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Control of an ISWEC Wave Energy Harvest System

Giovanni Bracco#, Ermanno Giorcelli#, Giuliana Mattiazzo#, Michele Pastorelli*, Mattia Raffero#

Department of Mechanics and Aerospace Engineering, *Department of Energy , Politecnico di Torino
C.so Duca degli Abruzzi, 14, 10129 Torino (TO), Italy
michele.pastorelli@polito.it

Abstract — The control of the motion of a Wave Energy Converter (WEC) is a key factor for its wave power extraction capabilities. If a gyroscopic device is employed to get the reaction torque, the gyro self spinning speed is an additional control parameter of the system. To maximize the power harvest, the PTO stiffness, the PTO damping and gyro self spinning speed have to be tuned by a proper adaptive control algorithm.

In order to test such adaptive control the performance of an ISWEC device, with rated power of 3 kW and located in the Alghero site (Mediterranean Sea), is simulated, with different float configurations, to derive a convenient design trade-off for the considered application.

I. Introduction

In the past four decades wave power has been extensively investigated [1]-[3] and several devices have been proposed for the exploitation [4]-[6].

The ISWEC (Inertial Sea Wave Energy Converter) is a device exploiting the gyroscopic effects, it can be defined as a WAB (Wave-Activated Body, since it is excited by the incident wave to oscillate around a reference point) to be located offshore. The ISWEC has some interesting peculiarities: it is enclosed in a sealed shell and there is no contact between moving parts and the sea water. The problem related to system durability in the sea can be afforded by the available technology employed by the naval industry.

During storm condition, the gyroscope can be stopped and the energy production suspended. In this case the ISWEC became a passive buoy slackly moored to the sea bed. One of the problems to be solved in the design of a wave energy converter is the “reaction problem” [7]. Since the device is not fixed to the sea bed the reaction must be supplied by another part of the device or by inertial forces. In the ISWEC [8] [9] the system converting mechanical power into electrical power reacts on the inertial effects produced from a gyroscope. In 2009 Perez et al. [10] provided an approach for control optimization of a device for the harvest of energy from sea waves by a gyroscope.

This paper expands the approach used by Perez et al. by using the flywheel velocity as a further degree of freedom and taking into account PTO constraints of torque (max value and rms value) and oscillation angle. The work describes how a 3 kW rated ISWEC device can be controlled to increase the yearly average power extraction.

II. Modeling

Fig. 1 represents the gyroscopic system suspended inside the device. The gyroscopic system is composed of a flywheel rotating with angular velocity $\dot{\varphi}$, carried on a platform, when the float is excited by the sea waves, it rotates along the pitch coordinate (δ angle).

From the combination of the float angular velocity $(\dot{\delta})$ and the gyro self-spinning speed $(\dot{\varphi})$, a torque along the precession axis ε is generated. During the precession period the mean value of the torque, required for the self-spinning of the gyro, is zero (only the mechanical losses due to friction and aerodynamic drag have to be supplied to the gyro). If a load torque is applied to the ε axis, the precession motion is slowed down, thus follows that mechanical power can be drawn out from the PTO.

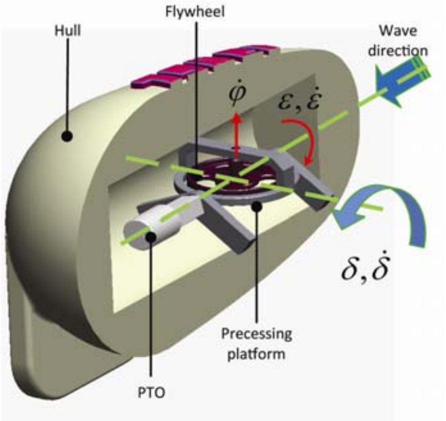


Fig. 1 – Scheme of ISWEC device.

In order to evaluate the behavior of the whole system and define a control strategy, the problem can be faced starting from a simplified model.

A sinusoidal pitch function is imposed

$$\delta(t) = \delta_0 sin(\omega t) \tag{1}$$

(the system hydrodynamics behavior is assumed as hypothesis), the torque applied to the PTO is equivalent to a spring–damper system

$$T_{PTO}(t) = k\varepsilon(t) + c\dot{\varepsilon}(t) \qquad (2)$$

The moment of inertia J of the flywheel can be assumed equal to the momentum of inertia of the whole gyroscopic system along the axis of the PTO [9].

Thus a simplified equation of the system can be written as follows:

$$J\ddot{\varepsilon} + c\dot{\varepsilon} + k\varepsilon = J\,\dot{\varphi}\omega\,cos\,(\varepsilon)\,cos\,(\omega t) \qquad (3)$$

The solution of the equation (3) is a sinusoidal function and can be written as:

$$\varepsilon(t) = \varepsilon_0\,sin\,(\omega t + \theta) \qquad (4)$$

From a purely mechanical point of view, to maximize the absorbed power, the gyroscopic system must be wave-resonating by a proper choose of the stiffness k. In a linearized model and in such resonance conditions, the average extracted power $P_{d,res}$ is:

$$P_{\,d,res} = \frac{1}{2}J\dot{\varphi}\omega^2\varepsilon_0\delta_0 \qquad (5)$$

If the hydrodynamic model accounting for the behaviour of the floater [11] is then added to the model, the equations that characterize the system became:

$$\big(M + A(\omega)\big)\ddot{X} + B(\omega)\dot{X} + KX = F_E + F_L \qquad (6)$$

Where M is the mass matrix of the system, A is the added mass matrix, B is the damping matrix, K is the stiffness matrix. A,B and K are due to the fluid. X is the buoy position/rotation vector, F_E is the excitation generalized force due to the waves' action on the floater and F_L is the load generalized force due to the gyroscopic actions.

F_L has two non-zero component only that are the torque on the PTO T_ε and the torque along the pitch axis T_δ that follows from the two velocities $\dot{\varphi}$ and $\dot{\varepsilon}$, combined together.

The phasors that represent T_ε and T_δ can be expressed as:

$$T_\varepsilon = \left(J\dot{\varphi}j\omega - \frac{J^2\varphi j\omega^3}{k - J\omega^2 + cj\omega}\right)\delta_0 \qquad (7)$$

$$T_\delta = \frac{(J\dot{\varphi}\omega)^2}{k - J\omega^2 + cj\omega}\,\delta_0 \qquad (8)$$

The float plays a key role in the system operation, because it must be able to transmit a reaction, from the waves to the gyro, opposite to T_δ as high as possible, while pitching as much as possible. Thus the gyro self spinning speed must be regulated to cope with the hydrodynamic capabilities of the float to maximizing the power harvest.

III. System characteristics

The model is here employed to analyze an ISWEC full scale device, with rated power of 3 kW, deployed in the Alghero site.

A. *Site features*

Among the Mediterranean sites, the Alghero site, on North West of Sardinia (Italy) is the most powerful site. The site is monitored by ISPRA, by using a DATAWELL Directional wave MKI buoy put in a point with water depth of 60 m at 40°33'11".99 N 08°07'0".01 E. In 2007 the yearly average wave parameters were: significant wave height H_s = 1.19 m and zero up-crossing period T_z = 5.24 s. The yearly wave power density of the site is 13.1 kW/m and its scattering diagram is shown in Table I [12, 13]. Light blue cells refer to areas with more than 5% of the yearly occurrences, while light red cells refer to areas with more than 1.8 %. The sum of all the blue and red cells encloses almost the 70% of the occurrences, however the ISWEC is in production in all the non zero occurrences.

TABLE I
SCATTER DIAGRAM OF THE ALGHERO SITE
(OCCURRENCES IN % - 2007 YEARLY AVERAGE)

		Tz [s]										
		3.25	3.75	4.25	4.75	5.25	5.75	6.25	6.75	7.25	7.75	8.25
Hs [m]	5.75											0.1
	5.25										0.2	
	4.75									0.2	0.3	0.1
	4.25								0.1	0.4	0.3	0.2
	3.75								0.4	0.4	0.2	0.3
	3.25						0.1	0.4	0.6	0.4	0.4	0.6
	2.75					0.2	0.5	0.7	0.8	0.8	1.0	0.7
	2.25				0.2	0.7	0.8	1.1	1.2	1.2	1.1	0.4
	1.75			0.2	0.9	1.4	1.8	1.8	1.8	1.2	0.4	0.3
	1.25		0.9	2.1	3.2	3.0	2.9	2.2	1.4	0.4		
	0.75	2.2	3.8	5.1	6.1	5.2	2.9	1.2	0.4			
	0.25	3.0	6.4	8.9	5.4	1.9	0.5	0.2	0.2	0.2	0.1	0.1

B. *ISWEC system features*

The device considered in this paper is a 3 kW rated power device designed for distributed generation. The system was designed with reference to the 2007 average wave parameters by using some simplified considerations on the float dynamics [14]. The main system parameters are shown in Table II.

The ISWEC is designed to fit into a standard 15' marine container (4500 mm L x 2600 mm H x 2440 mm W).

C. *Floaters*

The float hydrodynamic is also included in this analysis, to assess the ISWEC performances with real floats. The floats considered in this paper are built using the standard commercial components Resinex PEM 43 (dia 4300 mm total length 8500 mm) and composed together to build the whole float.

TABLE II
MAIN SYSTEM PARAMETERS

Symbol	Quantity	Value
J	Flywheel moment of inertia	1250 *kgm*^{2}
$\dot{\varphi}$	Flywheel max. angular speed	975 *rpm*
m_g	Flywheel mass	1400 *kg*
m_c	Gyroscopic system and container mass	~ 6000 *kg*
m_f	Module floater mass	*14400 kg*
V_f	Module floater volume	*52.4 m*^{3}

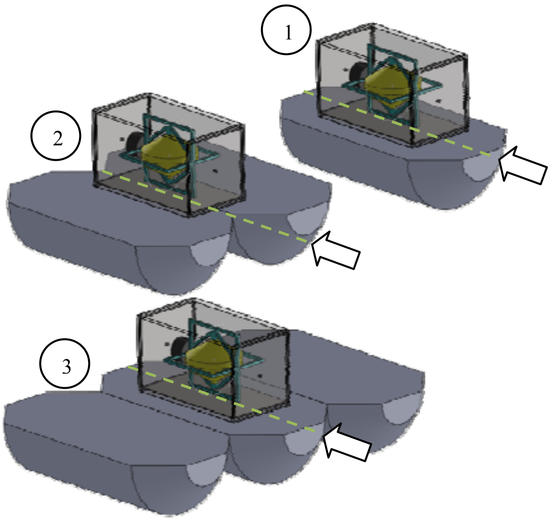


Fig. 2 - ISWEC device on a float composed by 1-3 Resinex PEM 43 modules.

D. Constraints

In this paper the yearly power production of the system is evaluated taking into account the following electro-mechanical constraints:

1. maximum torque on the PTO: 7200 Nm (power electronic converter limit)
2. rms value of PTO torque: 5000 Nm (electrical machine rated torque limit)
3. flywheel maximum speed: 1000 rpm
4. max oscillation angle (ε_0): 80 deg
5. float composed by 1 to 5 modules

IV. System Analysis

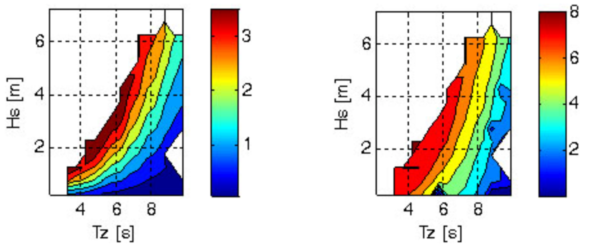
The analysis of the yearly ISWEC productivity is carried out by two control strategies:

a) PTO stiffness and damping control;
b) PTO stiffness, PTO damping control and gyro speed control.

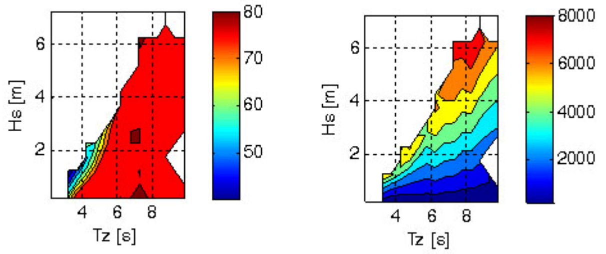
The wave is modelled as a regular wave with period and wave height evaluated to maintain it as powerful as the real sea state (assumed as a fully developed Pierson Moskowitz sea [15]). All the hydrodynamic parameters are evaluated by ANSYS AQWA R13.

The full simulation model (6 DOF: Floater hydrodynamics + Gyroscope) is implemented in the Matlab/Simulink environment, (the model selects for each wave frequency the relative a) and b) matrices and Haskind coefficient).

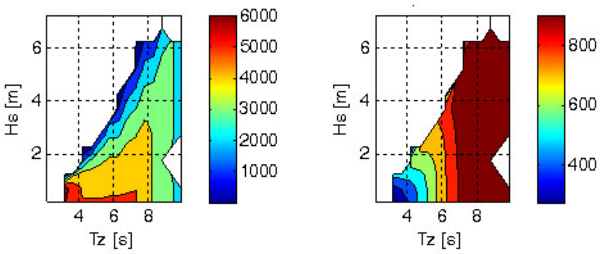
A numerical optimization is carried out in order to evaluate the target control parameters, maximizing the active power extracted from the device, but respecting the previously mentioned constrains. The optimization method was implemented in Matlab environment.



(a) Average power [kW]
(b) Peak power [kW]



(c) ε_0 [deg]
(d) damping c [Nm s/rad]



(e) stiffness k [Nm/rad]
(f) gyro self spinning speed [rpm]

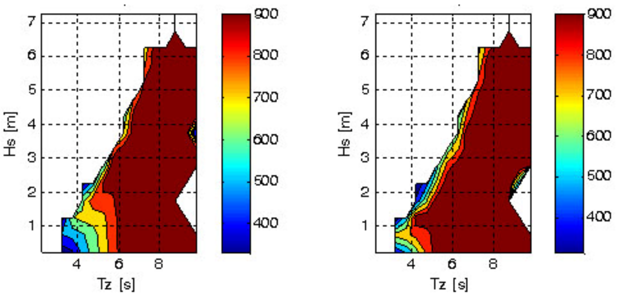
Fig 3 - Control strategy b): average and peak power available at the PTO, PTO damping, stiffness and gyro self spinning speed (2 float modules) vs the incident wave parameters (H_s and T_z).

It is worth noting that, representing each sea state by a single iso-energetic monochromatic wave, leads to a higher power absorption than the corresponding real sea state: thus this analysis is a best case reference for the ISWEC final design. The results are summarized in Table IV while Fig. 3 shows the values of average and peak power available at the PTO with PTO damping, stiffness and gyro self-spinning speed for the b) control type strategy with the float composed by 2 modules.

Fig. 4 shows the gyro self spinning speed when the modules in the float are incremented up to 3 and 5.

TABLE IV
AVERAGE GROSS POWER HARVESTED IN A YEAR

# float modules	Control a)	Control b)	Power increment
1	0.182 kW	0.949 kW	+421%
2	1.41 kW	1.85 kW	+31.2%
3	1.8 kW	2.01 kW	+11.7%
4	2.07 kW	2.21 kW	+6.76%
5	2.27 kW	2.31 kW	+1.76%



(a) 3 modules (b) 5 modules

Fig 4 - Control strategy b): gyro self spinning speed with 3 and 5 modules vs the incident wave parameters (H_s and T_z).

V. Constraints Sensitivity

With reference to the float composed by 2 modules and the control strategy with gyro speed control, an analysis of the constraint sensitivity can be carried out.

An important parameter in the economy of the system is the flywheel angular momentum. By reducing this parameter the size of the flywheel itself (production cost of the device) and the losses to keep it in rotation are reduced. In Fig. 5 the average power available at the PTO, as function the maximum gyro self spinning speed, is shown. The analysis has been carry out up to the maximum speed of 1000 rpm, that is, for the assumed mechanical size, a reasonable speed limit to avoid critical mechanical design.

The average gross yearly power vs max gyro self spinning speed that a reduction of the maximum speed of 40% produces a 13 % reduction of the power available at the PTO. In the final design of the gyro device dimensions and the self spinning speed must be defined after an economic evaluation of the device cost and estimated energy extracted from the sea waves.

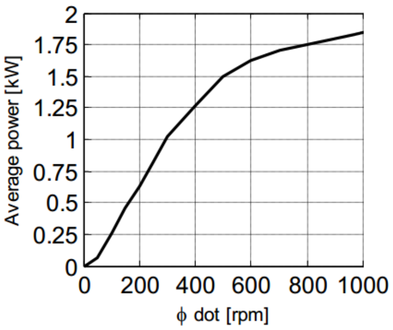


Fig. 5 - Average gross yearly power vs max gyro self spinning speed.

VI. Conclusions

The paper analyses the advantages that can be obtained when an ISWEC device is controlled by adapting he gyro self spinning speed, in addition to the stiffness and damping of the PTO. Numerical results based on a location at Alghero site in the Mediterranean Sea are shown. The control of the gyro self spinning speed, according to the sea state, is a key factor to maximize the power converted by the device and the ISWEC device looks to be conversion systems able to maximize the power harvest with variable sea conditions.

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I. REFERENCES

[1] A. Muetze, J. G. Vining, “Ocean Wave Energy Conversion – A Survey”, IEEE Industry Applications Conference Forty-First IAS Annual Meeting, Vol. 3, pp. 1410-1417, 2006.

[2] A. Clement, P. McCullen, A. Falcao, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, S. Petroncini, M. T. Pontes, P. Schild, B. O. Sjostrom, H. C. Sørensen, T. Thorpe, “Wave energy in Europe: current status and perspectives”, Renewable and Sustainable Energy Reviews Vol. 6 (5), pp. 405-431, 2002.

[3] T. Torphe, “A brief review of Wave Energy”, AEA technology for the DTI, Crown copyright, 1999.

[4] I. Russell, H. C. Sørensen, “Wave Dragon: Results From UK EIA and Consenting Process”, Proc. 7th Europ. Wave & Tidal Energy Conference, Porto, Portugal, 2007.

[5] F. Neumann, A. Brito-Melo, E. Didier, A. Sarmento, “Pico OWC Recovery Project: Recent Activities and Performance Data”, Proc. 7th Europ. Wave & Tidal Energy Conf., Porto, Portugal, 2007.

[6] M. G. de Sousa Prado, F. Gardner, M. Damen, H. Polinder, “Modelling and test results of the Archimedes wave swing”, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Vol. 220 (8), pp. 855 – 868, 2006.

[7] M. J. French, “On the difficulty of inventing an economical sea wave energy converter: a personal view”, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, Vol. 220 (3), pp. 149-155, 2006.

[8] G. Bracco, E. Giorcelli, G. Mattiazzo, “Experimental testing on a one degree of freedom wave energy converter conceived for the Mediterranean Sea”, TMM 2008, Liberec, Czech Republic, 2008.

[9] G. Bracco, E. Giorcelli, G. Mattiazzo, M. Pastorelli, J. Taylor, “ISWEC: design of a prototype model with gyroscope”, IEEE Conference Procedings, ICCEP, Capri, Italy, 2009.

[10] T. Perez, M. Santos-Mujica, J. P. Ruiz-Minguela, “Performance Analysis and Control Design of a Gyro-based Wave Energy Converter”, Proc. of the 8th European Wave and Tidal Energy Conference, 2009.

[11] J. Falnes, “Ocean waves and oscillating systems” Cambridge University Press, Cambridge, 2002.

[12] (2010) ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale (the Italian Institute for Environmental Protection and Research) website. [Online]. Available: www.idromare.it

[16] D. Vicinanza, L. Cappietti and P. Contestabile, “Assessment of wave energy around Italy”, Proc. of the 8th European Wave and Tidal Energy Conference, 2009.

[17] G. Bracco, E. Giorcelli, F. Marignetti, G. Mattiazzo, “ISWEC: application of linear tubular generators”, IEEE International Symposium on Industrial Electronics (ISIE 2010), Bari (IT) July 4-7, 2010, pp. 5, pp. 2426-2430, 2010.

[18] W. H. Michel, "Sea Spectra Revisited", Marine Technology, Vol. 36 N.4, pp.211-227, 1999.