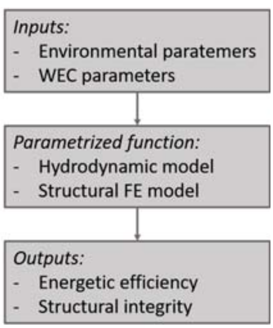


Fig. 1.: Flowchart of the simulation process.

The input parameters of the computational tool are the environmental and the WEC design parameters. The environmental parameters are the water depth h, and the incident sea state defined by its significant wave height H_s, and peak period T_p. The WEC consists on a bottom-fixed OWC (Fig. 2) with radius a, draft d, emergence e, and thickness ζ. This system is equipped with a Wells turbine with rotational speed N_s, and outer rotor diameter D_t.

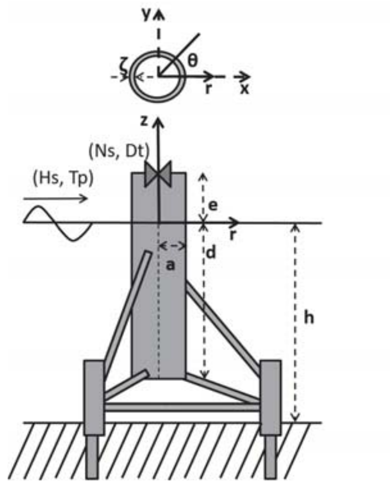


Fig. 2.: Scheme of the bottom-fixed OWC.

The output parameters of the computational tool are the energetic efficiency and the structural integrity. In this sense, the power extracted from the irregular waves and the accumulated fatigue damage are adopted as representative values of the energetic efficiency and the structural integrity, respectively. Their calculation is presented in the next sections.

2.2. *Energetic efficiency*

The time-averaged power extracted from the irregular waves P_{avai} is adopted to quantify the energetic efficiency of the system. It is given by (Jalón et al., 2016):

$$P_{avai} = \frac{K D_t g^2 \rho_\omega^2}{N_s \rho_a} \int_0^\infty S_\eta(f) F(f) df \qquad (1)$$

where K is an empirical factor that depends on the turbine; D_t is the outer diameter of the turbine rotor; g is the gravity acceleration; N_s is the rotational speed; ρ_a is the static air density; ρ_w is the water density; $S_\eta(f)$ is the energy density spectrum; and F is defined by:

$$F(f) = \frac{|\widetilde{\Gamma}(f)|^2}{(\chi(f) + \widetilde{B}(f))^2 + (\beta(f) + \widetilde{C}(f))^2} \quad (2)$$

where $\widetilde{\Gamma}(f), \widetilde{B}(f), \widetilde{C}(f)$ are the dimensionless hydrodynamic coefficients; and $\chi(f)$ and $\beta(f)$ represent the turbine and the air compressibility in the chamber, respectively.

The dimensionless hydrodynamic coefficients are calculated from the hydrodynamic model, which is analytically solved following the methodology of Martins-Rivas and Mei (Martins-Rivas and Mei, 2009). Their methodology assumes non-rotational flow, incompressible and inviscid fluid, and the problem is formulated in terms of the diffraction and radiation velocity potentials. In this sense, the velocity potential expressions for a partially immersed circular cylinder (Garrett, 1970; Evans and Porter, 1997) are considered in this paper.

In addition, the available wave power P_w is calculated to quantify the energetic content of the incident sea state as:

$$P_\omega = \rho_\omega g \int_0^\infty S_\eta(f) C_g(f) df \quad (3)$$

where $C_g(f)$ is the group velocity of the sea state at a specific frequency f.

2.3. *Structural integrity*

The structural response of the interaction between the incident sea state and the bottom-fixed OWC is modeled with a structural finite-element (FE) model using ABAQUS (Hibbitt et al., 2001). The OWC is represented by a shell-type cylindrical structure considering the steel as structural material, and four fixed points at the bottom of the system to represent the support structure.

The input loads are the gravity, the subpressure, and the temporal pressure field calculated from the hydrodynamic model (see Jalón and Brennan (2020)). Specifically, the unsteady Bernoulli equation is applied to obtain the temporal pressure field below the mean water level ($z \leq 0$), whereas Taylor series are applied to obtain the temporal pressure field above the mean water level ($0 < z < \eta$). Further details are found in (Dean and Dalrymple, 1991).

Then, the FE model is run for the specific simulated time, and the maximum principal stresses σ along the time are measured at a reference point. From the obtained stress values, the number of cycles n_i and the stress ranges $\Delta\sigma$ are calculated by applying the rainflow counting algorithm. These values allow us to calculate the accumulated fatigue damage D using the expression (Schijve, 2001):

$$D = \frac{1}{\bar{a}} \sum_{i=1}^{s} n_i \Delta\sigma_i^m \quad (4)$$

where m and $\bar{a}$ are the parameters from the S-N curve of the material.

3. Results

3.1. *Case studies*

The proposed methodology is applied for a particular environmental conditions defined by the water depth $h = 10$ m, and the sea states S_1 : $H_s = 1.17$ m, $T_p = 4.22$ s; S_2 : $H_s = 1.64$ m, $T_p = 5.43$ s; and S_3 : $H_s = 2.10$ m, $T_p = 7.86$ s.

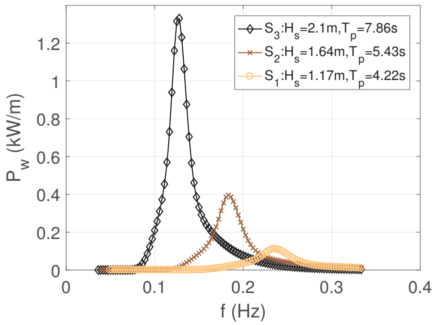
The selected bottom-fixed OWC is characterized by a radius $a = 3.5$ m, draft $d = 8$ m, emergence $e = 5$ m, thickness $\zeta = 0.02$ m, turbine diameter $D_t = 1$ m, rotational speed of the turbine $N_s = 294.14$ rpm, and empirical factor of the turbine $K = 0.45$.

The environmental and the OWC parameters represent the sea states and the annual power-optimal configuration at a particular location of the Gulf of Cádiz in Spain (see Jalón et al. (2016)).

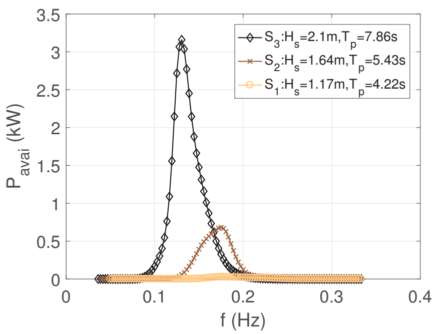
3.2. *Energetic efficiency*

Figures 3a and 3b represent the available wave power (Eq. 3) and the time-averaged power extracted from the irregular waves (Eq. 1) for the different sea states, respectively.

The area beneath the curves correspond with the total values, and it has been calculated and showed in Table 1 for each of the sea states. As expected, the more energetic sea state (with $P_w = 17.54$ kW/m) corresponds to the greatest H_s and T_p. To the contrary, the less energetic sea state



(a)



(b)

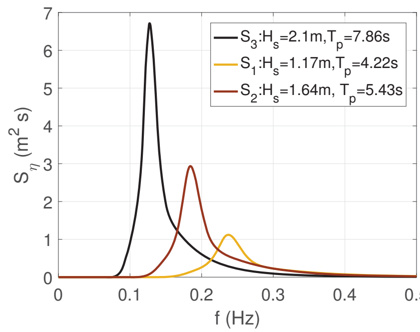
Fig. 3.: (a) Available wave power. (b) Power extracted from the irregular waves.

(with $P_w = 2.45$ kW/m) corresponds to the lowest H_s and T_p.

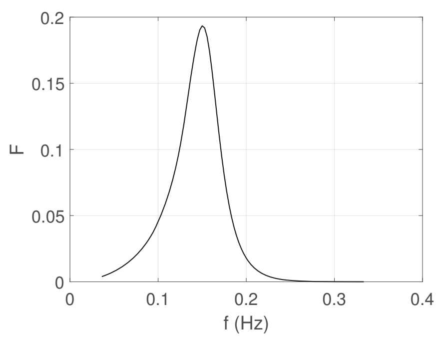
For the interpretation of the low extracted power of S_1 ($P_{avai} = 0.6$ kW), the energy density spectra S_η for the different sea states, and the function F are represented in Fig. 4. The function F depends only on the configuration of the system, and affects the spectrum of the incident sea state in Eq. (1). This function F shows a resonant behavior of the chamber at frequency $f = 0.15$ Hz as it is observed in Fig. 4b, far away to the peak frequency of the energy density spectrum of S_1 ($f = 0.23$ Hz) (Fig. 4a). In this sense, we can conclude that the low value of P_{avai} in S_1 is due to the difference of peak frequencies between S_η and F, apart from the low value of the available wave power.

Table 1.: Value of the available wave power, and the power extracted from the irregular waves.

Sea State	P_w (kW/m)	P_{avai} (kW)
S_1:H_s=1.17 m, T_p=4.22 s	2.45	0.6
S_2:H_s=1.64 m, T_p=5.43 s	7.19	10.89
S_3:H_s=2.1 m, T_p=7.86 s	17.54	40.10



(a)



(b)

Fig. 4.: (a) Energy density spectra. (b) Function F.

3.3. *Structural longevity*

The structural FE model is run for the different sea states, and time series of the resulting stresses $\sigma(t)$ are measured at the representative point given by to $r = a, z = 0, \theta = \pi$, and showed in Fig. 5.

Then, the number of cycles n_i and the stress ranges $\Delta\sigma$ are calculated from $\sigma(t)$ and showed through the rainflow matrix in Fig. 6. It is observed very similar values of the stresses for the

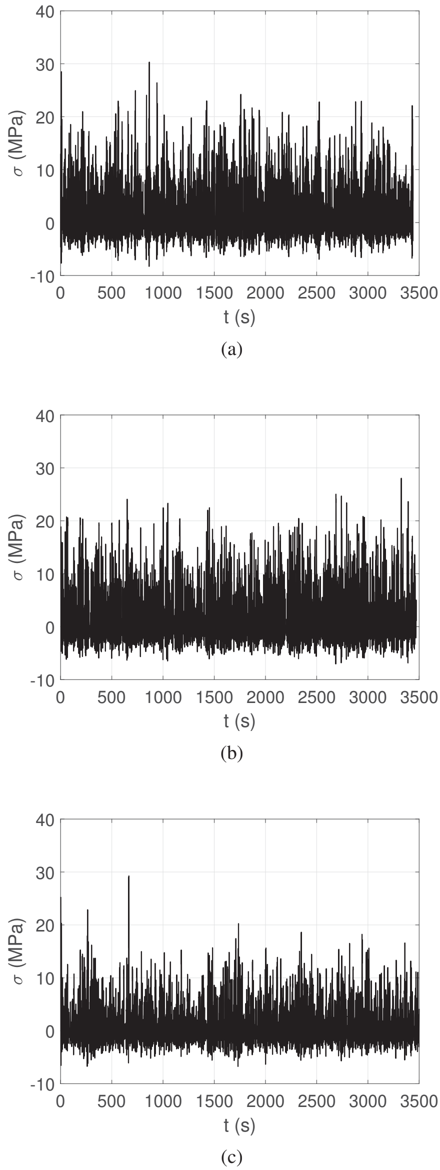


Fig. 5.: Maximum principal stresses: (a) S_1, (b) S_2, (c) S_3.

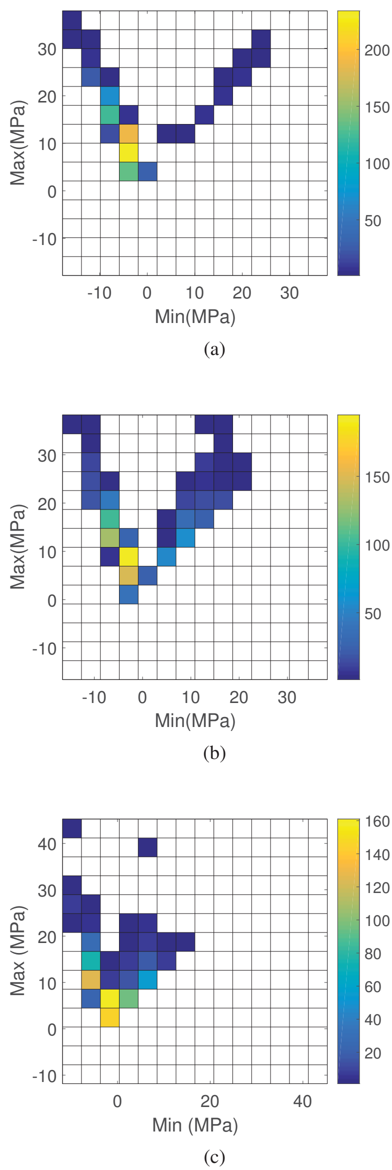


Fig. 6.: Rainflow matrix: (a) S_1, (b) S_2, (c) S_3.

different sea states (Figs. 5a, 5b, 5c), although the medium energetic sea state (S_2) presents the highest number of cycles (Fig. 6b).

Finally, the accumulated fatigue damage D (Eq. 4) is calculated based on the number of cycles n_i and the stress ranges $\Delta\sigma$ (Figs. 6a, 6b, 6c). To this end, the S–N Curve D for steel in seawater with cathodic protection (see Veritas (2010)), with fatigue properties $log(\bar{a}) = 11.764, m = 3$ if $N \leq 10^6$ cycles, and $log(\bar{a}) = 15.606, m = 5$ otherwise, is adopted as a conservative design assumption. Figure 7 represents the S-N Curve D adopted.

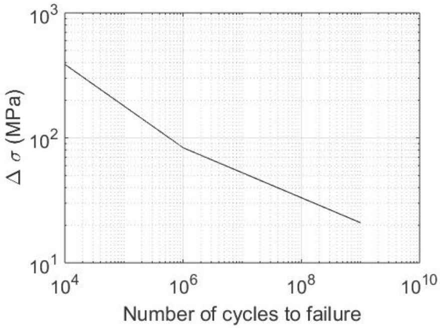


Fig. 7.: S-N Curve D

The results (Table 2) show that the highest accumulated fatigue damage is reached for the medium energetic content sea state (S_2).

Table 2.: Value of accumulated fatigue damage.

Sea State	D
S_1:H_s=1.17 m, T_p=4.22 s	1.3028 10^{-6}
S_2:H_s=1.64 m, T_p=5.43 s	1.3529 10^{-6}
S_3:H_s=2.1 m, T_p=7.86 s	4.8429 10^{-7}

3.4. *Comparative analysis*

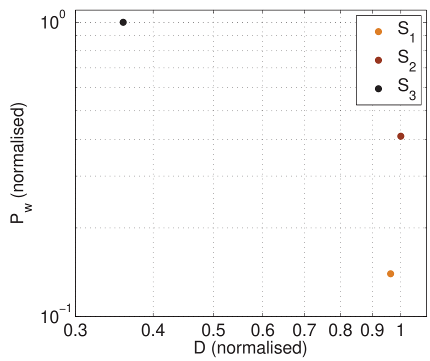
Finally, the dimensionless values $\widetilde{P}_w$ (Eq 5b), $\widetilde{P}_{avai}$ (Eq 5b), and $\widetilde{D}$ (Eq 5c), are calculated to compare the obtained results.

$$\widetilde{P}_{w,i} = \frac{P_{w,i}}{\max(P_w)} \quad i = 1, 2, 3 \tag{5a}$$

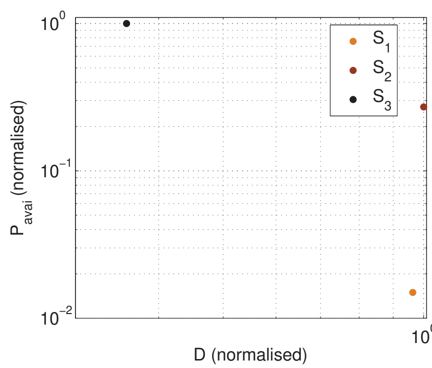
$$\widetilde{P}_{avai,i} = \frac{P_{avai,i}}{\max(P_{avai})} \quad i = 1, 2, 3 \tag{5b}$$

$$\widetilde{D}_i = \frac{D_i}{\max(D)} \quad i = 1, 2, 3 \tag{5c}$$

Figure 8 represents the dimensionless values of the available wave power and the power extracted from the irregular waves against the dimensionless values of the accumulated fatigue damage. As can be observed, less energetic sea states (S_1, S_2), which present lower values of the power extracted from the waves, are more prone to damage than higher energetic sea state (S_3) with higher values of the power extracted from the waves.



(a)



(b)

Fig. 8.: (a) Available wave power and (b) power extracted from the waves, against fatigue damage. Normalised values.

4. Conclusions

This paper proposes a methodology to analyze the trade-off between the extracted wave power and the accumulated fatigue damage of WECs in irregular waves. The methodology is developed using a computational tool, which can lead to a digital twin within the context of structural integrity. As an example, the computational tool is applied for a specific bottom-fixed OWC with an annual power-optimal configuration, and different energetic content sea states.

The overall results have revealed that less energetic sea states, with less power extracted from the irregular waves, could reach higher fatigue damage than higher energetic sea states with higher power extracted from the irregular waves. In this sense, further work is needed to find better solutions for marine renewable energy applications by mutually considering the extracted wave power and the accumulated fatigue damage in irregular waves.

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