Performance of a flap-type wave energy converter on the Uruguayan Atlantic coast

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***Abstract*— Marine energy is an untapped resource, which could make a significant contribution to the renewable and clean energy generation matrix. Amongst the marine sources, wave energy is the most promising one in a microtidal and template zone like the Uruguayan oceanic coast. In this article the performance of a flap-type wave energy converter was analyzed in the basis of an analytical model and spectra wave hindcast data at a specific location of the Uruguayan coast. The results of our study allowed us to estimate the amount of energy that may be harvest for this particular site and device.**

***Index Terms*-- Renewable energy, ocean waves, analytical modeling, flap-type wave energy converter.**

I. INTRODUCTION

In most countries marine energy is an alternative energy source that is yet to be exploited, and which have the potential to significantly contribute to the generation of clean and renewable energy [1]. It is possible to identify at least five types of marine energy sources: waves, tides, ocean currents, thermal gradients and saline gradients. Wave energy, however, is the one with the greatest potential [2]. This is particularly true for microtidal regions in template zone such as is the case of the Uruguayan coast.

In a previous work [3] the first author has presented an assessment of wave energy resource in Uruguay. The wave energy potential for the Uruguayan coast is significantly lower than for other coasts (e.g. U.K, Chile, and Portugal). Nevertheless the theoretical potential, along the 200km of Atlantic coast and at 20m of depth , almost doubles the actual amount of electrical energy generated in Uruguay. In addition, the low variability in medium and long term of the resource and the relative benign extreme wave conditions make Uruguay an attractive place to invest in this type of source.

In what follows, theoretical potential, refers to the annual average of energy contained in waves of a specific site; and technical potential refers to the fraction of the theoretical potential that it is possible to harness with a particular energy converter. Therefore, to estimate technical potential at a particular site a wave energy converter (WEC) must be defined. In this article, a flap-type WEC installed on La Paloma harbor breakwater is considered. This will allow us to have a first estimation of the technical potential of a WEC installed on the only breakwater on the oceanic coast of the country.

A flap-type is one kind of WEC among many other variants developed. It consists briefly on a buoyant flap, ideally orientated perpendicular to the incident waves. The flap spins around a fixed horizontal axis as it is forced by the waves. Commonly, these types of devices are combined either with piston system, which pumps water to an onshore turbine (e.g. Oyster, [4]), or with a linear generator.

For the purpose of this study a simplified analytical model of the WEC configuration that maximize the energy captured under a frequent wave condition in La Paloma was defined. And the performance of this configuration was assessed for a perpendicular acting wave of different wave periods (i.e. efficiency curve for the period was obtained).

Finally, the optimized geometry was used combined with the directional wave spectra series at the site considering the flap orientation and the analytical efficiency curve. This allowed us to obtain an estimation of the energy harnessed by an optimized flap-type wave energy converter installed at La Paloma harbor breakwater (i.e. technical potential) and the variability of the resource for different time scales, assessing the performance of a WEC on the Uruguayan Atlantic coast for the first time.

II. MATERIALS AND METHODS

In this section, the analytical model used to define the "optimal" device configuration and its efficiency curve is presented (A); the hindcast wave data are presented (B); and the proposed methodology for the estimation of the device technical potential is presented (C).

This work was supported by the Uruguayan Agency for Research and Innovation (ANII) through its Energy Funds program (FSE), contracts numbers PR-FSE-2009-1-12 and FSE-1-2013-1-10748

978-1-4673-6605-2/15/$31.00 ©2015 IEEE

A. Analytical Model

The model presented next is a simplified analytical model, which allows to calculate the power captured by a flap-type WEC under the perpendicular incidence of a monochromatic wave train, which propagates over an horizontal depth. The model is bi-dimensional, and boundary effects are not considered. On Figure 1 a scheme of the device defining all its geometrical parameters is shown: b is the semi-thickness of the flap, c is the length of the flap, h is the still water depth, and H is the wave height.

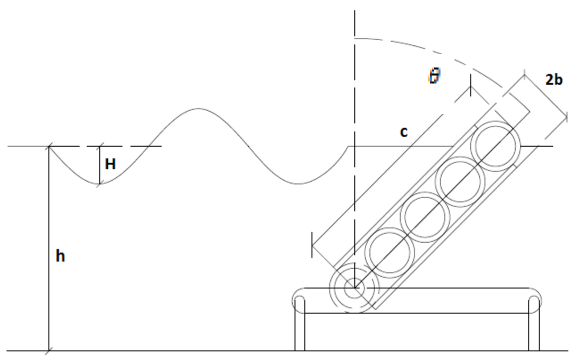

Figure. 1.-Scheme of the flap-type wave energy converter.

That is the Newton Second Law for rotation projected on the spin axis of the device, gives the equation of motion of the device:

$$Is\ddot{\theta} = Tg + Tw + Tpto. \tag{1}$$

Where I_s is the moment of inertia about the spin axis, *Tg*, *Tw* y *Tpto* are the weight torque, hydrodynamic torque, and Power take off (PTO) torque, respectively. Meanwhile, θ(t) is the angle formed by the flap and a vertical (see Figure 1).

The torque due to the flap interaction with the water (*Tw*) can be decomposed in a buoyant term (*Te*) and a term associated with the dynamic wave action on the flap. Assuming first order Linear Wave Theory the dynamic torque can be calculated as the superposition of the torque due to an incident wave on a fixed flap (*Ti*) and the torque due to a flap oscillating through still water (*Td*), giving

$$Tw = Te + Ti + Td. \tag{2}$$

Since both the weight and buoyancy torque are proportional to θ(t), it is possible to group them together and define a restoring coefficient (ke) as follows:

$$Te + Tg = ke.\theta\,, \tag{3}$$

$$ke = \frac{c}{2} Mw\left(1 - s\right) \quad . \tag{4}$$

With *Mw* the water mass associated with the flap volume and *s* the flap water density ratio. Then *Td* is decomposed into a term proportional to the flap angular acceleration and other term proportional to the flap angular velocity, with the added inertia (*Ia*) and the radiation damping (*Bd*) as proportionality constants, respectively, to obtain:

$$Td = -Ia\ddot{\theta} - Bd\dot{\theta} \tag{5}$$

Modeling the Power Take Off as a linear damping, the external torque is proportional to flap velocity thorough a proportional constant *Bpto*,

$$Tpto = -Bpto\dot{\theta}\,. \tag{6}$$

In this way, equation (1) can be rewritten as:

$$\left(Is + Ia\right)\ddot{\theta} + \left(Bpto + Bd\right)\dot{\theta} + ke\theta = Ti\,. \tag{7}$$

The time dependence of *Ti* and the flap motion can be assumed to be

$$Ti = \mathrm{Re}\left\{F_i e^{-iwt}\right\}, \tag{8}$$

$$\theta(t) = \mathrm{Re}\left\{\frac{i\Omega}{w} e^{-iwt}\right\}, \tag{9}$$

$$\dot{\theta}(t) = \mathrm{Re}\left\{\Omega e^{-iwt}\right\}, \tag{10}$$

$$\ddot{\theta}(t) = \mathrm{Re}\left\{-i\Omega w e^{-iwt}\right\}. \tag{11}$$

Where F_i and Ω are the complex amplitudes of *Ti* and the angular velocity of the flap, respectively, and w is the angular frequency of the incident wave. Substituting (8), (9), (10) and (11) in (7) a relation among the involved parameters is obtained:

$$-i\Omega w\left(Is + Ia\right) + \Omega\left(Bpto + Bd\right) + \frac{i\Omega}{w} ke = F_i\,.(12).$$

The power harnessed by the WEC (P) is defined as:

$$P = -Tpto\dot{\theta}(t) = Bpto\dot{\theta}(t)^2\,. \tag{13}$$

Averaging over a wave period and taking Ω from (12), it follows that,

$$P=\frac{1}{2}Bpto\Omega^2=\frac{1}{2}Bpto\frac{\|Fi\|^2}{\left[\left(\frac{ke}{w}-w(Is+Ia)\right)^2+\left(Bpto+Bd\right)^2\right]}. \quad (14)$$

Then we obtain an analytical expression for the power harnessed by the WEC as a function of the geometry, the power take-off damping, and the hydrodynamic parameters (*Ia*, *Bd* and F_i). Typical values for *Ia*, *Bd* and F_i can be found in the references [5], [6] and [7].

In order to define main characteristics of the device (i.e. geometry, density of the flap and the *Bpto* constant), it is necessary to define a reference wave condition of the future WEC placement site. For the present case a 9 s period wave propagating over a depth of 8 m was assumed. Then, the resonance condition for the system, where the *Bpto* constant was equal to the radiation damping (*Bd*) was imposed, and the thickness (2b) of the flap, for which the efficiency was the largest possible and the *Bpto* constant was relatively small, was obtained. With the thickness of the flap defined, a sensibility analysis of the efficiency due to variations of the vertical position of the flap and its density was performed. Finally, the device efficiency curve was obtained. This provided the efficiency of the device for a range of incident wave periods, with 9 s as a reference.

B. *Wave hindcast data*

For the present study the wave spectra obtained in [3] at 34°38'S - 53°54'W were used. This point is located 21km away from the breakwater in a mean water depth of 22 m, and hereinafter it is referred as the Reference Point.

Wave spectra are available every 3 h covering the years 1980 to 2010. Each spectrum is discretized in 24 directions uniformly distributed and 25 frequencies distributed in a logarithmic grid covering the 0.0418 Hz - 0.4114 Hz. range, with consecutives frequencies linked by a 1.1 factor,

$$f_{i+1}=1.1f_i. \quad (15)$$

C. *Technical potential estimation*

For the WEC performance analysis each wave spectrum is conceived as the superposition of 600 waves (24 directions x 25 periods). Each of these components corresponds to a combination of direction and period and with a height associated with the energy contained in a particular bin of the spectrum. Using linear wave theory (see e.g., [8]) each wave component was propagated towards the breakwater.

The selected device can only harness the wave energy flux perpendicular to the flap. Therefore, the energy flux of each propagated wave component is projected in the perpendicular direction to the breakwater, as it is considered that the flap is installed parallel to the breakwater.

Finally, for each wave component, the projected energy flux is affected by the efficiency obtained with the analytical model. In this way, it is possible to achieve an estimation of the power harnessed by the device for each wave component of the spectrum. Adding the contribution of each component, the total power harnessed for each wave spectrum is obtained.

In summary, the followed steps were: 1) distribute the energy of the spectrum in waves with different directions and periods, 2) propagate each wave towards the breakwater, 3) project the energy flux over the breakwater, affecting the result by the efficiency, 4) add the contribution of each component. This procedure was repeated for each spectrum, obtaining an estimation of the WEC energy output over the analyzed period.

III. Results and Discussion

A. *Analytical Model*

Figure 2 (left graphic) shows the variation of the *Bpto* coefficient on resonance condition (*Bpto = Bd*) or maximum efficiency, as a function of the dimensionless thickness of the flap (b/h). Figure 2 (right graphic) graphic shows the efficiency of the device for *Bpto=24*, as a function of the dimensionless thickness of the flap.

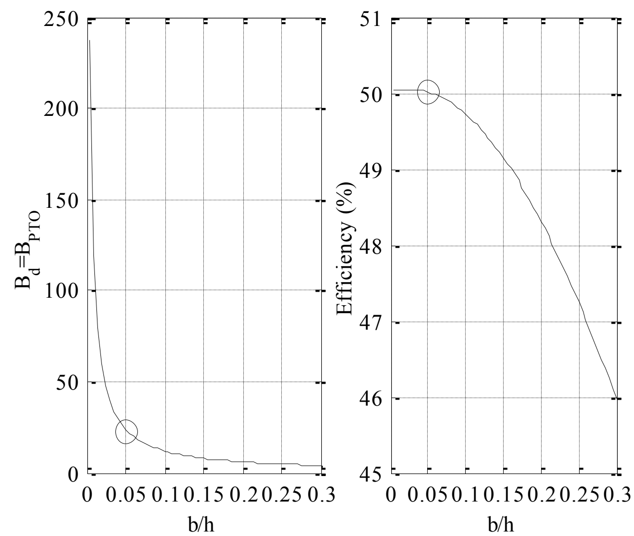

Figure. 2.-Bpto vs b/h for resonance conditon (Bpto=Bd) and optimal performance (left) and Performance vs b/h for Bpto=24, c/h=1, s/h=0.25 and T=9 s.

These results allowed for the selection of b/h=0.05, which gives a high efficiency and a not so large value of the *Bpto* parameter. On Figure 3, the variation of efficiency with the dimensionless length of the flap (c/h) (upper graphic) and the density of the flap (lower graphic) are shown.

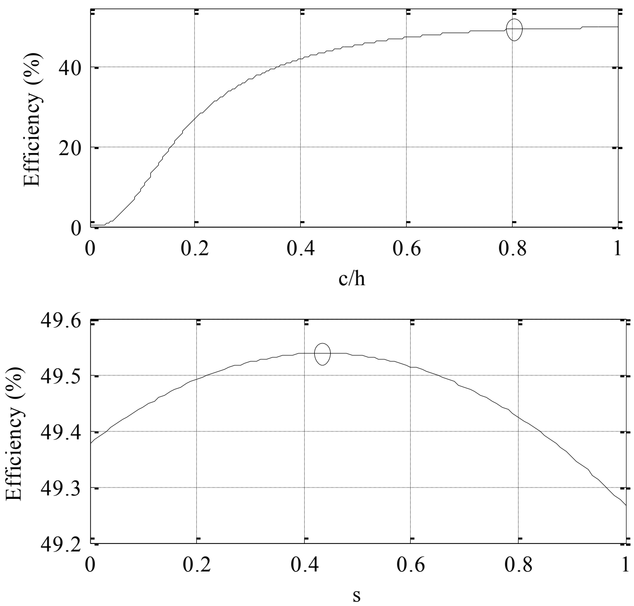

Figure. 3.-Performance sensibility to c/h (upper), s (middle) and Bpto (lower). In all the graphics b/h = 0.05, h=8 m and T=9 s are considered.

From these results, c/h=0.8 was selected, as for larger values of c/h resulted on insignificant increments of the efficiency. It can be also observed that the efficiency does not vary much with flap density, and reaches a maximum for s=0,45.

Table I shows the proposed configuration, and the obtained efficiency curve is shown on Figure 4.

TABLE I. SELECTED VALUES OF THE DIFFERENT PARAMETERS OF THE DEVICE

b/h	*c/h*	*s*	*Bpto*
0.05	0.8	0.45	24

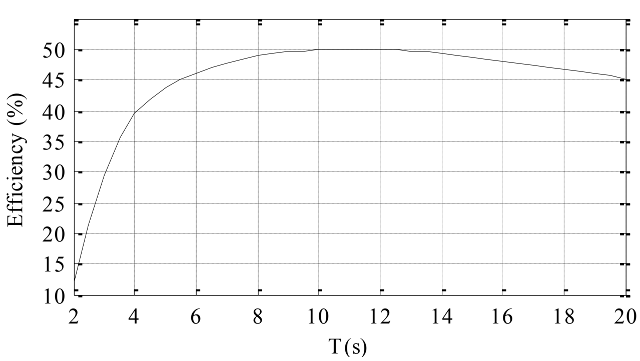

Figure. 4.-Performance curve of the proposed device.

B. *Technical potential estimation*

A selection of the time series of the estimated WEC power output is presented superimposed to the omnidirectional waves power on the Reference Point, is shown in Figure 5. Figure 6 shows the annual omnidirectional wave energy on the Reference Point during the analyzed years (upper graphic), the estimated annual WEC energy output (middle graphic), and the annual performance (lower graphic). The annual performance is defined as the ratio of the annual WEC energy output and the annual omnidirectional wave energy available at the Reference Point.

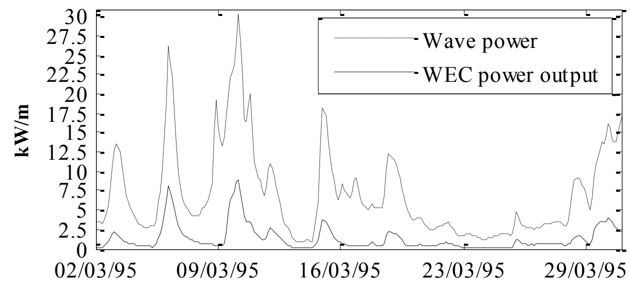

Figure. 5.-Comparison of temporal series of estimated power captured and omnidirectional power of waves at the reference point

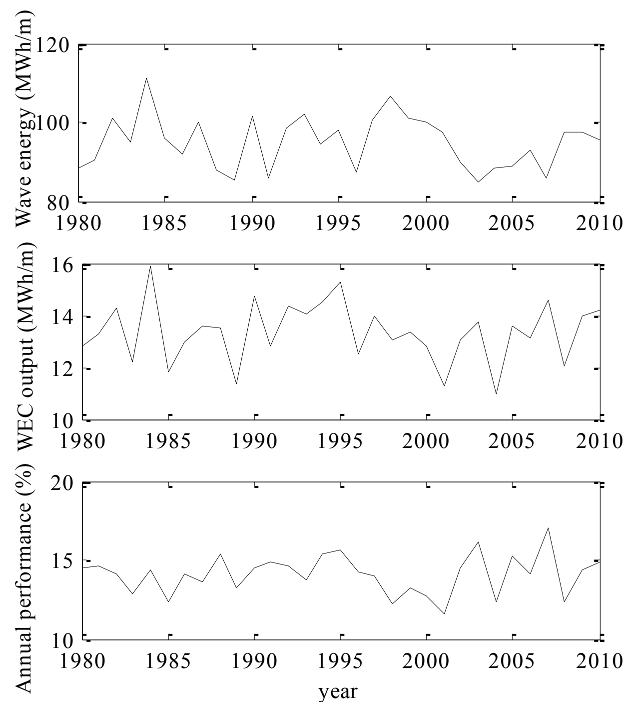

Figure. 6.-Annual wave energy at the reference point (upper), estimated annual captured energy (middle) and annual performance (lower).

The computations resulted on a mean annual WEC energy output estimation of 13 MWh per meter of flap width, corresponding to an average annual performance of 14.1%.

It is understood that a major fraction of the wave energy can't be captured due to the orientation of the incident waves to the breakwater. Thus, in order to improve the WEC performance, it is necessary to locate the WEC away from the breakwater pointing to the predominant waves, or alternatively to look for another type of WEC that allows to harness the wave energy coming from any direction (e.g. Point absorber WEC).

Regarding the temporal variability, small differences are observed along the different years. However, Figure 7 shows the estimated monthly average WEC power output, which shows a clear seasonal cycle. Note that the June output doubles the December or January ones.

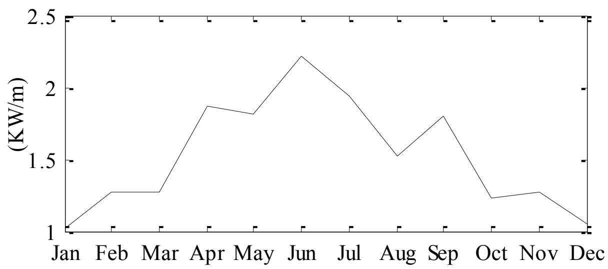

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Figure. 7.-Annual cycle of monthly mean power captured.

IV. CONCLUSIONS

A simplified analytical model of a flap-type wave energy converter was described. The model allowed to define the main characteristics of a device that maximize the energy harnessed working under a typical wave conditions of the Uruguayan Atlantic coast. The efficiency curve of the device was also obtained.

Combining the efficiency curve with wave spectra data available for the zone, and the orientation of the flap, a method to estimate the output energy of the device (i.e. technical potential) was proposed.

Considering a device located on La Paloma Harbor breakwater, the orientation of the device was assumed. For that orientation, the WEC is capable of harness the 14.1% of the average annual wave energy.

Regarding the temporal variability of the estimated output energy, a low inter-annual variation and a clear seasonal variation were observed.

In order to improve the reported results, two analysis are planned. First, a physical model of the proposed device will be installed in a large wave flume. This study, will allow to improve the efficiency curve. Second, a detailed wave propagation from the Reference Point to the breakwater will be performed in order to have a better characterization of the incident wave climate.

Beyond the improvements that could be reached with a more and deeper analysis, the obtained results are considered a reasonable approximation to the study of the technical potential of a flap-type WEC installed on La Paloma harbor breakwater. This study showed that due to the oblique orientation of the breakwater with predominant waves, a flap-type WEC would not be able to harness much of the wave energy, and in order to increase the technical potential, a flap-type WEC must be located away from the breakwater pointing to the predominant waves.

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