ASSESSMENT OF LOADS AND PERFORMANCE OF A WAVE ENERGY CONVERTER FOR THE MEDITERRANEAN SEA

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Keywords: Wave power, Wave Energy Converters (WECs), WEC numerical simulation, Mediterranean Sea, Renewable energy

Abstract

The device PeWEC (Pendulum Wave Energy Converter) developed by a partnership between ENEA and the Politecnico di Torino University, was simulated by using the open-source wave energy converter simulation tool WEC-Sim complemented by a Boundary Element Method (BEM) code for the calculation of hydrodynamic coefficients. Numerical results were compared to experimental data carried out at INSEAN laboratory tank tests. Free-decay simulations were performed numerically in order to determine the natural frequencies of the system. Moreover, a set of simulations was carried out with regular waves by varying the wave period and keeping the amplitude constant. The dynamic response of the device and the absorbed power were analysed and compared to experimental results. The code better predict the evolution of the oscillations of the pendulum rather than those of the hull but, more generally, the experimental and the numerical power curve presented good agreement. For the wave periods close the natural ones of the system, by neglecting viscous damping the absorbed power by the device is strongly overestimated by the numerical approach, while, considering this effect, an improved agreement is noticed. For the other wave periods numerical and experimental data show similar values. Finally, simulations were conducted by giving the user-defined wave elevation time-history measured by one of the probes in the test tanks. Even if mean and maximum values of the dynamic response were already well predicted, such a simulation permitted to know the dynamic of the system at any given time with a major precision. The usage of only open-source codes could provide to both industries and new WECs designers an efficient and straightforward tool to study and improve wave energy converters technology.

1 Introduction

A transition from fossil fuels energy resource to a flexible, clean and renewable energy system is one of the biggest challenge that the European Union (EU) will have to face in next years. Oceans cover approximately 70% of Earth's surface and it is unquestionable that marine energy could give a significant contribution to world's electricity needs. Even if studied and conceptualized for over a century, the idea of producing electricity from the sea has just recently entered in industry interest and it is estimated that, as soon as this technology will become mature, wave energy could meet 10% of the EU's power demand by 2050 [1]. Between the various forms of energy available in the seas (power can be absorbed from tides, currents, temperature and salinity gradient) wave energy is one of the most promising and studied. Unlike the wind industry, where a horizontal two or three blade turbine has become the clear choice, there is a wide variety of wave energy technologies which have been proposed and these arise from the various ways that the energy can be absorbed from the waves. However, for several constructing and testing problems, a mature WEC system from both a commercial and technological point of view has still to arise from the realm of research [2]. Because of the high cost and long period necessary in experimental and field testing, accurate and validated numerical modelling tools aiming at designing and optimizing WEC devices have a central role in the future developing of such a technology. The wave energy absorption is a hydrodynamic process, in which relatively complex diffraction and radiation wave phenomena take place [2]. Moreover, the multidisciplinary aspect of the energy conversion makes the developing of accurate numerical modelling tools not easy. In the present work, the open-source wave energy converter simulation tool WEC-Sim [3], developed by the Sandia National Laboratories and US Renewable Energy Laboratory with the support from US Department of Energy, was chosen to simulate the WEC device. Several papers can be found in open literature using and describing the code, see for instance [4], [5], [6].

In last years, because of the increasing attention that marine energy is achieving, some challenges have been proposed to demonstrate the accuracy of existing simulation codes. In the framework of the WEC3 project, for example, some of the WEC existing codes were compared in two phases: firstly a code-to-code comparison was carried out. Then a code-to-experiment comparison was developed [5]. In the first phase of the project, the codes (InWave, WaveDyn, ProteusDS and Wec-Sim v1.0) were compared by simulating a multibody oscillating device (F3OF), which was used as reference test case. Hydrodynamic coefficients databases and mechanical device responses were analysed. A decay test was performed to compare hydrodynamic coefficients computed using different Boundary Element Methods (BEMs) solvers. Furthermore, the response amplitude operators (RAOs) were generated to compare the dynamic response of the device. All the four codes demonstrated to be in a good agreement in their predictions, and the way of modelling viscous effects was proved to have an important role as well as the ability of the BEM solver to take into account the hydrodynamic body-to-body interactions. Another hydrodynamic modelling competition was organized by the Centre of Ocean Energy Research (COER) [6]. Participants were challenged to predict the dynamic response of a floating rigid-body device that was previously experimentally tested. By using both regular and irregular wave fields, numerical simulations achieved by using WEC-Sim and FAST codes and experimental data were shown to be in good qualitative and quantitative agreement only in one (surge motion) of the two degrees of freedom of the floating body. This was partially explained by observing that the exciting wave field had a peak close to the natural period in the second natural period of the device (heave motion), while the natural surge period was significantly below the predominant frequencies of the wave field. The fully coupled time domain aero-hydro-servo-elastic simulation tool FAST was also used in [7] to investigate loads on a wind turbine induced by different wind and wave conditions typical of the Mediterranean Sea.

If, on the one side, accuracy in the prediction of the dynamic response of WEC device is needed, on the other side, a high resolution assessment of the wave energy resource is necessary to evaluate the effective wave energy potential. In fact, feasibility studies of wave energy plants require a detailed knowledge of energy occurrence. Even if wave energy atlases for the Mediterranean Sea developed using data measured by buoys are the most accurate, they present the problem to describe wave field only locally and to present large data gaps [8]. Some recent projects addressed this problem by providing accurate wave climate analysis for the Mediterranean Sea ([8]-[10]).

The device simulated in the present work is the Pendulum Wave Energy Converter (named "PeWEC") developed by a partnership between ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) and the Politecnico di Torino University (Italy). The 1:45 scale prototype was previously simulated by using a simplified analytical model. This allowed to avoid to perform the hydrodynamic characterisation of the hull. Obtained results were compared to experimental tests showing an overall good agreement [11]. Furthermore, the inertial device was shown to be a promising option for the typical wave field of Mediterranean Sea.

In order to contribute to WECs technology and modelling development, this paper focuses on the simulation of the 1:12 prototype of the PeWEC device. A full hydrodynamic description of the floating body was given by using the open-source BEM code NEMOH [12]. Loads and motion of the chosen device were investigated and then compared to experimental data carried out at INSEAN laboratory tank tests.

2 System modelling

WEC device interaction with waves is simulated by using WEC-Sim modelling tool. In this section a brief description of the device and its hydrodynamic characterization are given. The modelling process is illustrated in Figure 1. Firstly, wave specifications, such as wave period and height for regular waves or wave spectrum for irregular wave fields, are needed inputs to model the wave-device interaction. The computation of hydrodynamic coefficients requires the specification of device geometry and of mass properties. This can be done by using various CAD programs. The hydrodynamic modelling is divided in frequency-domain simulation (fully linear) and time-domain analysis, where non-linear effects can be introduced and dynamic analysis of the system can be performed. The hydrodynamic coefficients are computed by an external BEM code. After the Wave-Sim module generates wave time-series from the wave specifications, the user has to create a time-domain multi-body dynamics model of the device. A library of pre-built WEC components, such as bodies, constraints, PTO and mooring, is used for this step. Finally, SimMechanics 6-DOF multi-body solver performs the simulation using a 4th order Runge-Kutta integration scheme [13].

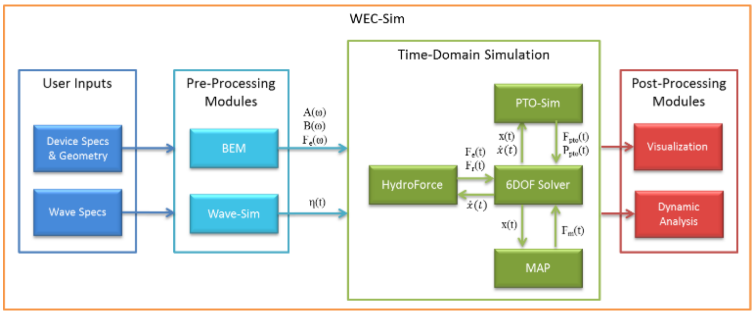

Figure 1: The WEC-Sim code structure [13].

2.1 The device

The Pendulum Wave Energy Converter "PeWEC" is an inertial device made of a semi-cylindrical hull, which contains a mechanical pendulum and a series of electrical devices inside its structure. Figure 2 shows a CAD of the 1:12 scaled prototype simulated in the present work. The concept is to make the pendulum oscillates using the hull's motion caused by the incident waves. The semi-cylindrical shape was chosen to exploit the higher motions of the hull due to its relatively high instability in the water. The mechanical energy of pendulum is then converted into electrical energy by the power take-off (PTO) located where the pendulum is hinged to the hull's structure. Figure 3 illustrates a schematic representation of the PeWEC and of its relevant parameters. Angle δ describes the pitch motion of the hull in the global reference system where *x*-axis indicates the direction of the propagating waves, *z*-axis is pointing upward and *y*-axis can be defined by right-hand rule; finally, ε is used to indicate the relative pitch motion of the pendulum. Prototype configuration as well as geometrical and mass properties are summarised in Table 1, where l is the length of the pendulum, d refers to the distance between the hinge point and the mass centre of the hull, and r and w respectively are the radius and the width of the hull. The masses of the hull and of the pendulum were called m_h and m_p, respectively. I_h and I_p are the moments of inertia of these bodies around the axis perpendicular to the XZ plane, computed in the mass centre (G) for the hull and in the hinge point (A) for the pendulum.

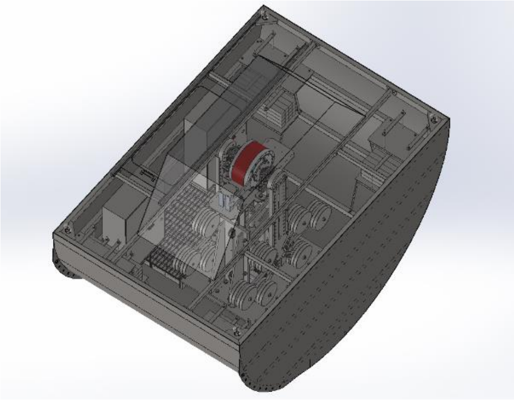

Figure 2: CAD of the 1:12 scale prototype [14].

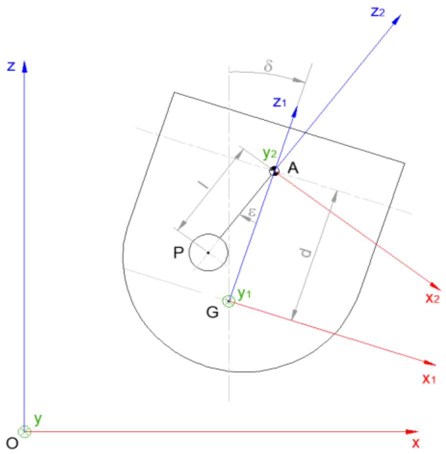

Figure 3: Schematic representation of the device and of its motion in the plane [14].

l (m)	d (m)	r (m)	w (m)	m_h (Kg)	m_p (Kg)	I_h (Kg m^2)	I_p (Kg m^2)
0.886	0.858	1.5	2	3176	410	2168	88.18

Table 1: Prototype configuration and geometrical and mass properties.

2.2 Hydrodynamic coefficients

The first step of hydrodynamic modelling a WEC device is a frequency domain analysis aiming at the computation of first order wave loads as added mass, radiation damping and diffraction forces. The wave-body interaction leads to reflection, refraction and diffraction phenomena and this complicated problem cannot be solved without some simplifying assumptions. The BEM solutions are obtained by solving the Laplace equation for the velocity potential, which assumes the flow is inviscid, incompressible, and irrotational [15]. In radiation problem (*i.e.* forces are created on the body by its moving in still water conditions) loads are formulated in terms of hydrostatic restoring loads, and frequency dependent added mass and damping forces. Diffraction problem (*i.e.* body is assumed to be stationary and flow is deflected from its course because of the presence of the body) resolves the part of the wave excitation loads. In this study we used NEMOH, which is an open-source Boundary Element Method (BEM) code based on linear potential flow theory for computations of first order hydrodynamic coefficients. The code has been developed by the *Laboratoire de recherche en Hydrodynamique, Énergétique et Environnement Atmosphérique* (LHEEA) [12]. Assuming linearity allows for rapid simulation times and frequency domain analysis can be the basis for a time domain analysis where nonlinearities can be introduced.

2.3 WEC-Sim, Simulink model and computational details

WEC-Sim (Wave Energy Converter SIMulator) is an open-source wave energy converter (WEC) simulation tool. The code is developed in MATLAB/SIMULINK using the multi-body dynamics solver SimMechanics [16].

WEC-Sim solves the WEC's governing equation in 6 degrees of freedom (DOF) using the approach first described by Cummins [17].

$$-\int_{-\infty}^{t} \mathrm{f_r}(t-\tau)\dot{x}(\tau)d\tau - \mathrm{F_{hs}}(x) + \mathrm{F_e}(t) + \\ +\mathrm{F_v}(\dot{x}) + \mathrm{F_{ext}}(x,\dot{x}) = (\mathrm{m}+\mathrm{m_\infty})\ddot{x} \qquad (1)$$

The first term of Eq. 1 is the convolution integral which represents wave radiation forces. F_{hs} is the hydrostatic force, while F_e, F_v are the wave excitation force and the viscous drag force, respectively. F_{ext} indictaes the externally applied forces, *e.g.* the power-take-off system forces and mooring system forces. On the right-hand side of Eq.1, m is the mass matrix and m_∞ is the added mass matrix at infinite frequency. More information about the implementation of the code are available for example in [13] or on the reference website [3].

The SimMechanic model used in this work is reported in Figure 4 which shows how the components are connected together and where the PTO is located. The hull is constrained to the Global Reference Frame, which in this case is the base of the tank test, with 3 degrees of freedom (surge, heave and pitch motions). The other three DOFs are neglected as we considered the propagation of the wave only in x-direction on a symmetric device respect to xOz plane. While the hydrodynamic coefficients calculated for the hull are a necessary input for WEC-Sim computation, the pendulum is set to be a non-hydrodynamic body since it is not in direct contact with the waves. The PTO is set to the location of rotation point of the pendulum where it is hinged to the hull.

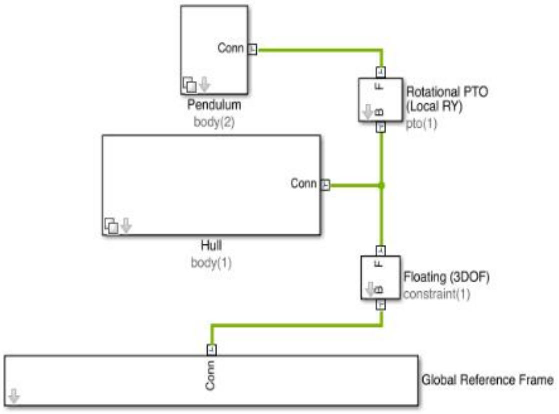

Figure 4: WEC-Sim block diagram system representation of PeWEC device.

3 Results and discussion

WEC-Sim was used to perform different sets of simulations. This section presents the results from each set of simulations and compares them with the experimental results achieved in the Marine Technology Research Institute (INSEAN) test tank. The experimental tests, conducted thanks to the collaboration between ENEA and Politecnico di Torino, were performed on a 1:12 scaled prototype of PeWEC to measure the real dynamic response of the prototype with regular waves by varying their period. The characteristics of the ship model basin of INSEAN are summarised in Table 2:

Test Tank	
Length	220 m
Width	9 m
Depth	3.5 m
Regular Waves	
Wave length	11 – 17 m
Period	1.9 – 2.9 s
Height	0.15 m
Slope	1 – 9 °

Table 2: Characteristics of the test tank of INSEAN.

During the tests, wave profile, motion of the hull and motion of the pendulum were analysed and subsequently the following quantities were registered: angular amplitude of the hull in pitch δ, angular amplitude of the pendulum ε and extracted power P. The frequency of acquisition of these data was set to 50 Hz. In the simulations, the same frequency has been set to make the results easier to compare. For further information about the experimental tests, see [14].

The simulations performed with WEC-Sim can be divided in three different sets:

1. Free-decay simulations
2. Regular-wave simulations
3. User-defined wave simulations using the wave time-series based on an exact experimental wave serie reproduced in the tank test

Next sections describe each of the set of simulations performed and, when available, results are compared to experimental data.

3.1 Free-Decay Test Results

A free-decay test of pitch motion was carried out to perform a preliminary verification of the natural frequencies of the system. For these frequencies we expected to have greater motion responses of the system. Figure 5 shows pitch time dependent response of the hull due to an initial rotation of about 25° from the equilibrium position. A frequency spectrum analysis was then carried out by computing the Fast-Fourier transformation (FFT) of the system response.

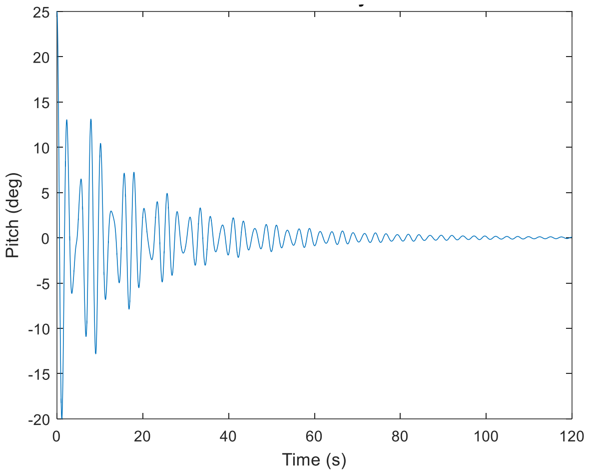

Figure 5: Time dependent free-decay test for pitch rotation of the hull.

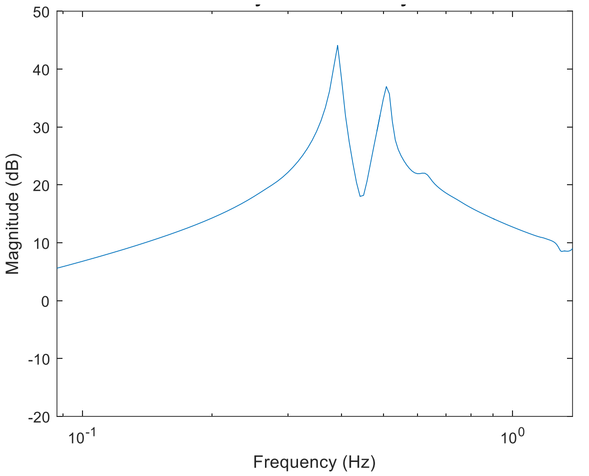

Figure 6: Semi-logarithmic plot of the FFT of the free decay pitch response of the hull.

The two peaks in the FFT plot presented in Figure 6 represent two natural frequencies of the system, which correspond to the periods T_1 =1.967 sec and T_2 =2.553 sec. Further investigation on free-decay test is left to future research efforts.

3.2 Regular-wave simulations

WEC-Sim was then used to study the dynamic response of the device in regular wave fields with a constant amplitude of 75 mm and varying the periods between 1.9 and 2.9 s. As told before, we used a BEM method to compute hydrodynamic coefficients. The accuracy of such class of methods is believed to be dependent on the number of boundary elements (panels) used for the domain discretisation. Hence, the first set of simulations was performed using different numbers of panels to compute the hydrodynamic coefficients to ensure that mesh resolution did not significantly affect the NEMOH and so the WEC-Sim results (see Figure 7). This preliminary mesh-refinement study was undertaken in order to find the right combination between good accuracy in the results and low simulation time.

Table 3 presents results achieved in this first phase and the relative error between numerical and experimental data with different mesh resolutions. Simulations were carried out for a wave period of T=2 sec and the relative error was computed with the experimental value as reference number. The mesh with 450 panels was chosen for all the subsequent simulations as a not decisive improvement is obtained with the finest grid.

Number of panels	82	450	800
Max relative pitch angle of the pendulum	29.5°	31.4°	31.7°
Relative error	7%	1%	0.05%

Table 3: Grid independence analysis.

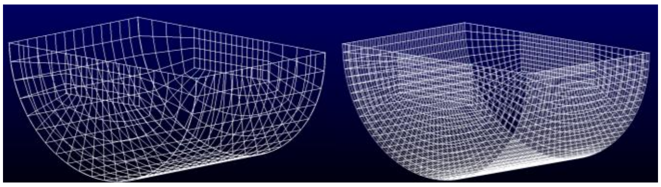

Figure 7: Mesh with medium (left) and fine (right) size panels.

In the next set of simulations, the dynamic response of the bodies was analysed by varying the period of the incident waves. Figure 8 shows the motion of the hull for the whole period of the test, while Figure 9 compares the pitch angle of the hull (δ), the relative motion of the pendulum (ε) and the power absorbed by PTO for an incident wave with a period T=2 sec in an interval of 5 seconds. The pitch response of the device shows excellent agreement with experimental data both in amplitude and in phase in the considered time interval. More generally, the code seems to better predict the evolution of the oscillations of the pendulum rather than those of the hull even if those are related to each other. The same trend was also observed in [14] even if it was not fully explained.

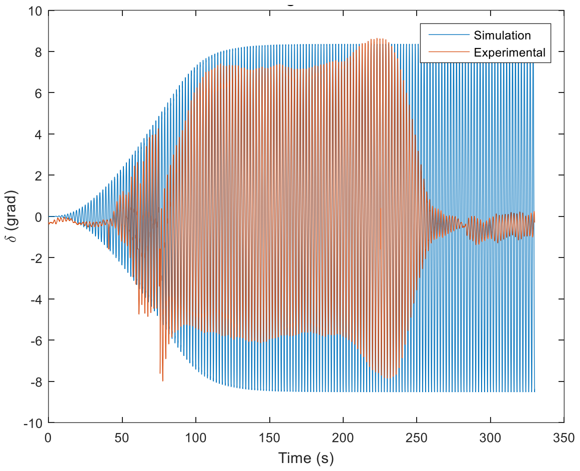

Figure 8: Dynamic pitch response of the hull for the whole test time with a regular wave with a period T=2 sec.

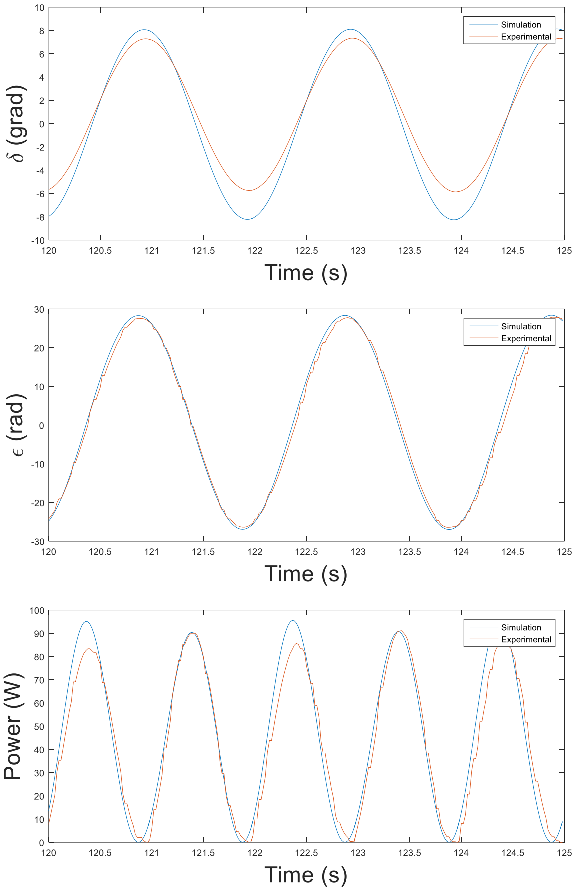

Figure 9: Comparison between numerical and experimental data of bodies motion in a generic time interval with a wave period T=2 sec. From top to bottom: pitch angle of the hull, pitch angle of the pendulum and power absorbed by the PTO.

Moreover, a power curve based on the mean values computed for each wave periods, was obtained by post-processing the computations results and it is presented in Figure 10. Simulations were conducted first neglecting and then introducing viscous damping. Usually, the effect of viscosity is included in WEC-Sim by specifying linear and quadratic damping terms to the equation of motion [3]:

$$F_v = -C_{ld}\dot{x} - \frac{1}{2}C_d \rho A_D \dot{x}\left|\dot{x}\right| \qquad (2)$$

where C_{ld} is the linear damping coefficient, C_d is the quadratic viscous drag coefficient, ρ is the fluid density and A_D is the characteristic area. In the present work only the quadratic viscous drag coefficient was considered. In fact, the linear damping has more importance for ship design and it is not usually applied in WEC system analysis and then it was neglected. However, not considering viscous effects leads to an unacceptable overestimation of the power generation and so this coefficient must be carefully selected.

As expected, in Figure 10 main differences between numerical and experimental data are noticed for wave periods close to the natural frequencies of the system. For these periods, the absorbed power is strongly overestimated by the numerical approach by neglecting viscosity effect, while, considering the viscous damping, an improved agreement is noticed. For all the other wave periods numerical and experimental data show similar values. Focusing on the critical periods of the exciting force, by neglecting the viscosity, power generated is overestimated of about 40% for a wave period T=2 sec and of almost 360% for a period T=2.5 sec. When damping effects are introduced the error is reduced to 17% for the first period and to 29% for the latter. The discrepancy observed in the latter cases could be due to an error in the estimation of the drag damping force, which plays an important role for waves with a frequency similar to the natural ones of the system. In fact, as the device has a very simple geometry, instead of tuning the linear and the quadratic drag coefficient by comparing free-decay tests or RAO response with experimental data (as reported in [6] and in [18]), we simply choose this coefficient from open literature where empirical data are available for simple submerged shapes [19].

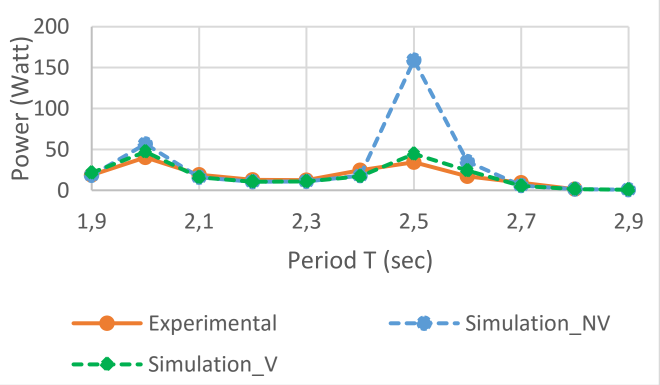

Figure 10: Power curve based on mean values for all the periods of the incident waves considered.

3.3 User-defined wave simulation

WEC-Sim has capacity to simulate the dynamic response of WEC systems also with irregular waves or with user-defined wave files; in the first case the free surface elevation is constructed from a linear superposition of a number of regular wave components, while in the latter it is created by a time-series wave elevation file. During the experimental tests, to verify the quality of the generated waves, 13 probes were located in different positions of the test tank in order to measure the wave profile. To better reproduce experimental tests, some simulations were conducted by giving the user-defined wave elevation time-history measured by one of the probes. The difference with previous sets of simulation is that in this case the device feels a wave which is influenced by different phenomena, *e.g.* the delay between turning on the wave generator to the moment that first wave arrives in the point of the device or waves reflection from the boards of the tank test. We took one of these experimental time-series wave elevations and used to perform simulations in WEC-Sim and results are reported in Figure 11. The dynamic evolution of the device has an improved agreement in this case in comparison to Figure 8. Even if mean and maximum values of the dynamic response were already well estimated, such a simulation permits to predict more accurately the dynamic of the system at any given moment. Furthermore, this code capability could be useful during a feasibility study of a wave energy plant: if buoy data are available, the energy potential of the plant could be in this way accurately predicted.

4 Conclusion

The open-source wave energy converter simulation tool WEC-Sim was used here to simulate the dynamic behaviour of the PeWEC device. The code-to-experiments validation tests here conducted was successful and the dynamic response of the device was well predicted by the numerical results. The damping viscous force plays an important role only when considering the wave periods close to the natural ones, allowing to improve the quality of the power curve prediction. A better estimation of the viscous effects could be necessary to minimize the discrepancy between numerical and experimental data. A tuning procedure of the damping coefficients by comparing numerical and experimental RAO or free decay test could be a guideline for future investigations. This approach was not followed in this work because such experimental test had still not been conducted. We demonstrated that mooring system was not needed in this case since it had been designed in such a way to not alter device dynamic. A more realistic prototype in bigger scale (1:5, 1:1) will be simulated in the real sea condition to estimate the annual energy production of the device and to verify if it can withstand the real sea conditions over its lifetime. We can conclude that the integrated solver obtained by the coupling of the two open-source codes NEMOH and WEC-Sim represents an useful and accurate tool to study and to improve our knowledge of the real behaviour of floating WEC devices.

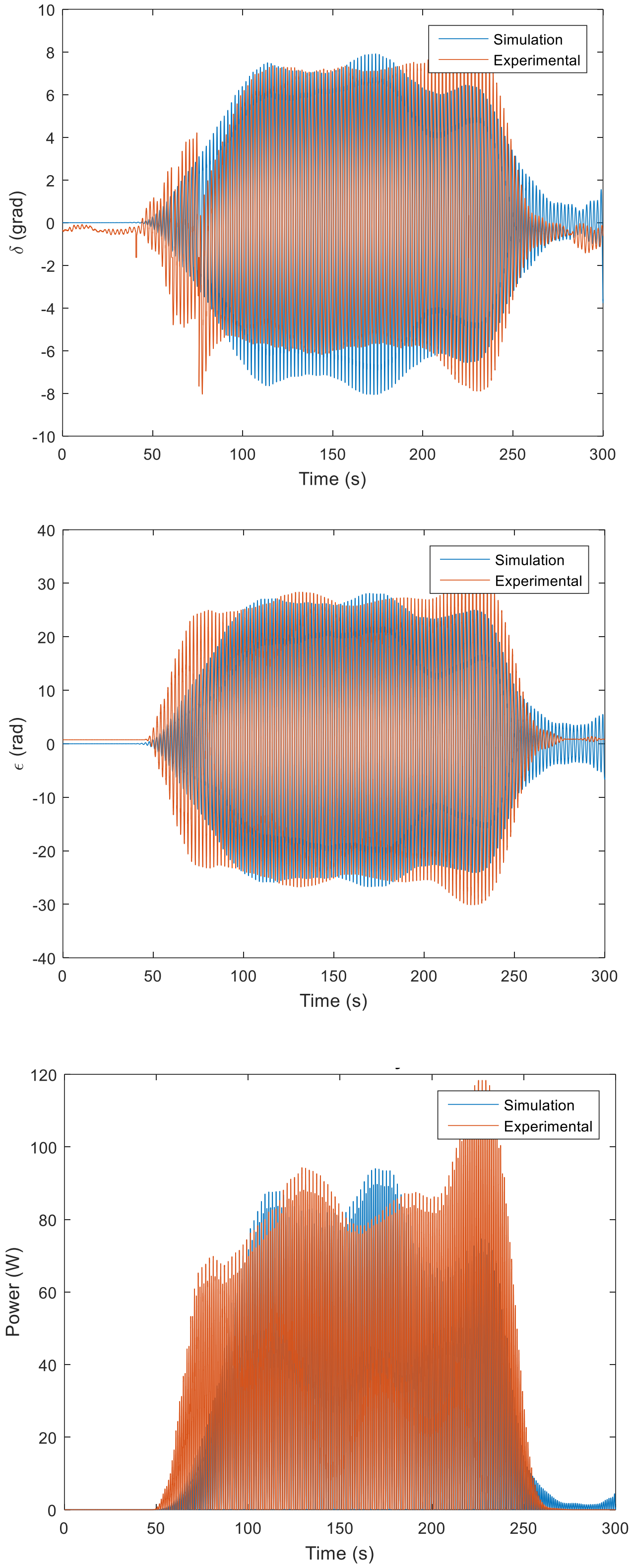

Figure 11: Dynamic response of the device with an user-defined wave time-series. From top to bottom: pith angle describing hull’s motion, pitch angle of the pendulum and power absorbed by the TPO.

Acknowledgements

We are grateful to Prof. Dionisio Del Vescovo from Sapienza Università di Roma and Prof. Carlos Michelen from SNL for their kind assistance during this project.

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