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Stochastic control applied to the ISWEC Wave Energy System

ISWEC (Inertial Sea Wave Energy Converter) is a floating marine device able to harvest sea waves energy by the interaction between the pitching motion of a floater and a spinning flywheel which can drive an electric PTO. In the ISWEC the hull dynamics is governed and controlled by the gyroscopic torque. The optimal control logic results in tuning the floater dynamics to the incoming waves in order to maximize the power transfer from the waves to the floater. In this paper the control problems of the ISWEC are stated and a control scheme based on the sub-optimal stochastic control logic is presented. The control scheme here presented has been tested using real wave records acquired at the deployment location in Pantelleria Island, which is one of the most energetic sites of the Mediterranean Sea.

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■ G. Bracco, M. Casassa, E. Giorcelli, M. Martini, G. Mattiazzo, B. Passione, M. Raffero, G. Vissio

Introduction

In the last two centuries many Wave Energy Converters (WECs) have been proposed to harvest the huge amount of power coming from sea waves. Nowadays, a few of them are reaching a pre-commercial stage [1]. In fact, a number of problems must be solved in order to make this technology competitive [2]: the optimization of the control strategy is crucial to ensure efficient performance. The ISWEC belongs to the gyroscopic converters type, which owes its origins to Stephen Salter, who proposed the Duck device at the University of Edinburgh in the 1970s [3, 4]. Gyroscopes were initially used in marine applications for roll stabilization [5, 6]. In wave energy harvesting, the basic principle is the same, but the energy direction

is opposite, as the gyroscopic torque is induced by the incoming waves and exploited by the electrical PTO. The gyroscopic technology is particularly suitable for closed seas, which are characterized by wave frequencies higher than the oceanic ones. From the viewpoint of the control, the ISWEC can exploit the gyroscope for two different control logics: the flywheel spinning velocity can be tuned to match the forecast sea state (mid-term control), while the PTO torque is controlled in real time to exploit the incoming wave. On the one hand, this may result in a more efficient energy extraction, but on the other hand the control strategy becomes more critical.

In this paper, after a brief presentation of the ISWEC working principle and its governing equations, a performance analysis is carried out based on the physical characteristics of the full scale prototype. The stochastic control algorithm has been tested using real wave records representative of the installation site. The results are compared with a linear reactive controller showing a 30% average increment in productivity. Finally, the influence of some parameters such as the hull mass constraint is evaluated.

■ Contact person: Giovanni Bracco
giovanni.bracco@polito.it

The ISWEC

The ISWEC [7, 8] 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 (Fig. 1). The core of the device is the gyroscopic system.

Figure 2 shows the three main components of the gyroscopic system: the flywheel (red), the gyro structure (blue), the PTO (green). To describe the system dynamics, two reference frames have to be introduced. The first, the green one, is fixed to the hull and its axes are x, y, z . The second, the blue one, is fixed to the gyro structure and its axes are x', y', z' .

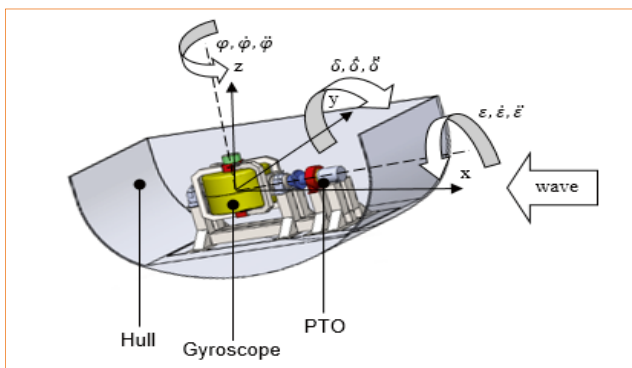


FIGURE 1 ISWEC scheme

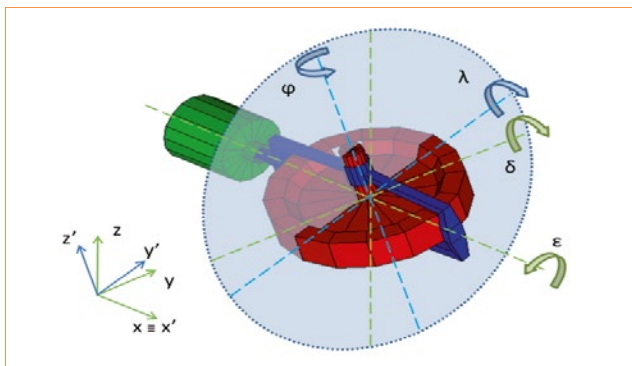


FIGURE 2 Gyroscopic system composed by the flywheel, structure and generator

Note that the origins of such reference systems are coincident with the flywheel center of gravity, so the gyro structure rotates around the PTO axis that matches the x axis. The x axis is oriented towards the bow, corresponding to the wave direction, while z is the vertical axis. The hull rotates around the y axis with the induced pitching motion δ due to the wave-floater-gyro interaction. As the flywheel rotates with angular speed $\dot{\varphi}$, its movement generates a gyroscopic torque around the x axis. The PTO exploits such torque to produce electrical power. The ISWEC is characterized by several advantages. First, every mechanical part is enclosed into the sealed hull, so there is little risk of both environment contamination and components corrosion. This characteristic allows to achieve high reliability and reduced maintenance. From a technical point of view, the flywheel speed is a control parameter that can be exploited to optimize the coupling between the ISWEC and sea waves, and consequently broaden the power generation capability of the WEC.

System equations

The device involves two main phenomena: the hull hydrodynamics and the mechanics of the gyroscope. There is a significant coupling between them due to torques and energy interactions.

Gyroscope equation

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

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

where T_e is the generator torque and can be either braking or driving, depending on the control scheme. There are two other equations to describe the gyro effect: the equation of motion around the z' axis (2) and the one around the y' axis (3):

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

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

The T_φ torque acts on the flywheel, has a zero mean and a small value [8], so the system involves only a small

gyro speed oscillation. The T_λ torque has a key role in the system behavior: its projection on the vertical axis z is a yaw moment, while the projection on the horizontal axis y is the pitch moment T_δ . The latter can be written as:

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

Hull equation

The hull hydrodynamics is described by six second-order linear differential equations, one for each degree of freedom [9]. They can be written in the following matrix equation, where the variable X groups the three positions and the three rotations of the rigid body expressed in the hull reference frame x, y, z :

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

The first term multiplies the acceleration vector and is composed by the mass matrix of the body M and the added mass $A(\omega)$ due to hydrodynamic forces. The second term $B(\omega)$ takes into account the hydrodynamic damping due to radiation forces. The last term in the left-hand side of the equation multiplies the position and is composed by the hydrostatic stiffness K . On the right-hand side of the equation the external forces acting on the rigid body are indicated: F_W due to waves excitation [9], gyroscopic forces F_G calculated with gyroscope dynamics (1), (3) and mooring forces F_M at this stage modeled simply as linear stiffness.

Control

WEC control

In this section, a review of the existing control algorithms for wave energy converters is given, so that the reader can have an overview of the state of the art in this field. In most cases, when analyzing the power extraction capabilities of a WEC, a one-degree of freedom system is analyzed. In the simplest case the hydrodynamic model of the device may be approximated by a second-order linear differential equation where coefficients are frequency dependent. Often, the first step is to develop a control strategy able to maximize the power output under plane (2D

problem), monochromatic waves. Of course, this means that the wave profile is composed of a single frequency contribution and this is not what happens in the real sea state. Afterwards, the case of plane, polychromatic wave is analyzed, generating a wave time series based on the spectrum of a specific sea state, or using acquired wave data. In the most recent studies, a 3D sea state is analyzed taking into account wave contributions coming from different directions. An emblematic example may be represented by the latching/declutching controller that has been firstly proposed for a heaving body by Falnes *et al.* [10]. This strategy is particularly suitable for waves longer than the WEC natural period; it basically consists in locking the floating body when its velocity approaches the zero value, by means of a clamping mechanism, and then releasing it at some point so that its velocity and the wave force will be at their highest point simultaneously; at this point the PTO force is set to its maximum value. The action on the system can thus be regarded as binary, that is either the body is locked, or moving under maximum PTO action - thus resulting in a highly non-linear control force. The declutching controller is similar to the previous one, but it is applied to waves shorter than the WEC natural period [11]. Differently from before, the floater is normally free to move and when its velocity reaches some desired value the maximum PTO force is applied.

The use of genetic algorithms indicated that, if applicable, the latching and declutching control is among the best control techniques for a wave energy converter, see Ringwood *et al.* [12]. A drawback of these strategies is that they need some kind of prediction of the incoming wave force, in order to actuate the device at the right time. Auto-regressive models and Kalman filters have been widely used in this context. However, these considerations apply to devices for which the control force is directly applied on the floater main degree of freedom, so that this could be locked or released at the desired time instant. The wave energy converter considered in this paper is not suitable for the implementation of this strategy, since in such a device it is not possible to lock/release the relative motion between floater and gyro at a desired time instant.

General considerations

In every energy converter the control strategy is of crucial importance in the whole system performance. The device needs to match the environmental conditions at best, in order to achieve the maximum power extraction taking into account the intrinsic physical constraints of the system. For the ISWEC, such constraints are represented by the torque and the power on the generator, and the flywheel speed specifications. The ISWEC control can be divided into two strategies characterized by different dynamics. The first one is a long-term control logic acting on the flywheel speed $\dot{\phi}$, according to a rough forecast of the sea state. The second one is a short-term control logic consisting in tuning the PTO torque on the basis of a more precise evaluation of the incoming wave parameters. In both cases, a forecast algorithm is needed, and this topic has already been addressed by different authors (e.g. [13-15]). In this paper the study is carried out using acquired wave data.

Sub-optimal control

The control strategy here presented is based on the optimal control theory discussed in [16, 17] and its objective is to maximize the power transfer from waves to the floater in a wide range of sea states. The idea is to obtain a unidirectional power flow from the waves to the WEC. This goal is achieved by producing a control force able to compensate the floater dynamics and then damp its oscillations. It is possible to apply a linear hydrodynamic theory using the Cummins' decomposition [18] so, since the ISWEC is essentially a pitching device, equation (5) can be written for one DoF as:

$$\begin{aligned} (M_\delta + A_{\infty,\delta})\ddot{X} + \int_0^t h_{r\delta}(t-\tau)\dot{\delta}(\tau)d\tau + \\ + K_\delta\delta = F_{w,\delta}(t) - T_\delta(t) \end{aligned} \quad (6)$$

From equation (6) it is clear that the gyroscopic reaction torque T_δ can be used as the control force, as it is the only variable that can be indirectly controlled. Assuming that all the state variables are deterministic quantities, it is possible to follow the analytical approach explained in [19], which leads to the optimal control torque that maximizes the mechanical energy absorbed from a given irregular sea state:

$$\begin{aligned} T_{\delta,opt}(t) = -(M_\delta + A_{\infty,\delta})\ddot{\delta}(t) - \\ - K_\delta\delta(t) + \int_{-\infty}^{+\infty} h_{r\delta}(t-\tau)\dot{\delta}(\tau)d\tau \end{aligned} \quad (7)$$

This clearly results in a non-causal control law, depending on the future values of the velocity $\dot{\delta}$. Such problem can be tackled with two approaches. The first solution is to evaluate future $\dot{\delta}$ with a prediction algorithm of the incoming wave based on a stochastic autoregressive model [20] or on neural networks [21]. Another option is to replace the non-causal term with a closely related causal process, leading to a sub-optimal control.

$$\int_t^{+\infty} h_{r\delta}(t-\tau)\dot{\delta}(\tau)d\tau \rightarrow 2b_c\dot{\delta}(t) \quad (8)$$

For the ISWEC, sub-optimal control has been chosen as a solution for the non-causality problem.

Since the irregular sea state is described by a spectrum, a stochastic approach is needed. It is legitimate to assume that the wave elevation can be regarded as a stationary zero-mean Gaussian process, and it is therefore possible to derive the optimal control law for known sea state conditions, using the linear stochastic dynamics theory [22, 23]. Under these assumptions, the pitching velocity and, in turn, the displacement and acceleration of the pitch DoF can be regarded as stationary zero-mean Gaussian, independent random processes.

For the sub-optimal control, assuming that all response processes are ergodic, the mean absorbed power becomes:

$$\begin{aligned} \bar{P}_a = E[T_\delta(t)\dot{\delta}(t)] = -(M + A_\infty)E[\dot{\delta}(t)\ddot{\delta}(t)] + \\ + 2b_cE[\dot{\delta}^2(t)] - E[K\dot{\delta}(t)] + \\ - \int_{-\infty}^t h_{r\delta}(t-\tau)E[\dot{\delta}(t)\dot{\delta}(\tau)]d\tau \end{aligned} \quad (9)$$

where the operator $E[\cdot]$ indicates the expected value. Applying the assumption of stationary process and the Wiener-Khinchin theorem, after some mathematical manipulation the equation for power becomes:

$$\bar{P}_a = \sigma_{F_e}^2 \left(\frac{1}{2b_c} - \frac{1}{4b_c^2} \int_0^\infty h_{r\delta}(u)\rho_{F_e F_e}(u)du \right) \quad (10)$$

where $\rho_{F_e F_e}$ is the auto-correlation coefficient function of the wave excitation force process.

The maximum for the absorbed power function is finally found for a damping value of:

$$b_c = \int_0^\infty h_{r\dot{\delta}}(u)\rho_{F_e F_e}(u)du \quad (11)$$

Therefore, once the sea-state and the hull hydrodynamic properties are known, it is possible to calculate the sub-optimal, unconstrained, stochastic value of the damping coefficient for the pitching DoF of the system.

Results and discussion

In the ISWEC device, one way to achieve the pitching torque for the sub-optimal control is by means of a velocity control on the PTO. As a matter of fact, there is a direct relationship between the gyroscopic reaction torque on the hull $T_{\dot{\delta}}$ and the rolling speed $\dot{\epsilon}$, so that a set value of the latter is defined for the linear gyroscope model:

$$\dot{\epsilon}_{set} = \frac{T_{\delta,opt}}{J\dot{\phi}} \quad (12)$$

A closed-loop speed control is implemented acting on the PTO torque. Moreover, since the gyroscopic torque that acts as a disturbance on the PTO axis is known analytically, it is possible to add a feed-forward torque as:

$$T_{\epsilon,ff} = -J\dot{\phi}\dot{\delta} = -L\dot{\delta} \quad (13)$$

The gyroscopic torque would force the PTO speed to deviate from its target value, and the feed-forward torque is used to cancel out this effect and improve the control. The resulting control system for the ISWEC device is shown in Figure 3, where, k_p is the proportional gain of

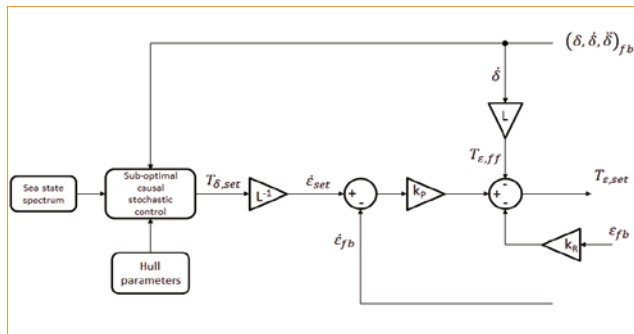


FIGURE 3 Closed loop optimal speed control for ISWEC

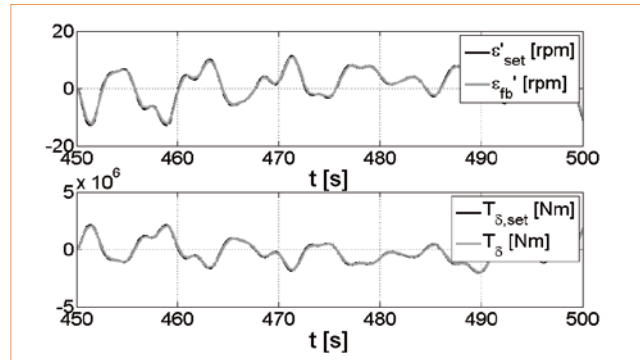


FIGURE 4 Set vs. feedback values for gyroscopic speed and torque

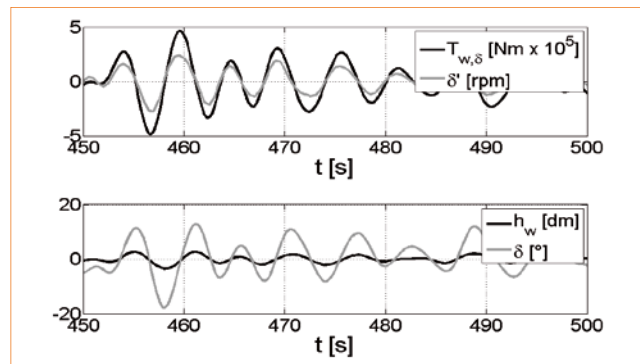


FIGURE 5 Wave force vs. pitching velocity (upper plot); Wave elevation vs. pitch angle (lower plot)

the closed-loop speed controller. It was necessary to introduce a relatively small stiffness k_R term in order to prevent position drifting in irregular wave conditions. Notice that the hull parameters are known since they are characteristics of the device, while the sea-state spectrum is given by the weather forecast and by an on-board monitoring system that will be installed for the sea-state evaluation and prediction. Figure 4 attest the control loop efficacy, since the set and the actual values are perfectly overlapping. The purpose of the sub-optimal control strategy was to force the response of the hull to be in phase with the excitation, meaning that their maxima occur at the same instants, as shown in Figure 5. Moreover, this implies that the power flux is always unidirectional from the gyroscope to the PTO, preventing the latter to act as a motor.

Conclusions

The discussion carried on so far in this paper highlights the main problems to face when a control strategy of a wave energy converter has to be designed. The first step is to define the level of approximation, hence complexity, of the model, in particular dealing with the 2D or 3D sea state and regular or irregular waves. Among others, the latching and declutching control strategy gained reliability and nice performances, but it is not compatible with the ISWEC device, since it requires a direct control of the main degree of freedom. However, the same need of a prediction algorithm is present in the sub-optimal control used for the

ISWEC. It is based on a stochastic description of the problem that leads to the definition of the stiffness and damping parameter of the control torque. The results show that the aim to put in phase the incoming wave with the gyroscope is perfectly accomplished. The accuracy and quality of this controller rely on the ability to forecast and predict the incoming wave in order to coherently tune the endogenous parameters to best match the exogenous ones.

Giovanni Bracco, Marta Casassa, Ermanno Giorcelli, Giuliana Mattiazzo, Biagio Passione, Mattia Raffero, Giacomo Vissio
Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Italy

Michele Martini
Environmental Hydraulics Institute "IH Cantabria", Santander, Spain

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