Application of a Passive Control Technique to the ISWEC: Experimental Tests on a 1:8 Test Rig

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Abstract. In this work, we address the use of Hardware In the Loop test rig for renewable energy application. Such test rig is designed to evaluate the performances of the wave harvesting system called ISWEC. The ISWEC is a floating, slack-moored, gyroscopic Wave Energy Converter. The full-scale prototype has an electric-mechanical Power take-off (PTO) composed by a gearbox and a brushless torque motor. The system is torque controlled to keep the gyroscope in the desired position range and to obtain maximum productivity. In order to obtain this, two different control methods are under study: a proportional-derivative (PD) law and a passive control method. The PD control law regulates the torque on the PTO providing a stiffness term to recall the gyroscope in the vertical position and a damping term to extract power. In this configuration, the PTO performs the recall effect, resulting in an increase of the torque load. To overcome such problems, the use of an eccentric mass to provide the stiffness term is analyzed. The experimental tests demonstrate the reduction of the PTO torque, justifying the gap in the system productivity provided by the passive control as assessed with the numerical model.

Keywords. Wave Energy Converter; Power take off; Reactive and Active Power; PD control; Passive Control; Hardware In the Loop (HIL);

1. Introduction

Considering the wide variety of the energy sources available in the sea (tides, currents, temperature and salinity gradient) wave energy is one of the most promising and studied [2]. Unlike the wind industry, a variety of WECs (Wave Energy Converters) exploiting different technologies exist, such diversities arise from the various ways that the Energy can be absorbed from the waves [3]. In particular, in these decades several technology solutions that harvest the wave power through an angular pitch motion of the floater have been designed ([8]-[9]-[10]). ISWEC (Inertial Sea Wave Energy Converter) is an all enclosed floating gyroscopic WEC, especially designed for the Mediterranean Sea ([4]-[5]-[6]-[7]). The device here presented is the 1 DOF ISWEC, a directional device brought from concept to full scale prototyping in Pantelleria in

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August 2015 [12]. The device was also conceived in the 2 DOF version, with omnidirectional properties, at present tested at small scale [16]-[17]. The 1 DOF system consists of a floating hull slack-moored [12], carrying inside a gyroscopic system: the pitching angular motion of the hull is converted to an inner precession oscillation of the gyroscope. The PTO (Power Take Off) subsystem converts the mechanical energy into electric energy. The peculiarity of the system lies in the fact that all the moving parts needed to produce energy are sealed inside a hull and therefore protected from the aggressive ocean climate. The full scale 100 kW ISWEC [12] has an all-electric PTO installed that exploits the high torques and low speeds of the gyroscope. The power extraction is controlled applying a torque with a proportional-derivative (PD) law. The derivative term extracts active power by damping the gyroscope and the proportional term provides the recall contribution ([7]-[13]), required for the vertical stabilization of the flywheel axis φ (Figure 2). To achieve this, a new solution is tested: a derivative control law with an eccentric mass (passive control method) configuration. The improvements carried by the passive control solution in term of PTO torque load, have been evaluated in [1] by means numerical simulations on the full-scale numerical model of the ISWEC.

In order to assess these improvements, several experimental tests on the HIL bench have been performed. The main purpose is to evaluate the system performance of the new control method on a scaled ISWEC system, focusing on the reduction of the values of the PTO control torque.

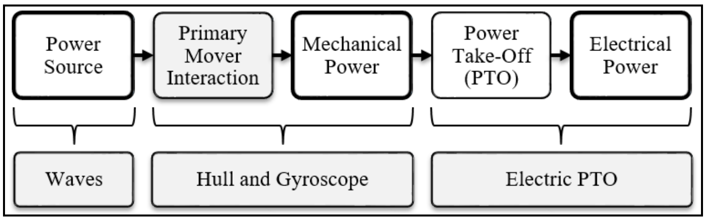

Figure 1 The ISWEC power path

2. ISWEC description

2.1. ISWEC Full-Scale Configuration

Figure 2 shows a simplified structure of the device carrying inside one gyroscopic unit. The full-scale system is composed of a steel-built hull containing two independent gyroscopic units. Each of the gyro units is equipped with a PTO composed of a gearbox coupled to an electric generator to increase the low gyroscope speed. An accurate description of the internal components of the full-scale device can be found in [1] and [5].

2.2. System Equations

The hydrodynamics of the ISWEC system can be studied considering 1 degree of freedom (DOF), taking into account only the pitching motion. This simplification is justified by the fact that this device extracts power by exploiting an angular motion of the pitch axis (δ in Figure 2) and the floater is designed to be stable in roll and amplify the pitch motion.

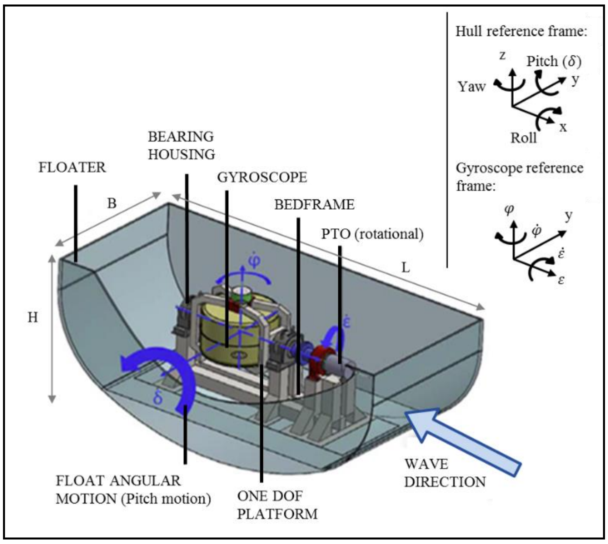

Figure 2 Simplified structure of the ISWEC

The equations of motion in the time domain can be written in body-fixed coordinates as reported in [1] and [6]. The angular motion of the hull around the δ axis combined with the flywheel angular speed results in a gyroscopic torque. The gyroscopic torque originates the precession motion of the gyroscope. Considering the whole gyroscopic structure, the dynamic equation of the gyroscope around ε axis is:

$$I_g \ddot{\varepsilon} = T_{gyro} - T_{\varepsilon} \tag{1}$$

Where:

- I_g gyroscope moment of inertia around ε axis
- $\ddot{\varepsilon}$ gyroscope angular acceleration around ε axis
- T_{gyro} gyroscopic torque obtained by combining the angular pitch speed of the hull and the speed of rotation of the flywheel
- T_{ε} PTO controlled torque acting on the gyroscope shaft.

Power is absorbed by imposing a controlled braking torque ($T\varepsilon$) on the gyroscope. At present, on the full-scale device a PD control law acts:

$$T_{\varepsilon} = c\dot{\varepsilon} + k\varepsilon \tag{2}$$

Where:

- c is the damping coefficient;
- k is the stiffness coefficient.

The PTO is modelled as a spring-damper system. The restoring component contributes to tune the gyroscope on the incoming wave, achieving also the elastic recall that avoids the stabilization of the gyroscope around its equilibrium point of 90°

(2). The damping part is responsible for the generation of the active power produced by ISWEC. This kind of control is active, as the PTO totally and directly exerts it.

The control torque contribution can be added in equation (1), obtaining the full dynamic equation of the gyroscope:

$$I_g \ddot{\varepsilon} + c\dot{\varepsilon} + k\varepsilon = T_{gyro} \qquad (3)$$

The mechanical power on the PTO axis is thus obtained as follows:

$$P_{inst}(t) = T_{\varepsilon}\dot{\varepsilon} \qquad (4)$$

3. HIL Test Rig

The HIL technique is a powerful tool to reduce costs in the design and manufacturing process of an engineering system. HIL techniques allow using real components inside a simulation of a mathematical model, obtaining experimental simulations and results in order to evaluate the real system behavior and performances [4].

In this way, for instance, if a part of the system is difficult to model or its cost is low, it can be replaced with the real part itself (gyroscopic structure and PTO, in our case study). On the other hand, if there is a part of the system expensive to manufacture (hull, in our case study), it can be replaced by its mathematical model. The complexity of the system is function of how much the simulation has to be reliable. For the purpose of the test rig and from the point of view of the gyroscopic system, a 1 DOF mathematical model of the system has been considered. Thus, the test rig has been designed to simulate the float pitch motion only.

The HIL bench is designed considering a sea state representative of a 1:8 scaled wave climate of Alghero (Sardinia, Italy) according to the Froude scaling law. It is the most powerful site among the ones monitored by the Italian wave gauge buoys system (RON – Rete Ondametrica Nazionale) [18]. With reference to Figure 3, the mechanical structure of the test rig is composed of a fixed base (part 1) carrying a rocking platform (part 2). The rocking platform supports the gyroscope (part 3) and rotates about a horizontal axis (part 4) giving rise to the pitching motion and therefore simulating the action of waves. The gyroscope rotates around its precession axis (part 5) driving the PTO (part 6). The flywheel rotates inside a vacuum chamber (part 7).

The inputs of the test rig is the wave profile. The wave profile is generated by a PXI CPU and, by means of the hydrodynamic equations, it is transformed on forces on the hull. The output of the numerical model is the pitching angle, set as the input signal for the angular position of the rocking platform. The combination of the pitching motion and the flywheel speed results in a gyroscopic torque. This torque drive the gyroscope rotation. The motion of the gyroscope is torque controlled by a proper driver in order to provide the PD control law following the equation (2).

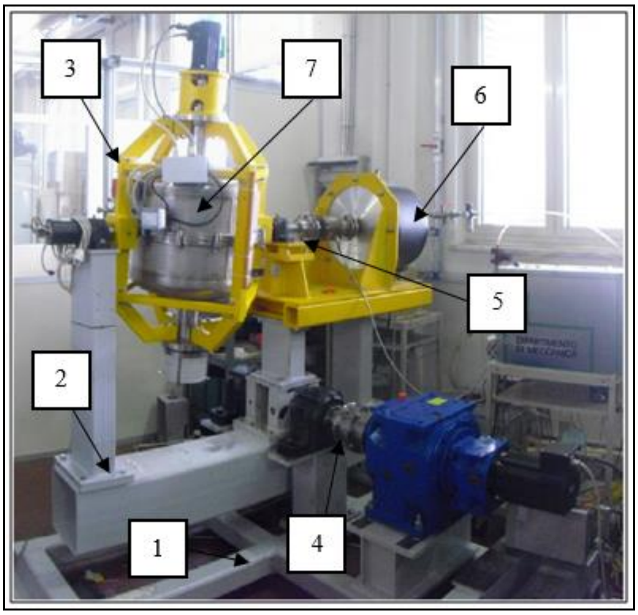

Figure 3 The 1:8 ISWEC HIL test rig

4. PTO Control Methods

To date, the PTO controller acts a PD control law in order to control both the position and extract power from the system. In order to reduce the root-mean-squared torque load on the PTO, a new passive control torque law has been examined. The new solution consists of an eccentric mass fixed at the base of the gyroscope (Figure 7), providing an elastic recall in place of the electric generator. In the following paragraphs, an example is reported in order to highlight the PD control law drawbacks. Then, an experimental campaign follows to evaluate the system behavior and comparing the two control method.

4.1. PD Control Law Drawbacks

The PD control law calculates the elastic recall term as a linear function of the angular position of the gyroscope. Looking at the instant power chart (Figure 4), sometimes the power sign is inverted. This means that sometimes the electrical-mechanical PTO works as a motor instead of a generator, inducing a flux of reactive power not directly involved in the power extraction, increasing the PTO torque. It is possible to rewrite the mechanical power substituting equation (2) in (4). Two terms are thus identified:

$$P_{inst}(t) = T_{\varepsilon}\dot{\varepsilon} = c\dot{\varepsilon}^2 + k\varepsilon\dot{\varepsilon} \qquad \textbf{(5)}$$

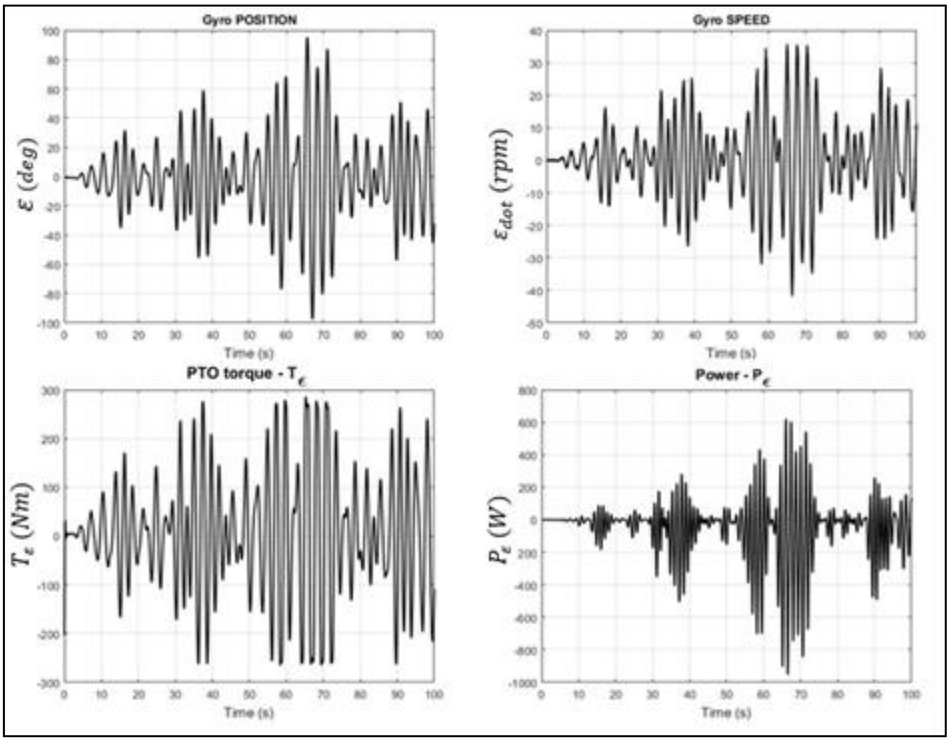

Figure 4 Experimental results – Gyroscope time histories – Irregular wave $H_{m0} = 0.27m$ and a $T_e = 2.86s$

The second term of the equation (5) represent the reactive power, a conservative term that gives no contribution to the average absorbed power. This term is actually provided by the electric generator, inducing a torque load on the PTO. To reduce the size of the electric generator, allowing a cost-effective solution, a different way to build the elastic recall term has been found: a passive control method. It consists in a damping term, once again achieved by the electric generator, and an elastic recall term, performed by an eccentric mass fixed at the gyroscope base (as shown in Figure 7).

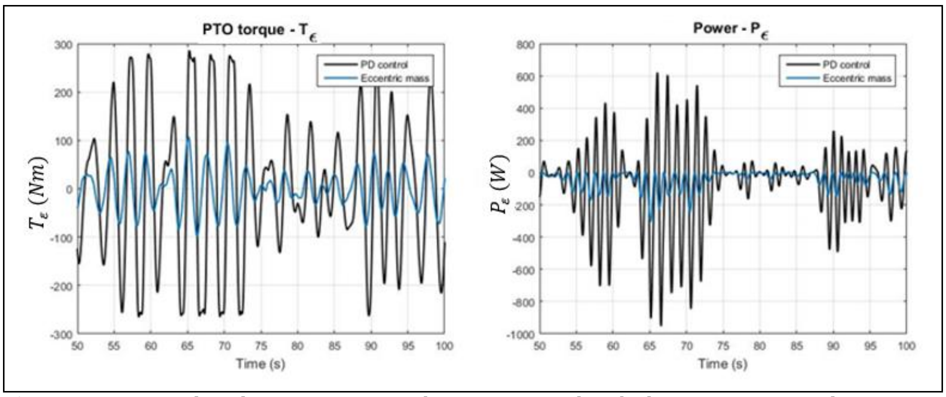

Figure 5 Experimental results – Gyroscope time histories – Control method comparison – Irregular wave $H_{m0} = 0.27m$ and a $T_e = 2.86s$

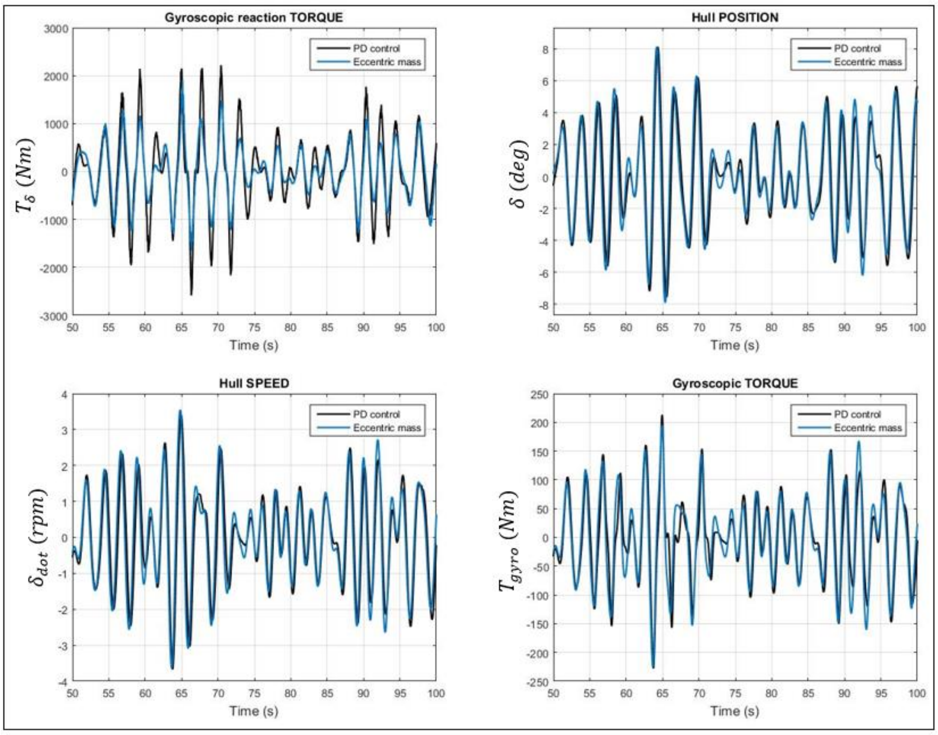

Figure 6 Experimental results – Hull dynamics time histories – Control method comparison – Irregular wave $H_{m0} = 0.27m$ and a $T_e = 2.86s$

4.2. Passive Control with Eccentric Mass

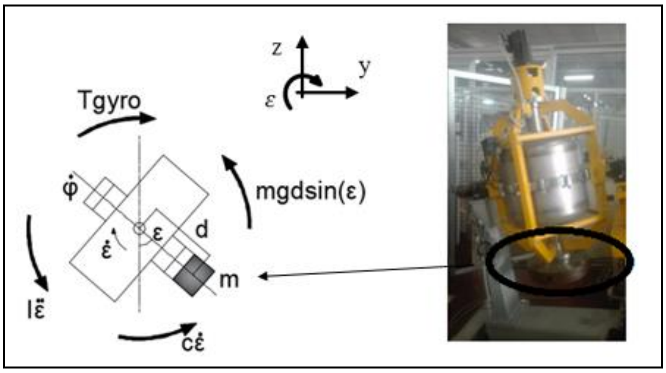

Figure 7 Eccentric mass system scheme and HIL test rig with the eccentric mass

Referring to Figure 7, the mass (m) is fixed at a proper distance (d) from the center of mass of the gyroscope structure resulting in an elastic recall due to the gravity force component perpendicularly projected on the flywheel axis (φ). Adopting this new configuration, the reactive component on the electric generator can be null, therefore only active power is employed. The Figure 5 explains this behavior, comparing the instant power for the two control method: the blue line never overcomes the zero power, meaning that the reactive power is null.

Moreover, the control torque provided by the electric generator is lower with the new control solution. On the other hand, the mechanical power extracted from the system is higher with the PD control (Table 1). In order to understand much more the eccentric mass effect on the system performances it is necessary to analyse also the hull dynamics. Considering the graphs of Figure 6 it is noticeable that the gyroscopic reaction (T_δ) on the hull is lower with the passive control (Table 2).

Table 1. Test rig performances for an irregular wave with $H_{m0} = 0.27m$ and a $T_e = 2.86s$

Torque control method	T_ε rms (Nm)	$\dot{\varepsilon}$ rms (rpm)	Mechanical power (W)
PD control	129	12	47
Eccentric mass	39	3	32

Table 2. Hull dynamics and gyroscopic effect for an irregular wave with $H_{m0} = 0.27m$ and a $T_e = 2.86s$

Torque control method	T_δ rms (Nm)	$\dot{\delta}$ rms (rpm)
PD control	659	1.11
Eccentric mass	503	1.14

This result in a wider pitching motion of the hull and then in a higher gyroscopic torque. In this way, the gyroscope speed should be higher with the passive control. Anyway, the gyroscope speed is lower as demonstrated in Table 1. This effect may be caused by two main factors:

- Friction effects: adding a mass on the gyroscope structure lead to a higher load on the gyroscope support bearings. This results in a higher friction action on the precession axis that brakes the gyroscope motion.
- Inertial effects: adding a mass to the gyroscope structure provide an inertia contribute that has the same order of magnitude of the whole gyroscope inertia. For example, the transport moment of inertia added by a 60 kg mass 0.5 m far from the ε axis is 15 kgm2 (the whole gyroscope structure inertia around ε is 40 kgm2).

Basing on the achieved results, an experimental campaign has been done in order to demonstrate why the passive control method lead to such relevant gap in the system productivity.

5. EXPERIMENTAL CAMPAIGN

To evaluate the improvements and drawbacks accomplished by the passive control, an experimental campaign on the HIL test rig has been done. The tests aimed to obtain the optimal control-parameters configuration for both control logics. The comparison is eventually made between the optimized configurations employing the extracted power for different sea states and PTO torque as comparison parameters.

5.1. Parameters

In order to study the eccentric mass effect on the system for different sea conditions, nine irregular sea states in terms of energetic wave period and significant wave height have been simulated on the test rig. The range of the energetic period was from 1.87s to 2.86s and the significant wave height from 0.083m to 0.249m (Table 3).

Table 3. Simulated Waves

Name	H_{m0} (m)	T_e (s)	P_w (W/m)
Wave 1	0.148	1.877	0.020
Wave 2	0.246	2.277	0.067
Wave 3	0.083	2.609	0.010
Wave 4	0.085	2.310	0.008
Wave 5	0.170	2.416	0.034
Wave 6	0.275	2.861	0.106
Wave 7	0.181	2.748	0.044
Wave 8	0.249	2.570	0.078
Wave 9	0.086	1.896	0.007

Moreover, for what concern the PD control law, different values of the stiffness coefficient (k) and damping coefficient (c) have been chosen to optimize the power production (Table 4). For the sake of simplicity, only one flywheel speed has been considered, equal to 1000 rpm. For what concern the passive control, the eccentric mass was equal to 60 kg, 0.5m far from the gyroscope axis, providing an elastic recall equal to 300 Nm/rad for small gyroscope angular displacement.

Table 3. Experimental campaign parameters

Name	Symbol	Values
Damping coefficient	c	30, 40, 60 (Nm/rads)
Stiffness coefficient	k	200,300,350,400 (Nm/rads)
Flywheel speed	$\dot{\varphi}$	1000 (rpm)
Eccentric mass	m	60 (kg)
Mass distance	d	0.5 (m)

5.2. Experimental results

The bar charts of Figure 8 relate on experimental results achieved for each irregular wave, in details: PTO torque, extracted power, gyroscope speed and gyroscopic torque.

The most relevant advantage of the eccentric mass solution is that it brings a reduction of the generator torque requirement. Figure 8 (left-top chart) highlights a reduction of almost 70% of the root mean square value of the PTO control torque, confirming the results showed in the previous example on a single wave (Table. 1). For what concern the extracted power, the eccentric mass solution results in a productivity gap with respect to the PD one. The PD control law can adapt the elastic recall with respect to the sea state resulting in a higher extracted power. Moreover, adding an eccentric mass produces a higher gyroscope moment of inertia. The added inertia affects the gyroscope dynamics, changing the resonance period of the system and decreasing the gyroscope speed. The bottom charts of Figure 8 show that the gyroscope speed is lower with the eccentric mass solution despite the gyroscopic torque is higher.

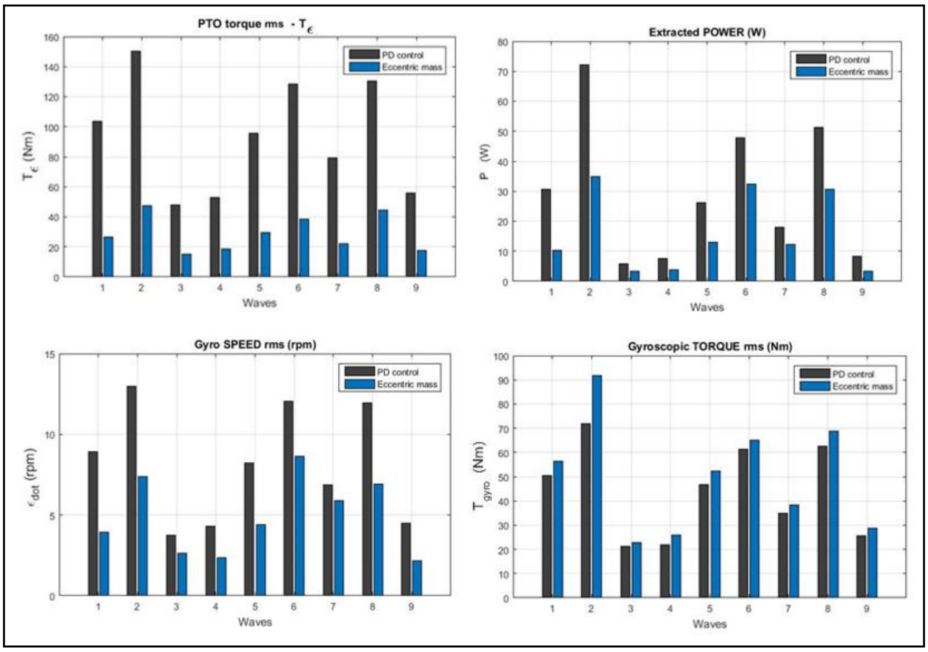

Figure 8 Experimental results: PTO torque rms value – Extracted power – Gyroscope speed – Gyroscopic Torque for different sea states and control methods

6. CONCLUSIONS

This works concerned some experimental tests on a HIL test rig simulating a 1:8 scaled prototype of the ISWEC device, an Inertial Sea Wave Energy Converter. After a brief description of the full-scale 1 DOF mathematical model, the HIL bench working principle has been presented. The main focus was on the control method of the device, proposing a new control method in order to improve the system performances in term of PTO torque load. As assessed in [1], numerical simulations with the time domain, non-linear ISWEC model have demonstrated a high reduction of the PTO torque levels compared to the low reduction of the annual productivity of the system. In the light of these results, experimental tests demonstrated the improvement carried by the passive control solution for different irregular sea state in term of reduction of PTO torque. On the other hand, experimental tests showed that for the scaled prototype the eccentric mass lead to a relevant gap in term of extracted power.

The extracted power values in Figure 8 are mechanical powers. To obtain the electrical power the electric generator efficiency has to be considered. This value is not constant, and it depends on both speed and torque of the PTO. With the passive control method, the reactive power flux on the electric generator is null, resulting in a higher efficiency of the PTO, not taken into account in previous calculations. In future works the electric generator efficiency may be considered.

Moreover, only one flywheel speed, four stiffness coefficients, three damping coefficients and one eccentric mass values have been considered in experimental simulations. The system may produce much more power with a wider range of control parameters, obtaining a different optimal combination of control parameters.

Overall, the passive control positively affects the PTO loads, resulting in less breakdown risks and reducing the overall maintenance costs. The PTO torque reduction allows considering a downsizing of the electric generator, decreasing the cost per kW of installed power [1].

In conclusion, the work suggests that further experimental tests on the full-scale prototype are needed in order to compare the two control solutions in real working environment and conditions, aiming to demonstrate that the productivity gap carried by the passive method is negligible respect to the relevant reduction of the PTO load.

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