Algorithm for the search of the secondary converter optimum impedance in a punctual wave energy converter

M.C. Paz, D. Simón, J. Porteiro, E. Suarez

Department of Mechanical Engineering ETSEI University of Vigo
Lagoas-Marcosende, 36200 Vigo Spain

Abstract

In this work an algorithm is presented with the purpose of calculating the design requirements that can be imposed to the secondary converter (composed by the electrical generator and other mechanisms) in order to allow the buoy of a wave energy converter system to extract the maximum power from the ocean in each scenario. The physical simulations are carried out by a Simulink model, coupled with a Matlab code that performs the optimization of the generated power.

Keywords: heaving buoy, wave energy converter, power optimization

1 Introduction

Every system for the production of electrical energy must be devised considering the minimization of the energy cost as the fundamental target, therefore the manufacture and maintenance costs and those derived from the consumption of the energy source must be taken into account. This work deals with punctual (a buoy) wave energy converters (WEC). Since the amount of energy contained in the seas is huge and it is free, the critical point in this case is to make the most of the system installed.

The WEC systems analyzed in this work can be divided into two main parts, based on the kind of energy implied. On the first hand, there is the primary converter being its mission the conversion of the wave energy into the alternative movement of the buoy; on the second hand, there is a secondary converter subsystem, formed by the mechanical transmission, the electrical generator and its regulator, the mission of which is to convert the movement of the buoy into electrical energy. In general, the efficiency of the primary converter is the most critical of both, hence it is extremely important to optimize this part of the system, while the secondary converter should be designed to fit to the conditions imposed from the primary converter[1, 2].

In this paper an initial exploration in this subject is carried out, and a search algorithm is shown for the optimization of the extracted energy with a given buoy geometry for all the different sea states. At present, it is couple to a unidimensional model, but the long run objective is its integration with a CFD code, thus the initial solution obtained with the unidimensional model can be refined with the much more advance and realistic physics that can be used in CFD.

© Proceedings of the 8th European Wave and Tidal Energy Conference, Upssala,Sweden, 2009

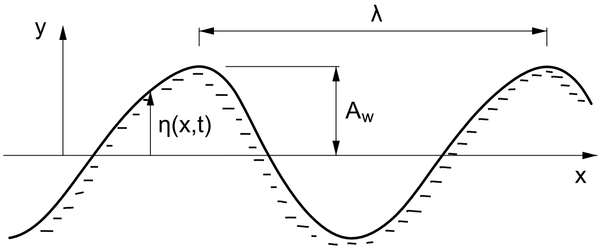

Figure 1: Parameters of a wave.

2 Linearized equations for monochromatic waves

The following hypothesis will be assumed:

- The linear theory for the wave physics can be applied.
- The sea has an infinite water depth.
- The waves only have progressive component.
- Monochromatic waves.
- Since this study is about punctual converters, the coordinate x is restricted to $x = 0$.

In this case, following [3], the expression for the free surface of the buoy is:

$$[\eta\,(x,t)]_{x=0} = \mathrm{Re}\left\{A \cdot e^{i\omega t}\right\} \tag{1}$$

or

$$\eta\,(t) = \mathrm{Re}\left\{\hat{\eta} \cdot e^{i\omega t}\right\} \tag{2}$$

where the hat symbol, "^" , denotes a phasor.

As shown in figure 1, the surface of the wave is measured from the equilibrium plane of the free surface when the ocean is at rest. This reference frame is applied to all the other magnitudes in this paper.

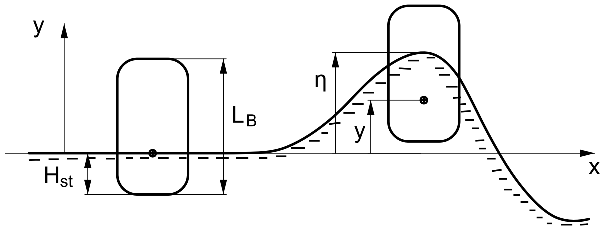

Figure 2: Reference frame for the buoy.

The pressure under the free surface of the wave can be expressed as:

$$p(y,t) = \rho g \left(\eta \cdot e^{\kappa y} - y\right) \tag{3}$$

For large periods, the hydrostatic approximation can be employed and the expression of the pressure becomes:

$$p(y,t) \approx \rho_w g \left(\eta - y\right) \tag{4}$$

3 Interaction forces between waves and solid objects

According to [4], if the following hypothesis can be made:

- the dimension of the buoy is much smaller than the wave length,
- the movement of the buoy is restricted to heave mode,

the total vertical force can be approximated by the pressure force plus the viscous drag:

$$f_y(t) = \rho g S_B (\eta - y) + \frac{1}{2} C_D \rho S_B (\dot{\eta} - \dot{y}) \|\dot{\eta} - \dot{y}\| \tag{5}$$

where the drag coefficient is reported to be around an unitary value [5]. Therefore, it is taken here:

$$C_D = 1 \tag{6}$$

As can be seen in figure 2, the position of the buoy is measured from the position of hydrostatic equilibrium. Therefore, the expression 5 is the sum of the interaction forces between the fluid and the solid and the self weight of the buoy.

Although this is a rough approximation of the implied forces, it must be remarked that the purpose of this work is initiate a path to search the optimum possible characteristic of the generator in every sea state. It would be desirably to continue with the refinement of the solutions that can be obtained through this approximation with the more realistic physics achievable by CFD.

4 Equation of the heave movement for a punctual buoy

The heave movement of a buoy floating on sea waves and connected to an electrical generator can be expressed as:

$$m_B \ddot{y} = f_y(t) + f_G(t) \tag{7}$$

where $f_G(t)$ is the force that the generator imposes to the buoy, whether directly or through any kind of mechanism.

Expanding the above equation and renaming the coefficients, we have:

$$m_B \ddot{y} = k_B \left(\eta \cdot e^{ky} - y\right) + b_B (\dot{\eta} - \dot{y}) \|\dot{\eta} - \dot{y}\| + f_G \tag{8}$$

$$k_B = \rho g S_B$$

$$b_B = \frac{1}{2} C_D \rho S_B$$

where the proportional coefficients k_B and b_B are a *stiffness* and a *mechanical resistance*, respectively.

Note that, although the physics of the waves is linear, the interaction between waves and buoys is nonlinear.

5 Searching algorithm for the optimum generator

5.1 Optimum generator for a linear system

For the sake of clarity, it is supposed in this paragraph that the movement equation of the buoy can be expressed in a linear form:

$$m_B \ddot{y} = k_B^{'} (\eta - y) + b_B^{'} (\dot{\eta} - \dot{y}) + f_G \tag{9}$$

This simplification is not maintained in the optimization algorithm (where 8 has been applied), it is employed only in this section to show the qualitative effect of the secondary converter over the system performance.

The above mentioned equation can be rearranged, moving all the terms that specifically depend on the buoy movement to the left, and all the terms that do not to the right (the generator force f_G will be shown to depend on the buoy movement too, but we will let it be in the right side).

$$m\ddot{y} + b_B \dot{y} + k_B y = f_E + f_G \tag{10}$$

$$f_E = b_B \dot{\eta} + k_B \eta$$

where f_E is the external excitation force of the buoy.

If an harmonic incident wave is assumed, the last equation can be rewritten in terms of phasorial magnitudes, depending on the velocity:

$$Z_i(\omega) \hat{U} = \hat{F}_E + \hat{F}_G \tag{11}$$

Note that the impendance is a complex magnitude formed by a real resistance and a imaginary reactance: $Z_i = R_i + X_i$

Following [3], the generator force acting on the buoy can be expressed as:

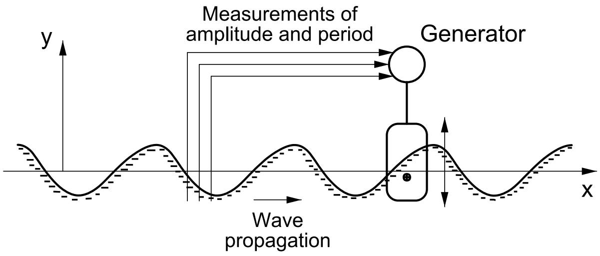

Figure 3: Control system for a punctual wave energy converter.

$$\hat{F}_G = -Z_G(\omega)\hat{U} \tag{12}$$

and the optimum power that the primary converter can pass to the generator is achieved when:

$$Z_G(\omega) = Z_i^*(\omega) \tag{13}$$

As shown, if the system is considered linear, the optimum generator could be calculated by hand, but there are two main problems with this approach:

- The real system is nonlinear. Although it was the first approximation made in 8 this hypothesis is too strong and a nonlinear approach should be considered.
- The generator impedance condition, as expressed above, implies that the wave-buoy system is resonant, hence very large amplitudes of the movement of the buoy are reached. This would imply indefinitely high buoys and maybe too heavy inertial forces in the mechanisms due to their velocity. Instead, a suboptimum generator impedance that fits to a finite, given buoy size is required. The buoy should never sink or emerge totally.

5.2 Searching algorithm for the realistic optimum generator

The main objective of this work is the implementation of a searching algorithm in *Matlab* that obtains the best possible secondary converter for each state of the sea. Therefore, the impedance of the generator is obtained as a discrete function of the wave amplitude and period:

$$Z_G = Z_G(A,T) = R_G(A,T) + X_G(A,T) \tag{14}$$

The algorithm is passed through matrix of sea state points -A,T pairs- and searches the impedance for the secondary converter that accomplishes the highest generated power respecting the amplitude limits imposed by the buoy.

Once a look-up table of the generator impedance values is obtained, it can be used to program a controller that measures the period an amplitude of the incoming waves and set the generator in consequence, as can be seen in figure 3.

For each sea state, the algorithm performs the searching as follows:

1. It Loops through the range of reactances: $X_G \in (-X_i, +X_i)$ with a big step. For every reactance visited, it performs a search of the best resistance that also fits the amplitude limitation, following a staircase type algorithm.
   (a) It starts with $R_G = 0$
   (b) Then, it moves to a bigger resistance, separated by a quite big step, and continues while a higher power is achieved.
   (c) When the maximum power is achieved, the distance between two consecutive iterants is reduced. The algorithm will then search in both directions (bigger and smaller resistances) trying to increase the generated power.
   (d) Once it cannot find a better point, the resistance step is reduced one more time
   (e) Finally, a fine tuning is performed.

   The purpose of the straightforward loop through reactances is to find a valid initial point, because many failures due to the amplitude limitation can occur for different rectances. This way, the algorithm will not stop until a valid reactance can be found.
2. Once a valid resistance-reactance pair is found, the algorithm starts to jump forward and backward with the same step trying to find a better reactance. At every iterant the subsearch of the best resistance will be performed, and the obtained power will characterize that particular value of the reactance.
3. When no higher power can be achieved, the step between reactances is reduced.
4. A final second refinement and a last tuning is made.

5.3 Simulink model for the buoy movement

The explained algorithm needs to be connected to some numerical model that computes the physics of the system. The searching algorithm passes values of wave amplitude and period and impedance of the generator, while values of the power produced are returned by the numerical model of the buoy-wave-generator system.

Simulink was used to build the numerical model, as is presented in figures 4, 5 and 6. Note that the generator is modeled to use an impedance of the form:

$$Z_G(\omega) = b_G - \left(m_G\omega - \frac{k_G}{\omega}\right)i = R_G + X_G i \tag{15}$$

which would have the same form as the conjugate of 13. Nevertheless, since obtaining a discrete lookup table of impedance is the main focus of this work, only one of the two imaginary components $m_G\omega$, k_G/ω is needed to be set. In this case, m_G was set to be null. while the desired reactance will be obtained through k_G, hence:

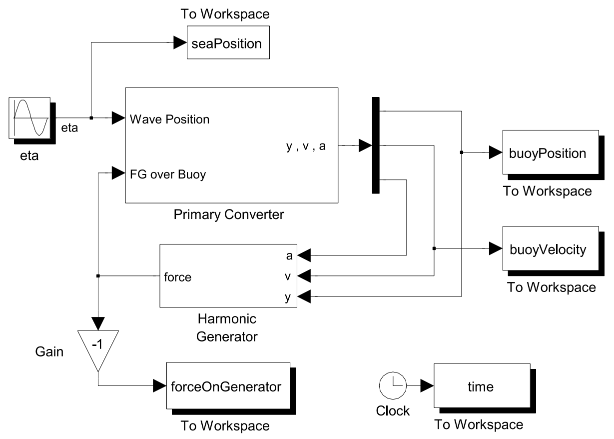

Figure 4: Simulink global model.

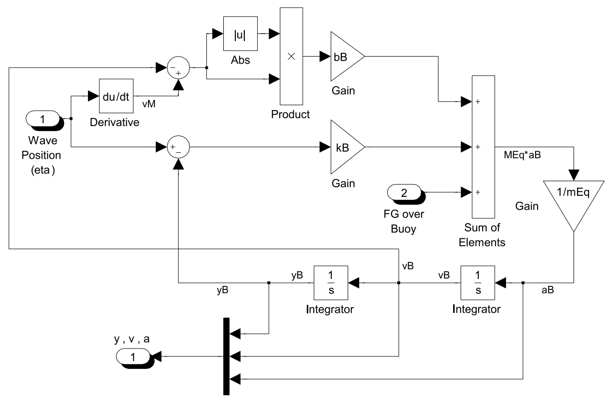

Figure 5: Simulink subsystem for the buoy.

$$R_G = b_G \tag{16}$$

$$X_G = \frac{k_G}{\omega} \tag{17}$$

6 Obtained results for a certain buoy

In order to illustrate the results that can be obtained with this tool, it is applied on a certain imaginary buoy, with the following parameters:

- Buoy diameter: $1.5\,m$
- Buoy height: $2\,m$
- Buoy specific gravity: 0.5

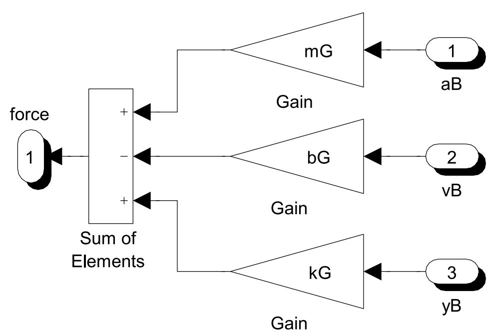

Figure 6: Simulink subsystem for the generator.

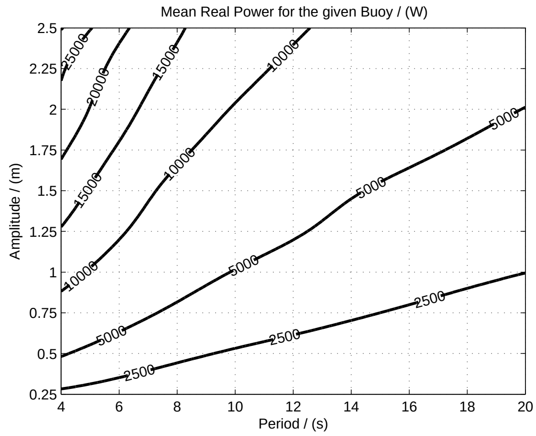

Figure 7: Maximum power achievable for the given buoy.

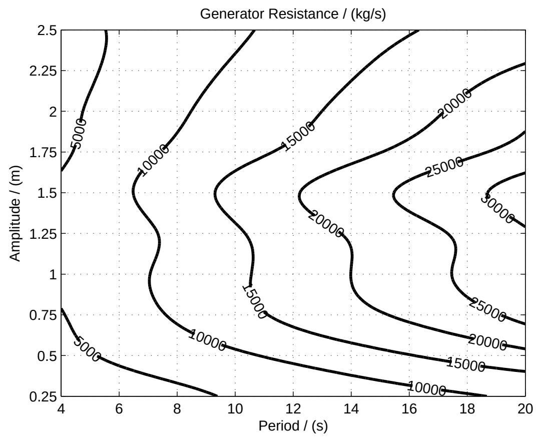

Figure 8: Resistance of the generator needed to obtain the maximum power

- Security factor in the maximum and minimum allowable difference between the positions of the wave surface and the buoy hydrostatic equilibrium point: 0.9. This means that the top of the buoy is limited to be $0.9\,m$ over the wave surface, and its bottom is limited to be $0.9\,m$ under the wave surface.
- Range of wave periods: $(4-20)\,s$
- Range of wave amplitudes: $(0.25-2.5)\,m$

The ranges of amplitude and period were chosen to cover all the measured sea states at Villano Cape, located in the northwest of Galicia, Spain, according to [6].

The obtained results for this case can be observed in figures 7 to 9. The maximum achievable produced mean power is shown in figure 7, while the impedance needed for that is presented in figures 8 and 9. In all the situations the path covered by the buoy is the maximum allowed.

7 Conclusions and future lines

An computer tool that helps on the design of controllers for secondary converters in WEC systems has been developed in this work. It obtains look-up tables

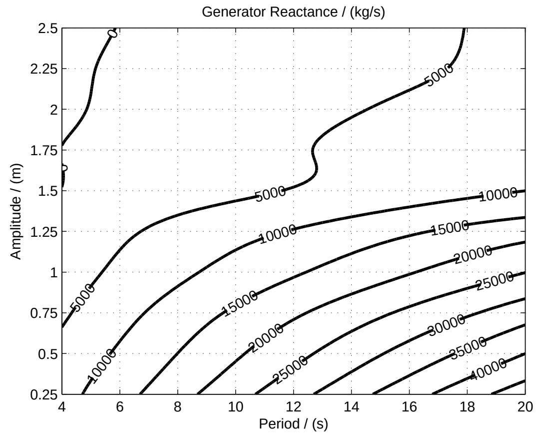

Figure 9: Reactance of the generator needed to obtain the maximum power.

for the required values of the impedance in this part of the system so maximum mean power can be produced. These values for the impedance depend on the specific wave amplitude and period.

An attractive next step in these search would be the implementation of these searching algorithm into a CFD code where, with the help of the VOF method, these rough initial solutions can be tested and refined with a much more realistic physics frame.

References

[1] J.K.H. Shek, D.E. Macpherson, M.A. Mueller, and J. Xiang. Reaction force control of a linear electrical generator for direct drive wave energy conversion. *IET Renew. Power Gener.*, 1:17–24, 2007.

[2] H. Lendenmann, K-C. Stromsem, M. Dai Pre, W. Arshad, A. Leirbukt, G. Tjensvoll, and T. Gulli. Direct generation wave energy converters for optimized electrical power production. In *Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal*, 2007.

[3] J. Falnes. *Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction*. Cambridge University Press; 1 edition, 2002.

[4] Prof. Dick K. P. Yue. *Marine Hydrodynamics*. MIT Open Courseware (online), 2005.

[5] A. Techet. *Design Principles for Ocean Vehicles*. MIT Open Courseware (online), 2005.

[6] Goverment of Spain Ministry of Public Works. Clima medio de oleaje. boya de villano (in spanish). 2007.