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CONTROL AND PRODUCTIVITY ANALYSIS OF THE FULL SCALE ISWEC PROTOTYPE

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Abstract— **In the past four decades, hundreds of Wave Energy Converters (WECs) have been proposed and studied, but so far a final architecture to harvest wave power has not been identified. Many engineering problems are still to be solved, like survivability, durability and effective power capture in a variable wave climate. ISWEC (Inertial Sea Wave Energy Converter) is a system using the gyroscope to extract power. The goal of this paper is to identify an optimal control strategy in order to maximize wave power exploitation of ISWEC. Here we present a new adaptive control technique and the results deriving from its application to an ISWEC device with rated power of 60kW. ISEWC with the new control strategy are finally applied to the test case of Alghero, and the results in terms of power potential and yearly productivity are shown.**

Index Terms— **wave power, gyroscope, wave energy converter, point absorber, control, modelling**

I. INTRODUCTION

Wave power is one of the most promising and resourceful sources of renewable energy for the future. About 2000 TWh/year can be produced through the exploitation of the wave energy potential. Moreover, wave energy has many advantages when compared to other technologies (i.e. higher energy density than solar energy, more predictable and constant than wind energy). So it comes as no surprise that in the past three decades wave energy received huge interest from both the research community and industrial sectors [1]-[3]. Nevertheless, in order to make this technology competitive, a number of problems must be solved. In particular, among others, the issues of the optimization of the control strategy must still be solved.

It is well known that, in order to extract energy from the waves, both an action on the PTO (i.e. a force or a torque) and a balancing reaction are needed. In the simplest case the action is given by the wave pressure on the device and the reaction is obtained from the sea bottom. This is the case of several devices that have been designed so far such as shore-fixed oscillating water columns (OWC) and near-shore point-absorber buoys.

While OWC reacts against the sea-bottom via the fixed enclosing structure, in the case of PAB the sea-bottom provides a reaction to buoy motion via extensible hoses or tethers. The advantage of obtaining a simple reaction from the sea-bottom generally makes such devices easy to control and very efficient in terms of energy absorption. However, greater energy is generally available in deeper waters where bottom-fixed devices may not be used. Moreover, floating devices in deeper waters are less expensive due to the reduced impact with extreme waves.

Amongst the large variety of floating WECs, the reacting body devices (RBD) use the inertia of a large mass to guarantee the reaction needed from the PTO. In the case of a simple inertial mass, the theoretically optimal control should adjust the dynamic parameters of the PTO, such as the spring constant, and energy absorbing damping, to maximize the energy absorption. In the solution proposed by Salter (i.e. Duck WEC) the inertial effect is provided by a gyroscope [8]. The gyroscopic technology is suitable for seas characterized by wave frequency higher than the oceanic ones, typical of closed seas. From the point of view of the acting-reacting problem, the gyroscope has an unique feature: the inertial effect can be varied controlling the spinning velocity of the gyroscope. While this additional degree of freedom makes the device potentially more efficient in wave energy extraction, the control strategy of the gyroscope becomes even more crucial.

Similarly to the Duck WEC, ISWEC (Inertial Sea Wave energy Converter) [9]-[14] uses a gyroscope to create an internal inertial reaction able to harvest wave power without exposing mechanical parts to the harsh oceanic environment. In the past few years, ISWEC has been successfully tested using two scale models (scales 1:45 and 1:8) and several extensive laboratory experimental campaigns. In this paper the design of the first full scale ISWEC prototype is presented along with its control system and a refined control strategy. Finally, the power potential and yearly productivity of ISWEC in the test case of Alghero are shown.

II. ISWEC: HOW DOES IT WORK?

ISWEC (inertial sea wave energy converter) [13], [14] is a wave energy converter designed to exploit wave energy through the gyroscopic effect of a flywheel. The system is enclosed in a sealed hull retained by a slack mooring line. From the outside, it looks like a moored boat. The core of the device is the gyroscopic system.

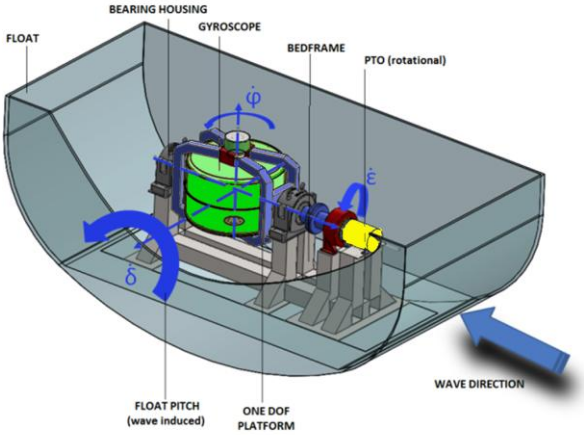

Fig. 1. Gyroscopic system composed by the flywheel, structure and generator.

The figure shows the three main components of this part: the flywheel inside its case (green), the gyro structure (dark blue), the generator (yellow). The x axis is oriented towards the bow, corresponding to the wave direction, while z is the vertical axis. So the hull rotates around y axis with the induced pitching motion δ due to wave-floater interaction. As the flywheel rotates with angular speed $\dot{\varphi}$, a gyroscopic torque about the ε axis comes into play. This is the torque the generator exploits to produce electrical power.

ISWEC is characterized by some advantages. First, every mechanical moving part is enclosed into the sealed hull, so there is little likelihood both of environment contamination and components attack by corrosive agents. Moreover, the system needs less maintenance and it is easier to operate.

The system regulation is performed acting over two parameters: the power absorption of the electric generator and the fly wheel velocity: this last parameter changes the dynamic response of the whole system and it helps to optimize the performances with respect to incoming wave. This means that the system is active, allowing high productivity over a broad spectrum of wave conditions; it is however obvious that keeping the flywheel spinning has its own cost.

Mathematical model

The device involves two main phenomena: the hull hydrodynamics and the mechanics of the gyroscope. There is a strong coupling between them due to the force exchanged during the operation.

From the derivation of the flywheel angular momentum, the equation of the motion around the ε axis is:

$$I\ddot{\varepsilon} + (I - J)\dot{\delta}^2 \sin\varepsilon\cos\varepsilon - J\dot{\varphi}\dot{\delta}\cos\varepsilon = T_\varepsilon \tag{1}$$

T_ε is the generator torque and can be either only braking or driving even depending on the control scheme. There are two other equation to describe the gyro effect: the equation of motion around the φ axis Eq (2) and around the axis orthonormal to the previous two Eq (3):

$$J(\ddot{\delta}\sin\varepsilon + \dot{\varepsilon}\dot{\delta}\cos\varepsilon + \ddot{\varphi}) = T_\varphi \tag{2}$$

$$I\ddot{\delta}\cos\varepsilon + (J - 2I)\dot{\varepsilon}\dot{\delta}\sin\varepsilon + J\dot{\varepsilon}\dot{\varphi} = T_\lambda \tag{3}$$

The T_φ acts on the flywheel, has a zero mean and a small value [14], so the system only see a little gyro speed oscillation. The projection of T_φ and T_λ on the vertical axis z is a yaw moment, while the projection on the horizontal axis y is the pitch moment T_δ. This last can be written as

$$\begin{aligned}(J\sin^2\varepsilon + I\cos^2\varepsilon)\ddot{\delta} + J\ddot{\varphi}\sin\varepsilon + J\dot{\varepsilon}\dot{\varphi}\cos\varepsilon \\ + 2(J - I)\dot{\delta}\dot{\varepsilon}\sin\varepsilon\cos\varepsilon = T_\delta\end{aligned} \tag{4}$$

The hull hydrodynamics is described by six second order linear differential equations, one for each degree of freedom [15]. They can be written in the following matrix equation, where the variable X groups 6 dof of the rigid body.

$$\big(M + A(\omega)\big)\ddot{X} + B(\omega)\dot{X} + KX = F_W + F_G + F_M \tag{5}$$

The first term multiplies the acceleration vector and it is composed by the mass matrix of the body M and the added mass A(ω) due to hydrodynamic forces. The second term multiplies the velocity vector and it is composed by hydrodynamic damping due to radiation forces. The last term in the left hand side of the equation multiplies the position and it is composed by hydrostatic stiffness. On the right hand side of the equation are indicated the external forces acting on the rigid body. So we find source forces F_W due to waves and calculated through the Froude-Krylov coefficients, gyroscopic forces F_G due to the moving flywheel and calculated with gyroscope dynamics, Eq (1) - (4), mooring forces F_M at this stage modeled simply as linear stiffness.

III. CONTROL

The ISWEC control strategy is based on two class of regulation: PTO torque and flywheel speed.

The first aims at exploiting every wave by tuning the control law parameter in order to set the optimal PTO torque in real time. The second regulation is a macro regulation of the gyro speed aimed to maximize the power conversion in the current sea state. This last regulation is based on wave parameters forecasts and has a long actuation time.

PTO Torque Control

The torque control law of electric generator is obtained by tuning two independent control parameters: damping and stiffness, to optimize the extracted power. Torque reference is define as follows:

$$T_{\varepsilon} = k \cdot \varepsilon + c \cdot \dot{\varepsilon} \quad (6)$$

As previously shown, ε indicates the generator shaft position angle with respect to the vertical configuration of the gyroscope axis, while its time derivative $\dot{\varepsilon}$ is the generator shaft speed.

Stiffness term is a torque proportional to the ε angle. This effect aims at taking back the gyro towards the vertical configuration. Moreover its value is tuned the system natural frequency with the wave frequency in order to maximize gyro oscillation. On the other hand this effect involves high peak torque values, so we must pay attention to the PTO maximum torque value. It is noteworthy that this part of the torque generates reactive power exchanged between mechanical and electrical devices. Reactive power could globally seem to be zero-sum, but due to the power conversion efficiency, we have negative balance.

Damping term generates the active power, i.e. the effective gross power generated. The damping viscous coefficient has to be tuned to extract the maximum power.

Flywheel Speed Control

Based on the sea state forecasts, it is possible to set an increasing or decreasing gyro speed in order to adapt the gyro effect to the incoming wave. Gyro speed $\dot{\varphi}$ is the key term able to define the dynamic response of the system, so it’s used for optimal system tuning in order to locate the frequency of maximum power extraction equal to the wave frequency [11]. Last but not least we have to pay attention to some system constraints such as the maximum PTO torque. Obviously higher gyro speed implies higher losses on bearings, so we could have some operating conditions where it is not convenient to work.

IV. POWER OPTIMIZATION

The power optimization is based on the system analysis over a number of different working conditions. First, we need to identify which sea conditions we are working with.

The sea states are described by two statistical parameters: wave period and wave height. So the first step in a WEC analysis is to discretize the sea state and generate a regular wave characterized by height and period evaluated to maintain the regular wave as powerful as the real sea. The table we obtain is the “scattering table” [12], [16]. It is worth noting that representing each sea state by a single iso-energetic monochromatic wave and tuning control coefficients on it leads to a higher power absorption than the corresponding real sea state. Thus the presented analysis should be considered as a best case reference for pre-design.

Control Parameters

On each cell a number of simulations are launched to find the parameter set that maximizes the power production. Notice that this analysis is valid only for steady conditions and regular waves. The analysis of the yearly ISWEC productivity is carried out with two different control logics, whose ground is explained in the dedicated section:

- PTO stiffness and damping control
- PTO stiffness and damping control + gyro speed control

A numerical optimization is carried out in order to evaluate the target control parameters maximizing the active power extracted from the device. Since real devices are characterized by physical limits, the power optimization has to respect these constraints.

Constraints

In this section the yearly power production of the system is analyzed taking into account some electro-mechanical constraints in order to preserve mechanical and electrical parts:

- PTO Torque: This value has to be checked because the peak and rms torque values have to be less or equal to the maximum allowed by the generator.
- Rated power of the power electronics: Power electronics can manage power up to a maximum value related to the maximum dc bus current: power electronics is designed for a double of the generator nominal power.
- Flywheel maximum speed: The gyro is the kernel of the machine. The fundamental parameter to reach a good productivity is the flywheel nominal angular momentum. A lot of energy during the design process is spent in evaluating the optimal value of that parameter and balancing gyro speed and moment of inertia. In fact higher speed implies higher loss, but higher inertia implies higher flywheel cost. So the maximum gyro speed value is another significant parameter to take care of.
- Bearings load: Other critical elements are the gyro bearings. Designing these components is challenging because it has to be kept in mind two targets:
  - Long fatigue life
  - Low losses

  It is important to identify which parameters have to be handled to reach a good trade off. Of course bearing loads and gyro speed are crucial in determining both life and losses. Looking at the last terms in Eq. (1) and Eq. (4), since $\dot{\varepsilon}$ is quite large compared to $\dot{\delta}$, the main contribution to loads are due to the T_δ so, in certain conditions we need to limit its value. Looking at the Eq. (4) the main term is the penultimate one, so bearing loads can be managed acting either on the gyro speed $\dot{\varphi}$ or the generator speed $\dot{\varepsilon}$. Since gyro speed regulation is slow, we can limit loads managing the generator speed in real-time. Obviously it could be hard to deal with maximum generator torque and maximum generator speed, so the gyro speed have to be controlled on the basis of sea state forecast both for productivity optimization and to work in conditions such that it is possible to manage generator torque and speed.

- *Pitch angle:* the last check we need to perform is the control of the pitch angle. This is useful because of the linear model reliability. In order to maintain a good model approximation, hull oscillations have to be less than 30 degrees. So, in case of higher pitch angle, it is not expected that model results are representative of the real device behavior. The optimization algorithm will search for optimal parameter set that meets the pitch constraint.

Parameters Optimization

When considering point absorber devices with a single degree of freedom, the problem of maximizing the output power has been extensively studied and fully solved in case of sinusoidal incident waves (and unconstrained motion). Optimum control [17], [18] can be obtained by tuning two independent control parameters, i.e. device damping and stiffness, to finally optimize the extracted power. However, in many practical cases, for the sake of simplicity, but at the expense of a reduced power extraction, only the device damping is adjusted [19], sometimes adopting non-linear control techniques [20], [21]. Such control techniques can also include some system constraints in order to improve the overall final system performance [22]. Following these investigation patterns, the first proposed control strategy is based on tuning both PTO damping and stiffness.

Devices like ISWEC exploiting a gyroscopic system for energy conversion, have however an additional degree of freedom, represented by the gyro speed. It can potentially be exploited as an additional control parameter to improve the power extraction from the considered system. In order to understand if the gyro speed is important to maximize the absorbed power, an analysis varying gyro speed is carried out.

The Tested System

In this paper the design of a full scale model is submitted, with rated power 60kW. The scaled scattering table is derived from real sea acquisitions and shown in the following figure. The location is near Alghero – Italy.

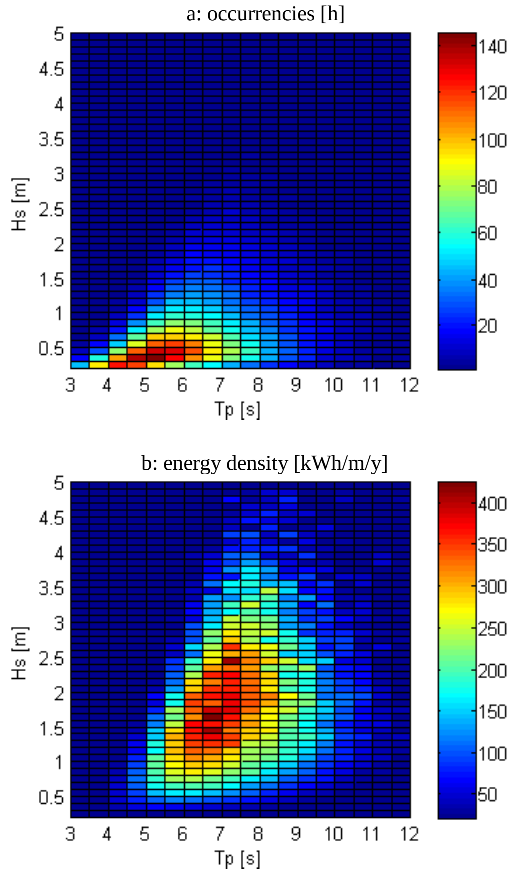

Fig. 2. Alghero annual wave occurrences based on statistical height and period discretization (a) and wave energy density (b).

In this paper the optimization was performed on a device designed on the Alghero scattering table shown in Figure 2. The main system features are shown in the following table:

TABLE 1.
DEVICE FEATURES: SCALED SYSTEM DESIGNED ON THE ALGHERO SCATTERING TABLE

Symbol	Quantity	Value	
J	Flywheel moment of inertia	30E6	kg m^2
L	Flywheel maximum angular moment	1.5E6	kg m^2/s
m_g	Flywheel mass	1.5E4	kg
m_f	Floater mass	300E3	kg
l	Floater length	15	m
b	Floater width	10	m

Furthermore constraints are crucial, so in the following table they are sown. These values are based on the real prototype design so depending on a cost/benefit analysis.

TABLE 2.
CONSTRAINT VALUES

Symbol	Quantity	Value	
$\dot{\varphi}$	Flywheel maximum speed	500	rpm
$\dot{\varepsilon}$	Generator maximum speed	20	rpm
T_ε	Generator saturation torque	200E3	Nm
P_ε	Power electronics max power	200E3	W
δ	Maximum allowed pitch angle	10	°

Results

In the following figures energy production and optimal parameter set are shown. With the c, k optimization and constant gyro speed, the yearly energy production is lower than what it is possible to obtain in case of variable gyro speed. In this case, the production increases by 40%.

TABLE 3.
PRODUCTIVITY SUMMARY

Optimization	Productivity
c,k $c,k,\dot{\varphi}$	68 MWh/y 95 MWh/y

Constraints effect is to amplify the gap between the two control techniques. In fact higher gyro speeds implies higher gyroscopic effect, so we also need higher braking torque etc.

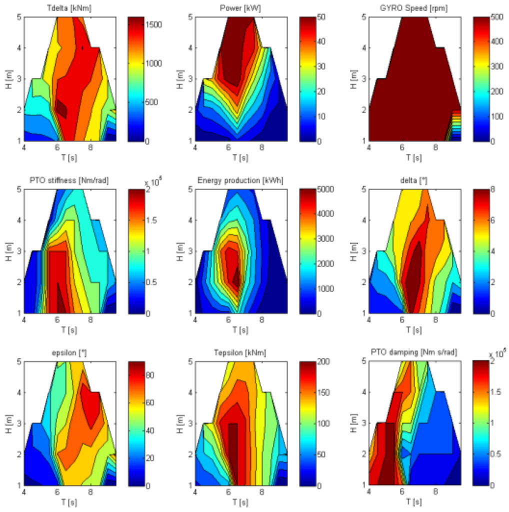

Fig. 3. Optimization results with maximum gyro speed, corresponding to the scattering table shown in Figure. 2.

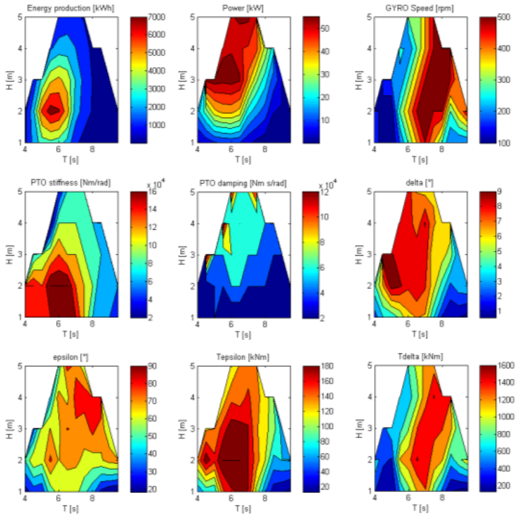

Fig 4. . Optimization results with variable gyro speed, corresponding to the scattering table shown in Figure. 2.

Previous figures summarize the main physical quantities related to the optimal parameter set in every scattering cell. It is possible to see that in every cell constraints are respected. Notice that the power optimization here shown involves different gyro speed values and if compared with the pervious case, with constant gyro speed, the left part of the graph, where there are higher occurrences, is affected by lower power production.

Looking at the Figure 5, it is possible to understand the effect of the maximum gyro speed. Higher speed limit allows exploiting higher number of cells, but in the right hand side of the graph we can see a lower production increasing. This means we have already a good scattering exploitation on most energetic cells. So it is not convenient to raise the gyro speed too much.

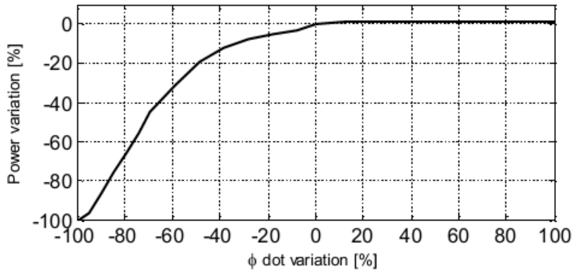

Fig. 5. Power variation in relation to the maximum flywheel speed

Increasing the maximum PTO torque is useful to raise the production but leads to higher device costs. Very similar results we can obtain with the driver rated power and these are summarized in the following figure.

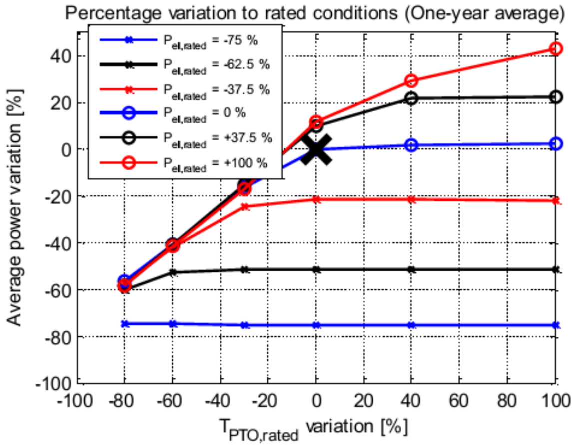

Fig. 6. Power variation in relation to the maximum PTO torque and electronics power.

During the design process it is important to find the maximum angular momentum, depending on the productivity, but also on bearing loads since these are high when the angular momentum is high too. Reducing bearing loads, it is also possible to reduce bearing size obtaining lower losses, so a productivity reduction due to angular momentum reduction in some scattering cells, can be recovered by lower losses all over the scattering table. Chosen the angular moment, the tuning between inertia moment and rotation speed is important to obtain a good compromise between losses (high speed) and costs (high mass).

V. CONCLUSIONS

A preliminary analysis of a 60kW ISWEC device deployed to the Mediterranean Sea has been performed. Some device configurations have been considered and compared. The yearly average scattering table of the site of Alghero has been then used to assess the performances of the device across the different sea states. The aim of the paper is to introduce a design tool for preliminary screening providing useful indications for an optimized pre-design of the ISWEC system. According to such analysis, the importance of having the gyro speed regulated according to the sea state clearly emerged as a key factor to maximize the power absorption and to respect system constraints. Simulations under irregular waves, floater shape optimization and a cost analysis will be then needed for the final design of the prototype.

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